

Numerical and Experimental Evaluation of the Use of a Glass Fiber Laminated Composite Materials as Reinforcement in Timber Beams

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Abstract Beams are structural elements present in most structures. In the case of materials commonly used in construction highlight the wood, being a renewable source material, low density and good mechanical performance. Structures built with wood, if not handled properly, can present problems that may impair the purposes for which they were designed, requiring solutions in the form of repair or reinforcement. This study aimed to assess, experimental and numerically, the mechanical performance with the employment of a glass fiber laminate composite as reinforcement in *Eucalyptus grandis* and *Pinus elliottii* wooden beams. The woods were mechanically characterized in bending, shear parallel to grain, strength compression parallel to grain and tensile parallel to grain. The fiber glass laminate composite was characterized in tensile and pullout in wood, allowing to verify the shear strength in the interface composite-wood. To check the mechanical performance of use of the reinforcement, the timber were tested experimentally and numerically according the three points static bending structural model, with the conditions: without defects, with defects and with and without the reinforcement. The results obtained proved to be efficient the use of the laminates composite as reinforcement in the wooden beams evaluated, and under the usual conditions of services, the numerical simulations have provided good approximations, demonstrating the strength of the materials being higher the active stress components.

Keywords Laminate composite materials, Timber beams, Structural reinforcement, Finite element method

1. Introduction

The woods stand out among the other building materials (steel and concrete), due to its good mechanical performance combined with low density [1], besides being a natural material and renewable [1-4], being present in bridges, roofing and other applications [5]. However, the conduct of some construction details combined exposure to different environmental conditions influence the durability of structural elements [6], which required strengthening or repair techniques for damaged structures.

Besides the condition of reinforcement structures already designed, the use of reinforcing materials in structural design to be executed increases the potential use of structural components made of wood, which according Miotto and Dias [7], the low modulus of elasticity of wood when

compared to other structural materials, causes deformations are limiting factors in a project of wooden beams.

Brazil has more than seventeen areas tumbled as patrimony of humanity. [7] However, the various constructions inserted in these areas of architectural heritage are largely made of wood, standing for decades without maintenance. In addition to the actions of the time, the wooden structures interact with the environment in which they live cycle, by helping reduce their initial properties, consisting biological attack as a major cause of degradation.

To rehabilitate the structural elements of wood, you can opt for the replacement of damaged parts or by solidarization elements that complement the mechanical capacity of the structural elements compromised. The first option is the most common technique, with limitations such as the unavailability of spare timber for proper replacement, environmental costs and yet the scarcity of the materials involved. Therefore, the second alternative becomes more attractive, and these limitations arise in the context of natural or synthetic bonding techniques fabrics impregnated with resin as a means of enhancing [8].

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Aiming to study the repair and reinforcement for wooden beams, many studies are being developed, emphasizing the use of fiber-reinforced polymer FRP [8].

Fiorelli [9] analyzed experimentally the mechanical performance of employing fiber-reinforced polymer (glass and carbon multilayer) fixed along the inferior part (tensile region) of wooden beams of the *Pinus elliottii* and *Eucalyptus grandis* species. In addition to other results, the authors concluded that the technique developed proved to be of simple application and presents an interesting feature, the presence of a large deformation before rupture, justified by lowering the neutral axis, causing compression of a large amount of wood, emphasizing the use of fiber-reinforced polymer FRP [8].

In this context, Campilho *et al.* [10] evaluated experimentally the influence of the use of laminated composite materials such as carbon fibers as reinforcing beams. For this, the authors made use of the four points static bending, simulating the presence of the defect with the removal of a portion of wood (*Pinus Pinaster*) over the region requested by tensile stresses (upper and middle point of the beam), as illustrated in Figure 1. The results of experimental analysis revealed that the laminated composite designed to tensile stresses, inserted in the same region as requested by compressive stresses, but still was able to increase the mechanical strength of the assembly.

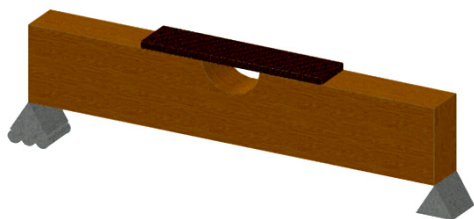


Figure 1. Mechanical model used to study the use of the laminate composite in carbon fibers

Other experimental work involving the use of rolled by synthetic fibers (glass and carbon) as reinforcement in wood pieces can be cited [11-20], proving to be favorable in all surveys, the use of composites as reinforcement in the structures investigated.

Besides the use of synthetic fibers in composites for the repair and reinforcement on wood, natural fibers also has been presented as alternative solutions to this problem.

Miotto and Dias [7] discuss the use of natural fibers (sisal) as a way of strengthening beams in glued laminated timber (MLC), showing up as a favorable alternative for a better use of forest resources in Brazil. The authors conclude, among others, that the addition of fibers pulled on the face of the wood ensures excellent mechanical performance in strength, however, being modest contribution in terms of rigidity. Also discuss the strength of the MLC can be improved by adding glass fibers or carbon pulled in the region, resulting in increased reliability of the material and a reduction of 30% to 40% in volume of wood used. It is further the reinforcement applied at a rate of 2% to 3% may increase the flexural beams MLC over 100%.

Carvalho *et al.* [21] investigated experimentally the influence of the employment of laminate composite in sisal fibers as reinforcement in wooden beams of *Eucalyptus grandis* and *Pinus elliottii* species, comparing the results of applied loads in the three points static bending between conditions: beam without defect, with defect and with and without composite, and the defect represented by withdrawing a portion of the timber located at the midpoint of the beam and on its lower face (tensioned), and defective beam and with the addition of the laminated composite, and the displacements at the midpoint of the beam limited the reason $L/200$ (L - length of the beam), measure small displacements defined by the Brazilian standard ABNT NBR 7190 [22] which ensures linearity and geometry of the beams tested. Among others, the authors concluded that the use of manufactured composite material was capable of increasing the load value as compared with the wooden beams with defect and without composite and the near lower value of the load applied on the intact timber condition (no defect).

In this context, the present study aimed to investigate, numerically (finite element) and experimental (mechanical characterization of materials), the contribution of the use of laminate composite in glass fibers as reinforcement in wood beams (specimens) of *Eucalyptus grandis* and *Pinus elliottii* species, allowing you to evaluate the accuracy of the numerical model, containing some simplifying assumptions calculation (disregard the anisotropy of wood and ideal interface between wood and composite), in anticipation of relations: load and displacements obtained from experiments (three bending test points). The largest displacements in trials (the midpoint of the parts) are limited as $L/200$ (L is the length of the part), as requires by the Brazilian standard ABNT NBR 7190 [22] for the limit state (ensuring linearity physical and geometric on the pieces), and experimental conditions investigated beam intact (no defect) and the beams defects (portion of material removed from the flexural test specimens) and with and without the presence of laminated composites. The results of numerical simulations can contribute by assisting in the development of projects involving both structural materials under service conditions.

2. Materials and Methods

As previously mentioned, the woods *Eucalyptus grandis* and *Pinus elliottii* species were tested numerically and experimentally.

To verify the efficiency of use of laminated glass fibers composite as reinforcements in beams, assays were performed with three points static bending, considering nineteen experimental conditions (EC) to be investigated for the species (Table 1), designed by the product of the experimental levels of factors: height (h) of the defect (5 mm; 10mm, 15mm), width default (L) (20mm, 40mm, 60mm) and the presence of the laminate composite (with, without) together with the reference condition (without defects), the defect in the timber designed for the removal of small

portions of material from the lower surface and the midpoint of parts, as illustrated in Figure 1.

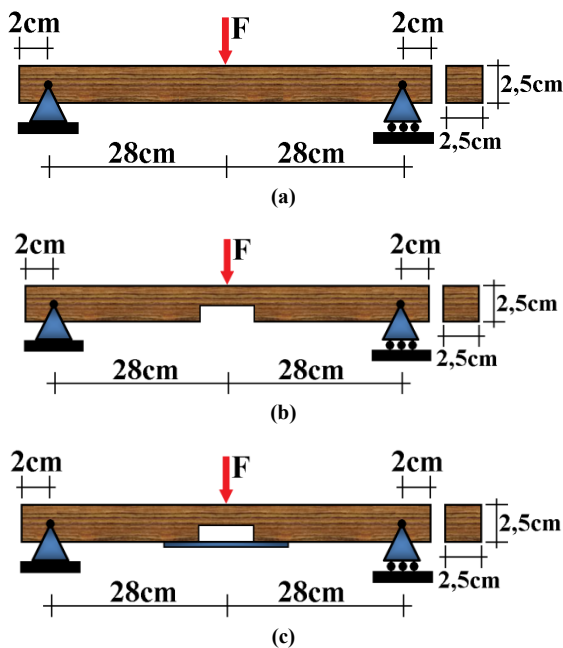


Figure 1. Beams intact (a), with defect and without the composite (b) and with defect and with the laminate composite

Table 1. Experimental conditions investigated by wood species

CE	h (mm)	Defect		Composite	
		A (mm)	with	without	
C1	0	0		X	
C2	20	5		X	
C3	20	10		X	
C4	20	15		X	
C5	40	5		X	
C6	40	10		X	
C7	40	15		X	
C8	60	5		X	
C9	60	10		X	
C10	60	15		X	
C11	20	5	X		
C12	20	10	X		
C13	20	15	X		
C14	40	5	X		
C15	40	10	X		
C16	40	15	X		
C17	60	5	X		
C18	60	10	X		
C19	60	15	X		

For experimental evaluation of the mechanical performance of the employment of laminated glass fiber composite as reinforcement, each of 18 experimental faulty conditions were prepared two timber specimens (60cm×2.5cm×2.5cm) "twin" a e a^* - Figure 2), obtained from six pieces of wood (7cm×9cm×140cm), three of each species.

The trials consisted in discovering, in each condition, the value of load in bending test responsible for causing an offset in the mid-span of approximately $L/200$ (L - are useful part),

thereby ensuring linear elastic behavior of wood tested [22]. Known values of the loads in all cases, these conditions were compared with defect and without composite (conditions C2 to C10, Table 1) and defective and reinforced (C11 to C19 conditions, Table 3.1), thereby judging the efficiency the use of laminates to reinforce it.

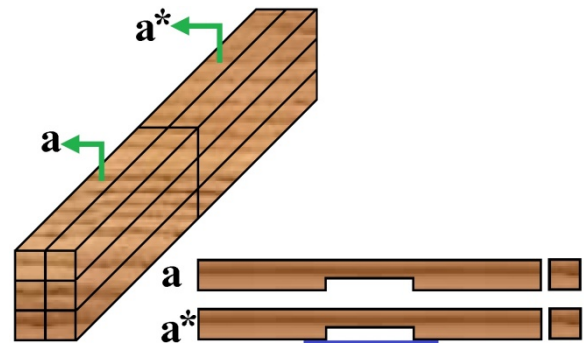


Figure 2. Obtaining specimens for bending tests

Six specimens (60cm×2.5cm×2.5cm) of each species were prepared and tested in bending (non-defective parts - references), obtained the elastic moduli and the respective values of the loads responsible for causing 2.8mm of displacement at the midpoint. With the average loads, this was compared with the values of the load of the eighteen other experimental conditions enabling evaluate primarily faulty conditions and the wit the composite (C11 to C19 conditions, Table 1) the values obtained between the loads.

With respect to numerical simulations, developed with the help of ANSYS® software, version 14, based on the Finite Element Method (FEM), they were made with possession of the load values obtained from experiments on the nineteen conditions evaluated, aiming to verify that the displacements obtained from simulations approached or not arising out of the trials (2.80mm). Besides displacement, was also evaluated with the help of software, the field of shear stress in the wood and in the interface between the wood and the composite, and the normal tensile stress (laminated wood) and wood in compression, enabling check, in the operating conditions [22] where the stresses acting exceeded or not the value of the respective strength of the materials used, these being properly characterized.

To perform the simulations relating to nineteen experimental conditions investigated was itself used the average value of the modulus of elasticity of six specimens of wood from both species, noting that these are obtained from different batches of wood used in trials involving the eighteen defective experimental conditions. The Poisson's ratio was null in the simulations, due to the lack of information regarding its acquisition by Brazilian standard ABNT NBR 7190 [22], a hypothesis commonly used in projects of wooden structures.

Although the simulations, the modulus of elasticity of the composite was used for the average value of the results of specimens (18) tested and Poisson's ratio (0.35) of the laminates was taken with the epoxy resin being obtained from the research of Ferreira et al. [8].

2.1. Characterization of Materials

As previously mentioned, the wood outside characterized in bending (modulus of elasticity in bending - E_m), tensile (tensile strength parallel to the grain - $f_{t,0}$), compression (compression strength parallel to the grain - $f_{c,0}$) and shear (shear strength parallel to the grain - $f_{v,0}$) and the composite in tensile (modulus of elasticity (MOE_t) and tensile strength - MOR_t) and pullout (shear strength in wood-composite interface - R_{cis}).

The woods were characterized according to the assumptions and calculation procedures of the Brazilian standard ABNT NBR 7190 [22]. It is noteworthy that the wood of both species had its moisture content adjusted to 12% [22], and further experimental tests were performed.

The glass fiber composites (two layers) were characterized according to American Standard ASTM D6856 [23], and with respect to pullout tests was used the Brazilian standard ABNT NBR 7190 [22], adapted to uniaxial tensile testing [9].

2.1.1. Wood

2.1.1.1. Bending

Bending tests (Figure 3) in solid wood beams or "damaged" of both species were executed with the help of the EMIC MEM 10000 testing machine, with load capacity of 10 tons, located on the mechanical laboratory test of the Department of Mechanical Engineering of the Federal University of São João del-Rei (UFSJ).

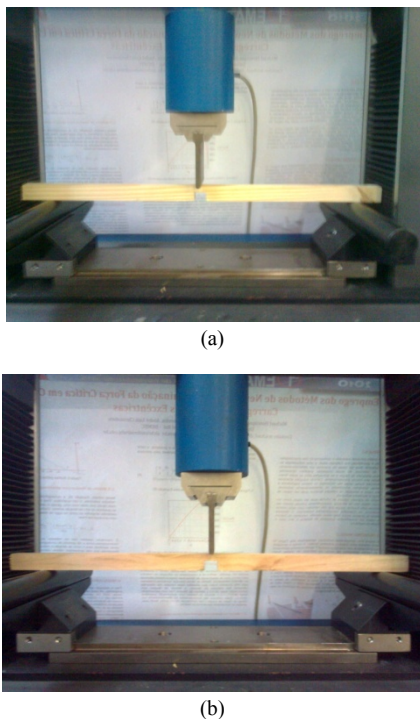


Figure 3. Bending test: (a) Pinus e (b) Eucalipto

The size of the specimens for the bending test by the Brazilian standard ABNT NBR 7190 [22] is $115 \times 5 \times 5$ cm,

whose relationship between effective length (L) of the piece (110cm) by height (h) of section (5cm) is greater than 21, as displayed in research of Rocco Lahr [24], stating that for ratios $L/h \geq 21$ the effect of shear forces in the calculation of the displacements may be discarded. The specimens tested here have small dimensions ($60 \times 2.5 \times 2.5$ cm), however, being respected the relationship between length and height of the cross section shown in the work of Rocco Lahr [24].

With respect to experimental conditions related to damaged wooden pieces with the use of reinforcement, regardless of length or width of the defect (20mm, 40mm, 60mm), the total area of bonding the composite was kept constant and is equal to 10.5 cm^2 at all cases (Figure 4).

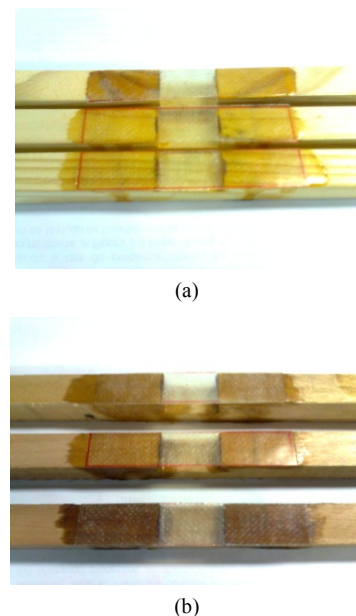


Figure 4. Pinus (a) and Eucalipto (b) timber beams reinforced with the laminate composite materials

2.1.1.2. Tensile and Compression Parallel to the Grain

Compression tests (Figure 5) and tensile parallel to the grain in the wood specimens (Figure 6) of both species were performed with the aid of a universal testing machine EMIC MEM 10000, being the same as used in static bending.



Figure 5. Compression test parallel to grain accomplished with the aid of the universal testing machine EMIC MEM 10000

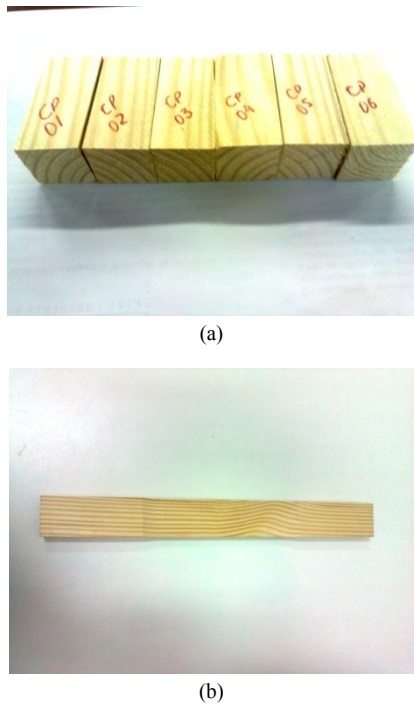


Figure 6. Specimens for compression tests (a) and tensile (b) parallel to the grain of the wood

To obtain the compressive strength and tensile strength parallel to the grain were manufactured six specimens per species [22].

2.1.1.3. Shear Parallel to the Grain

Assays for determining the strength shear parallel to the grain of the wood were carried out within the Laboratory of Wood Structures (LaMEM) Department of Structural Engineering, School of Engineering of São Carlos (EESC/USP), using six specimens by wood species [22].

2.2. Laminate Glass Fiber Composite

The matrix used in the preparation of laminated composites was epoxy type of Huntsman M[®] company, with ratio resin/hardener from 5 parts to 1 (Huntsman[®]), density 1.13 g/cm³, this being related to the set-resin hardener.



Figure 7. Woven glass fiber used in the manufacture of the laminate composite

The fabric of bidirectional glass fiber (Figure 7) used as reinforcements in composite materials is of type "E" from Owens Corning, 240g/m² basis weight and density of 2.65g/cm³, obtained, as well as Epoxy Resin, Mundo da Resina companies, located in Belo Horizonte (MG), Brazil.

After preliminary tests to determine the volumetric proportion of fiber/matrix, to avoid unnecessary waste of material, ensuring that the entire fiber surface was covered with resin in the process of manual lamination (Figure 8), was set up as the best condition to be used was about 70/30 (matrix/fiber).

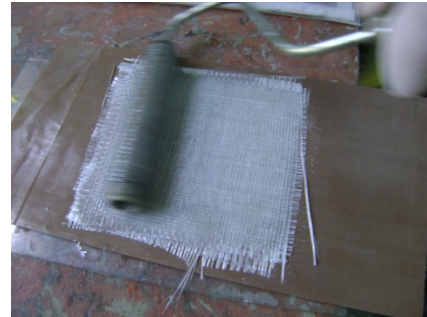


Figure 8. Manual lamination of the composites

Cut the two wovens (200×200mm) for manufacture of laminates was measured mass (m_f) fibers, and its known density (ρ_f), we determined the volume of fibers (v_f) by reason: $\rho_f = m_f/\rho_f$. Known their volume fibers, settled in three simple rule for the final compound with 70% matrix and 30 volume% of volume increase, enabling discover, from this, the volume ratio of the matrix, and the density matrix, its mass for the respective 70% by volume idealized.

The tensile tests were performed in a universal testing machine EMIC DL 500 (Figure 9), with a load capacity of 500kgf, located on the premises of the mechanical testing laboratory of the Department of Mechanical Engineering of the UFSJ.



Figure 9. Testing machine EMIC DL 500 used in the tensile test

To obtain the modulus and the tensile strength of the laminate composite (two layers), were produced two plates with dimensions: 200×200×1.3mm, being extracted nine samples (200×200×1.2mm) by plate (Figure 10).



Figure 10. Specimens of laminate composite for tensile tests

2.3. Pullout test

To perform the pullout tests, were manufactured two composite panels with measures $200 \times 200 \times 1.2$ mm, from which were withdrawn 20 specimens with dimensions $70 \times 15 \times 1.2$ mm, with 10 being fixed in ten specimens (sawn in half) of *Pinus elliottii* wood in tensile and the other ten specimens of *Eucalyptus grandis* species in tensile. Figure 11 illustrates a specimen of *Eucalyptus* wood for pullout testing.

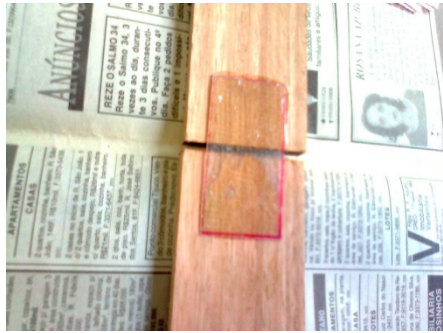


Figure 11. Specimen of *Eucalyptus* wood for the pullout test

The machine used in the pullout test was the same of test tensile, compression and bending (EMIC MEM 10000).

2.4. Numerical Simulation

The finite element used in the simulations was the PLANE183 element (ANSYS®), illustrated in Figure 12, having edge length of 0.30 mm for the beam and for the laminate.

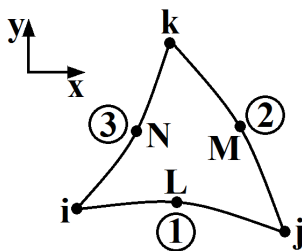


Figure 12. Finite element used in numerical simulations

As previously mentioned, to the achievement of numerical tests was considered as the wood was despised and isotropic material, and the composite Poisson's ratio was taken to be that of epoxy resin.

Wood, the modulus of elasticity used in the simulations was obtained for the average value of six specimens per species, and tensile modulus of the laminates composite was obtained from the average value of the eighteen specimens manufactured.

In addition to the normal and shear extreme stresses obtained from simulations, occurring at points in the angular geometry of the structure [25] located at the vertices of the notches (default), the vertices of the beam of rectangular geometry (at right angles) and the vertices of the composite laminate, the stress components were also obtained in mesh nodes predetermined as illustrated in Figure 13, making it possible to evaluate, in these regions the stress components acting exceeded or not the respective values of strength of wood and composite materials.

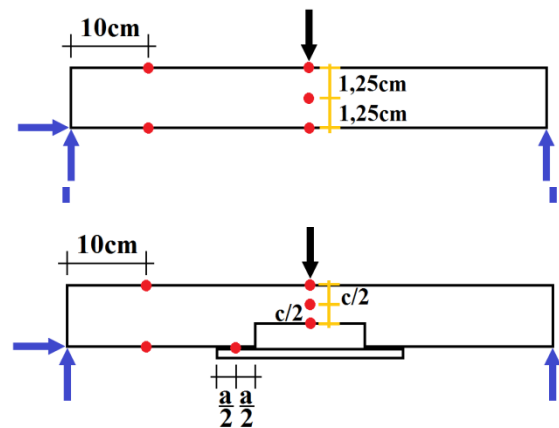


Figure 13. Mesh nodes selected to obtain the stress components

3. Results

Tables 2, 3 and 4 shows the mean values (X_m), the standard deviations (DP) and coefficients of variation (CV(%)) concerning the characterization of the mechanical properties of wood, the composite laminate and the interaction between the composite and wood respectively.

Table 2. Mechanical properties of wood

	<i>Pinus elliottii</i>			
	E_m	$f_{c,0}$	$f_{t,0}$	f_v
X_m (MPa)	10683	38,70	64,32	9,24
DP	1816	5,93	12,74	2,26
CV (%)	17	15	20	25
	<i>Eucalyptus grandis</i>			
	E_m	$f_{c,0}$	$f_{t,0}$	f_v
X_m (MPa)	11669	44,57	78,25	8,41
DP	3180	7,71	16,83	1,78
CV (%)	27	17	22	21

Table 3. Mechanical properties of laminate composite

	MOE _t (MPa)	MOR _t (MPa)
X_m	49676	851
DP	4492	61,02
CV (%)	9	7

Tabela 4. Pullout strength

	Pinus	Eucalipto
	R_c (MPa)	R_c (MPa)
X_m	11,70	15,22
DP	3,12	5,36
CV (%)	27	35

The mean values of tensile modulus and tensile strength of the laminates composite here manufactured (Table 3) were presented as intermediate values of stiffness and strength of composites with two layers of glass fibers manufactured by Fiorelli [9], obtained two distinct values of MOE (29187MPa; 71844MPa) and two distinct for MOR (410MPa, 1153MPa), justified by the different ways of calculation used.

The strength average pullout compounds glass fibers obtained from the interaction with the timber *Eucalyptus grandis* and *Pinus elliottii* in the research of Fiorelli [9] were respectively equal to 8.52MPa and 13.31MPa, being 11.70MPa and 15.22MPa the values of pullout strength of these species obtained in this study.

Tables 5 and 6 show the results of the load values obtained from the bending tests responsible for provoking displacements near 2.80mm on each of nineteen conditions investigated by type of timber, being CR the strengthened condition, SR the condition without strengthening and Diff the difference between the respective conditions.

Table 5. Results of strength tests on bending for *Pinus elliottii* wood regarding the nineteen experimental conditions investigated

Dimension (mm)	Forças (N)		
	SR	CR	Diff (%)
Referência	312,90		
20×5	200	230	13,04
20×10	120	160	25,00
20×15	120	280	57,14
40×5	300	330	9,09
40×10	120	140	14,29
40×15	100	120	16,67
60×5	120	160	25,00
60×10	100	170	41,18
60×15	50	110	54,55

Table 6. Results of strength tests on bending for *Eucalyptus grandis* wood regarding the nineteen experimental conditions investigated

Dimensões (mm)	Forças (N)		
	SR	CR	Diff. (%)
Referência	358,30		
20×5	260	290	10,34
20×10	150	190	21,05
20×15	60	180	66,67
40×5	230	290	20,69
40×10	170	230	26,09
40×15	90	210	57,14
60×5	230	300	23,33
60×10	110	200	45,00
60×15	60	160	62,50

Tables 5 and 6, as expected, the height of the defect showed more significant alleviation loads than the width of the grooves.

Table 7. Results of the numerical simulations for the *Pinus elliottii* wooden beams for the unreinforced condition

Dimension (mm)	δ_{max} (mm)	τ_{max} (MPa)
No defect	3,199	2,802
20×5	2,909	8,351
20×10	2,832	9,914
20×15	4,744	17,49
40×5	4,681	12,072
40×10	2,862	8,867
40×15	5,574	14,069
60×5	1,990	4,652
60×10	2,756	7,118
60×15	3,536	6,785

Dimension (mm)	$\sigma_{C,max}$ (MPa)	$\sigma_{T,max}$ (MPa)
No defect	17,439	14,022
20×5	20,222	30,869
20×10	20,523	31,898
20×15	43,909	62,584
40×5	30,426	44,649
40×10	20,297	30,765
40×15	36,354	50,376
60×5	12,13	17,206
60×10	16,889	24,708
60×15	18,197	24,296

Table 8. Results of the numerical simulations for the *Pinus elliottii* wooden beams for the reinforced condition

Dimension (mm)	δ_{max} (mm)	τ_{max} (MPa)
20×5	2,511	69,54
20×10	1,802	49,298
20×15	3,099	84,622
40×5	3,556	95,811
40×10	1,588	41,422
40×15	1,573	41,397
60×5	1,813	46,674
60×10	1,862	46,658
60×15	1,875	46,672

Dimension (mm)	$\sigma_{C,max}$ (MPa)	$\sigma_{T,max}$ (MPa)
20×5	21,042	94,109
20×10	14,917	66,714
20×15	25,605	35,556
40×5	28,985	129,644
40×10	12,532	56,050
40×15	12,530	56,042
60×5	14,306	63,306
60×10	14,178	63,285
60×15	14,275	63,275

With exception of defect 20×15mm for *Pinus caribaea* species in any of the remaining cases evaluated with the inclusion of the laminate was possible to obtain a value greater than the strength of the timber without defect (reference), contrary to the results found in the work of Campilho et al. (2010). However, it is noteworthy that the woods were not the same benchmark used in trials involving the use of composites, which can explain the differences

found between the results.

Comparing the results of the loads with and without the use of the laminate composite for the two wood species, it was found, the values of percentage differences found that the greatest contributions occurred in defects with dimensions 20×15mm followed by defects with dimensions 60×15mm.

Table 9. Results of the numerical simulations for the *Eucalyptus grandis* wooden beams for the unreinforced condition

Dimension (mm)	δ_{max} (mm)	τ_{max} (MPa)
No defect	3,514	3,362
20×5	3,204	10,045
20×10	4,372	18,432
20×15	8,707	35,063
40×5	3,437	9,680
40×10	5,251	17,770
40×15	12,276	33,489
60×5	3,653	9,326
60×10	6,069	17,125
60×15	15,596	32,614
Dimension (mm)	$\sigma_{C,max}$ (MPa)	$\sigma_{T,max}$ (MPa)
No defect	20,927	16,826
20×5	7,810	14,904
20×10	7,812	43,720
20×15	7,812	68,214
40×5	7,817	14,353
40×10	7,817	32,39
40×15	7,817	65,823
60×5	7,811	13,825
60×10	7,811	31,199
60×15	7,811	63,395

Table 10. Results of the numerical simulations for the *Eucalyptus grandis* wooden beams for the reinforced condition

Dimension (mm)	δ_{max} (mm)	τ_{max} (MPa)
20×5	2,98	84,750
20×10	1,98	55,512
20×15	1,879	52,561
40×5	2,949	81,386
40×10	2,39	64,524
40×15	2,656	69,900
60×5	2,567	66,070
60×10	2,075	53,025
60×15	1,780	45,000
Dimension (mm)	$\sigma_{C,max}$ (MPa)	$\sigma_{T,max}$ (MPa)
20×5	24,996	112,584
20×10	16,353	73,744
20×15	15,000	69,000
40×5	23,971	108,105
40×10	64,495	85,704
40×15	21,157	94,630
60×5	20,076	89,610
60×10	15,678	70,565
60×15	13,343	60,052

Tables 7, 8, 9 and 10 shows the results in maximum displacement and maximum stress components of the numerical simulations for the *Eucalyptus grandis* and *Pinus elliottii* wooden beams for the conditions with and without the use of the laminate composite respectively, δ_{max} is the maximum displacement, τ_{max} the maximum shear stress, σ_C the maximum normal stress compression and σ_T the maximum normal stress tensile acting on the beam.

The maximum shear stress in *Pinus caribaea* wood beams without the inclusion of laminated composite, obtained from regions of stress concentration, exceeded the threshold value of the shear strength of wood (9.24MPa) and wood-laminate interface (11.70 MPa) only in three cases (Table 7). The maximum compressive stresses were mostly lower than the compressive strength of wood (38.70MPa), higher than in a single case. The maximum tensile stresses are below the tensile strength of wood (64.32MPa) and the laminate composite (851MPa) in all cases, and the displacements were obtained in most close to 2.80 mm, which was significantly higher in four cases. It is emphasized that the differences between the displacements of both forms of calculation can be explained by use of the average modulus of elasticity in bending and not use the modulus of elasticity of each specimen being tested.

The maximum shear stress in *Pinus caribaea* wood beams with the inclusion of laminated composite exceeded the threshold value of the shear strength of wood and wood-laminate interface in all cases (Table 8). Compressive stresses were lower than the maximum compressive strength of wood in all investigated conditions. The maximum tensile stresses, increased by the inclusion of the former condition of the composite, except for two conditions were lower than the compressive strength of the wood and lower the tensile strength of the laminate composite in all cases. The displacements, except for two cases, were below the displacement threshold used in trials with the lowest value a difference of 44%, possibly explained by the modulus of elasticity used in the simulations are different modules of the woods tested in each condition.

The maximum shear stress in *Eucalyptus grandis* wood beams without the inclusion of laminated composite exceeded the threshold value of the shear strength of wood (8.41MPa) and wood-laminate interface (15.22MPa) in most of the conditions studied (Table 9). Compressive stresses were lower than the maximum compressive strength of wood (44.57MPa) in all cases. The maximum tensile stresses are below the tensile strength of wood (64.32MPa) and the laminate composite (851MPa) in all cases, and the displacements obtained were greater than 2.80mm under all conditions, the largest one (15.596mm) 457% upper limit. It is noteworthy that the differences between the displacements of both forms of calculation can be explained by the use of the average elastic modulus in bending each piece tested defective.

The maximum shear stress in *Eucalyptus grandis* wood beams with the inclusion of laminated composite exceeded the threshold value of the shear strength of wood and

wood-laminate interface in all cases (Table 10). The maximum compressive stress, except for a single condition, were lower than the compressive strength of the wood. The maximum tensile stress, enhanced by the inclusion of previous condition of the composite, were mostly superior strength to compression of the timber and lower the tensile strength of the laminate composite in all cases. The displacements, except for two cases, were below the displacement threshold used in trials with the lowest value a difference of 36.43%, possibly explained by the modulus of elasticity used in the simulations are different modules of the woods tested in each condition.

From the results of the extreme stress for both wood species, it is noted that inclusion of the laminate composite caused reductions in the intensity of compressive stresses and increases in intensity of shearing and tensile stresses.

The use of composite as reinforcement in beams caused significant reductions in displacement found at the midpoint compared with the displacements of the experiment (2.80 mm).

It is emphasized that the extreme components of normal and stresses occurred, as expected, in areas of stress concentration in the beam, as illustrated in Figure 14, and the measured stress at nodes of the mesh previously established (Figure 13) below [12%, 29%] in average to the respective strength in all cases evaluated, with the smallest difference caused by the shear stress components, thereby revealing the good approximation of the numerical model to the results of experiments.

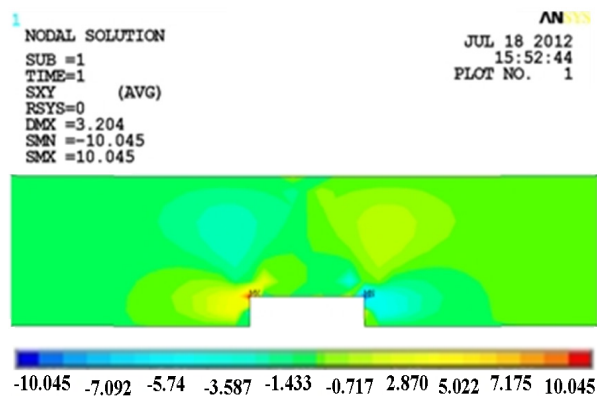


Figure 14. Shear stress concentration in the beam

The inclusion of the fiberglass composite was responsible for making all the cross sections of compressed wood beams in the vicinity of its attachment, appearing normal compression and tensile stresses in simultaneous sections furthest from the laminate. This behavior resembles that shown and discussed in the work of Fiorelli [9], wherein the laminated glass fibers was fixed across the lower face of the wooden beams, justified by lowering of the neutral axis, increasing the compressed region in the timber (providing greater resistance by crushing of fibers) and significantly reducing the tensile region.

4. Conclusions

The use of the glass fiber laminate composite material in *Eucalyptus grandis* and *Pinus elliottii* wood beams species is shown as an alternative in the form of reinforcement because even found no increase in strength responsible for displacement of 2.80mm with respect to the timber intact (references), but were still significant differences with those for the loads of the defective conditions and without the composite.

Numerically, the results of the stress components measured in points of interest (mesh nodes) in the beams gave lower values than the respective strengths of the materials investigated in all cases, except for the extreme stresses, caused by the angular geometry of the beam and the composite.

The results obtained with the same computational shortcuts used in the simulations, for the condition of small displacements (serviceability limit state), the results of numerical tests performed satisfactory, helping to spread the use of numerical tools in checking the mechanical performance of materials and structures.

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