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Analysis of the Strength and Stiffness of Timber Beams Reinforced with Carbon Fiber and Glass Fiber

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An experimental analysis of pinewood beams (*Pinus caribea var hondurensis*) reinforced with glass and/or carbon fibers is discussed. The theoretical model employed to calculate the beam's bending strength takes into account the timber's ultimate limit states of tensile strength and failure by compression, considering a model of fragile elastic tension and plastic elastic compression. The validity of the theoretical model is confirmed by a comparison of the theoretical and experimental results, while the efficiency of the fiber reinforcement is corroborated by the increased strength and stiffness of the reinforced timber beams.

Keywords: *timber, glass fiber, carbon fiber and reinforced structural*

1. Introduction

Problems relating to low efficiency of structural elements increased overload and degradation by aging are common in the construction industry. These pathologies have driven the development of new structural reinforcement and recovery techniques. The main purpose of recovering an element is not merely to repair it, but also to prevent and minimize the appearance of future problems. Timber structures require repairs in a variety of situations to render them suitable for renewed use, while in other cases they require reinforcement to increase the load capacity of their structural elements.

In the last few years, studies have focused on alternative materials for the recovery and reinforcement of structures, and much attention has been dedicated to the use of fibers reinforced with polymer (FRP). This material have high strength, low weight, corrosion resistance and electromagnetic neutrality that make fiber-reinforced plastic (FRP) a suitable candidate in many structural applications, including rehabilitation and strengthening as well as the development of new wood members. This material has been studied in the last ten years in United States and Europe with the objective of to reinforce timber structures. More specific glulam beams.

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2. Literature Review

Triantafillou & Deskovic (1992)[1] establish a technique to reinforce timber members involving external bonding of FRP sheets on their tension zones. In this work is presented an analytic model that establish a relation between stress and strain for timber. This model considers the timber with an elastic-linear behavior under tensile and an elastic-plastic behavior under compression. The fiber is considered as an elastic linear material.

Solid beams of wood were experimentally appraised, reinforced with woven unidirectional of carbon fiber, fastened with sticker epoxy, with thickness varying from 0.55 to 0.75 mm. This material was used to reinforce structures to present high strength, high stiffness and low density, combining the advantages offered by the materials composites with the efficiency of the external reinforcements, resulting in structural beams with excellent mechanical properties of strength, stiffness and ductility. They got an increase of about 20 to 40% in the capacity of load of the reinforced structural piece.

Belperio & Grad (1999)[2] present a theoretical analysis comparing the suffered strain for glulam beams with two different species of wood reinforced with FRP and glulam beams without reinforcement. For the evaluation of the stiffness of the beams the method of the transformed section was used, and for the calculation of the strength, was used a similar analogy used to calculate beams of reinforced concrete.

For the distribution of stress in the cross section of the reinforced beam, in the failure phase, it was considered that each area acts with the maximum strength. The part of the section above the neutral line was requested by the maximum strength of compression, and below the neutral line, the tensiled section of the timber was considered with lineal distribution of stress, acting together with the resulting force of the reinforcement material.

Lindyberg (2000)[3] presented a nonlinear probabilistic model for the analysis of reinforcement Glulam Beams in bending. This work has two principal components. The first part is a deterministic numeric model that calculates the curve of load-deflection of the reinforced beam. This model is based on the Moment Curvature (M-ϕ), method previously used to analyze beams of concrete. The second part incorporates the deterministic model into a probabilistic model. For the development of the deterministic model inside of the probabilistic it was used the Monte Carlo computational simulator.

In this work it is assumed a concept that was presented by (Buchanan, 1990)[4] where the timber, when submitted to tensile efforts, presents an elastic-linear behavior, and when submitted to compression efforts the timber presents an elastic-linear behavior and a nonlinear inelastic behavior (Fig. 1).

Tingley, D. & Kent, S. (2001)[5], evaluated box beam reinforced with aramid fiber applied along the longitudinal direction of the to grain of the wood. These fibers possessed value of elasticity modulus 59,000 MPa and tensile strength 1034 MPa. As result, observed an increase of 21.5% in the strength and 4.69% in the stiffness, comparing with results obtained for beams without reinforce. The failure type observed in the reinforcement beams was for compression in the superior fibers, after the occurrence of a great plastic strain. Different from the failure of the beams without reinforces that was for tensile.

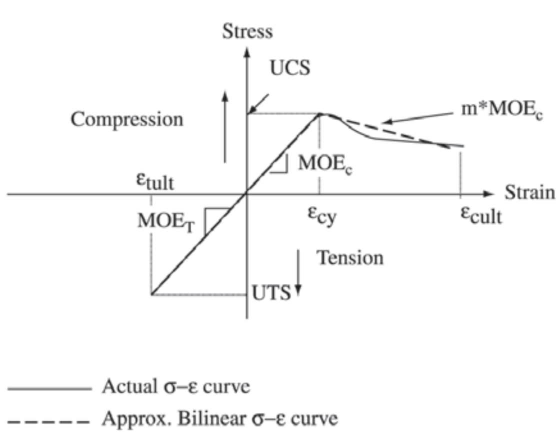

Figure 1. Constitutive relationship for wood in tension and compression parallel to grain (Buchanan, 1990).

Durability of the FRP-wood bond is often a critical factor in the feasibility of a reinforcement technique.

Tingley, D.A. & Cegelka, S. (1996)[6] present some problems that can arise in reinforced wood products. These include shear performance between the reinforcement layers and the wood, dimensional stability of the wood in relation to that of the reinforcement and shear under wet service conditions. Fluctuating moisture content does not affect the dimensional stability of the FRP as it does in wood. This could cause large shear stress to develop at the interface of the FRP and wood over time since wood and wood composites can change in dimension by as much as 5 - 7% versus less than 0.01% for FRP. Depending on species and glue line shear capacity, shear failure at the FRP wood interface could occur from this problem alone without applied load.

Dagher, H.J. (2000)[7] explained that the principal problems of the reinforced are generally related to incompatibilities between the wood and the reinforcing material. The differences in hygro-expansion and stiffness between the wood and reinforcing materials can lead to separation at the glue-line, or torsion failure in the wood near the glue-line.

Starting from the analysis of the researches in process, this work presents an experimental analysis of timber beams of the species *Pinus Caribea Var. Hondurensis* reinforced with woven unidirectional of glass fiber and carbon fiber. The experimental results obtained in this research were compared with theoretical values. The calculation model considers the method of the section transformed for the determination of the stiffness. For the calculation of the moment of failure is used a theoretical model, which considers the plastic elastic behavior of wood, subjected to compression loads and the fragile elastic behavior of reinforcement fibers and of timbers subjected to tensile.

3. Materials And Methods

This topic present the experimental procedure used in this work. The bending tests were made with wood beams of *Pinus Caribea Var. Hondurensis s*pecies. The cross-section of the beams, length and the type of reinforcement are presented in Table 1.

After the accomplishment of the bending test in the beams, small size samples were retreated from them, to the accomplishment of parallel compression and parallel tension to grain tests. The mechanical properties of strength and stiffness of the glass fibers and of carbon fibers used in the reinforcement of the timber beams were also determined.

3.1 Characterisation of the Fibers

The properties of tensile strength and elasticity of the glass fibers and carbon fibers were determined by code ASTM D3039/95 – Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials[8], of the American Society for Testing and Materials.

3.2 Method of Application of the FRP

The lamination process that can be used to fix FRP in wood is the manual. In this process the adhesive is applied on the surface of the fibers. The final product is a laminated material (fibers + adhesive). For the application of the reinforcement is necessary to clean the timber structure. The Fig. 2 presents the process of application of the fibers.

3.3 Bending Test in Reinforced Timber Beams

The experimental analysis consisted of preparing and testing timber beams of *Pinus caribea var. hondurensis* species. The beams were evaluated through bending tests, according to the ASTM D198/84 standard, Method of Static Tests of Timbers in Structural Sizes, of the American Society for Testing Materials[9].

A static design of a simply supported beam was adopted for the tests, with the application of equal loads at one-third intervals of the span (Fig. 3). The values of the displacements were measure in central region of the beam with a dial indicator.

The velocity of load application was of 10 MPa per minute, in normal stress maximum.

The volume of FRP relative to volume of timber was 1.0% of glass fiber or 0.4% of carbon fiber, glued with epoxy resin AR-300, onto the internal face of the element, since that is the region subjected to the strongest stresses. Beam number 09 was reinforced with 3.0 % of glass fiber. The reinforcements of fibers have the same width of the beam.

Table 1. Information of the wood beams.

Number of the beam	Dimensions (cm)	Type of reinforcement
01	6 × 12 × 300	Glass Fiber
02	6 × 12 × 300	Glass Fiber
03	6 × 12 × 300	Carbon Fiber
04	6 × 12 × 300	Carbon Fiber
05	6 × 16 × 300	Glass Fiber
06	6 × 16 × 300	Glass Fiber
07	6 × 16 × 300	Carbon Fiber
08	6 × 16 × 300	Carbon Fiber
09	6 × 12 × 300	Glass Fiber

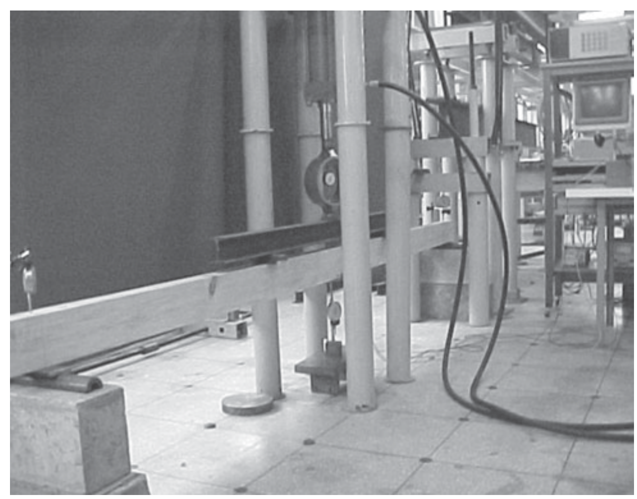

Figure 3. Bending test.

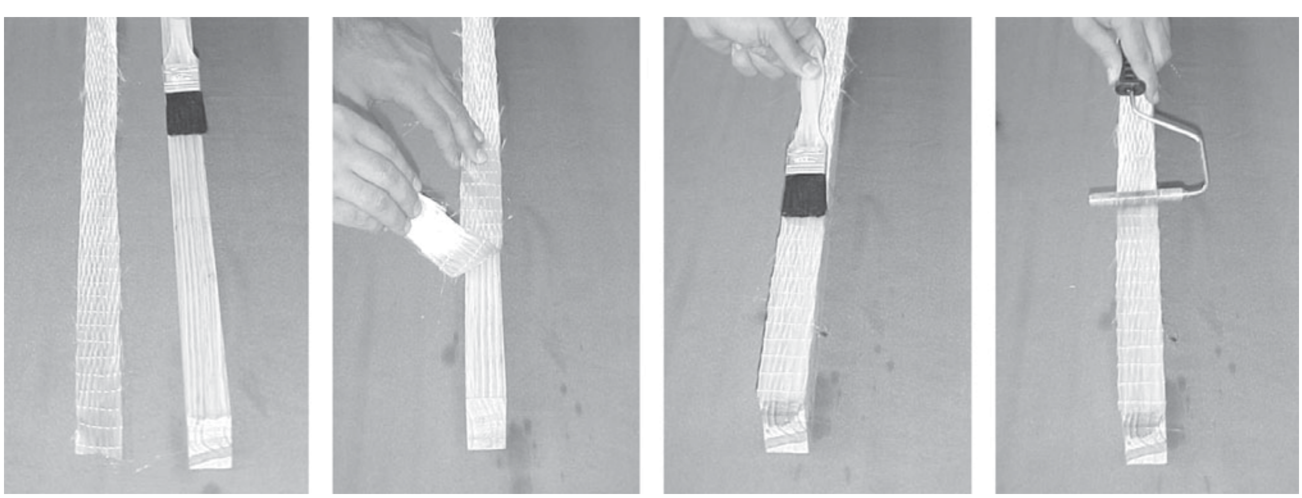

Figure 2. Procedure of application of glass fibers in timber beams.

The beams were instrumented with five extensometer, Kyowa trade mark, type KFG-10-120-C1-11, fixed in central position (Fig. 4). The objective of this procedure was to evaluate the strain in the cross section of the beam.

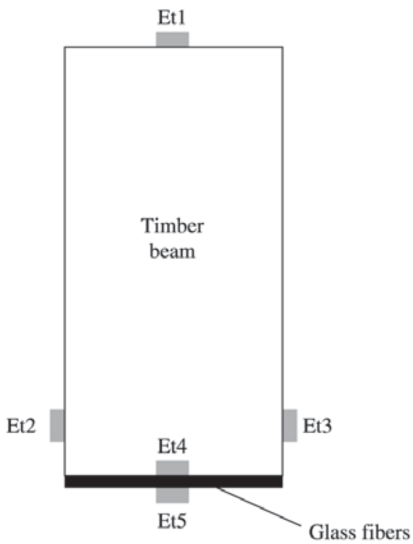

Figure 4. Position of the extensometer in the cross section of the beam.

Table 2. Strength and stiffness values.

Unidirectional fiber	Characteristics		
	Tension Strength (MPa)	Modulus of Elasticity (MPa)	Density (g/cm^3)
Glass	1100	70,000	2.55
Carbon	2200	180,000	1.75

3.4 Characterization of the Timber

The timber beams used in the bending tests were characterized through the Brazilian code NBR 7190/97 – Projeto de Estruturas de Madeira[10]. In these analyses the values of strength and elasticity modulus under compression and under tensile parallel to the grain of the timber, using small size simple, were determined.

4. Results

4.1 Test of Characterization of the Fibers

Table 2 presents the mechanical properties of the glass fiber and carbon fiber used in experimental work.

4.2 Bending Test

The results of moment of failure, bending stiffness (EI) of the bending test with timber beams reinforced with glass fibers and carbon fibers and the failure mode are present in Table 3.

Fig. 5 e 6 presents the strain in a beam 03 of section 6 × 12 cm reinforced with 1.0% of glass fibers. The behavior, of the other beams evaluated, was similar the behavior presented for this beam.

4.3 Test of characterization of the timber

Table 4 present the values of strength and elasticity modulus the compression (f_{c0} and E_{c0}) and the tensile (f_{t0} and E_{t0}) parallel to grain of the wood.

6. Analysis of the Results

6.1 Theoretical Model

The development of a calculation model that determines the value of the ultimate bending strength of fiber-reinforced timber beams is crucial to the material's correct and safe

Table 3. Experimental values of moment of failure and bending stiffness.

Reinforcement	Beam	Section (mm)		Experimental moment of failure(kN.cm)	$EI_{exp.}$(exp.) (kN.cm^2)	$EI_{r,exp}$(exp.) (kN.cm^2)	Failure mode
Glass fiber	1	11.6	5.4	920	556,371	711,534	Tensile
	2	11.6	5.4	1051	958,128	1,081,958	Tensile
Carbon fiber	3	11.7	5.4	978	705,910	914,934	Compression
	4	11.6	5.4	1072	1,054,281	1,236,808	Tensile
Glass fiber	5	15.3	5.3	1094	1,303,614	1,463,894	Tensile
	6	15.4	5.4	1301	1,450,813	1,669,113	Tensile
Carbon fiber	7	15.4	5.4	1491	1,999,199	2,279,938	Tensile
	8	15.4	5.7	1060	1,389,845	1,611,869	Tensile
Glass fiber	9	11.8	5.5	1118	913,062	1,440,282	Tensile

use in structural reinforcements and repairs, as well as to its broader use in civil construction.

The Brazilian Code NBR 7190/97, Projeto de estruturas de madeira[10], is based on the Limit State Method for verification of structural safety. In the specific case of fiber-reinforced beams, the following limit states should be checked:

- service limit state in terms of maximum vertical displacement (deflection);
- ultimate limit state in terms of normal stresses caused by the bending moment;
- ultimate limit state in terms of tangential stresses caused by shear stress.

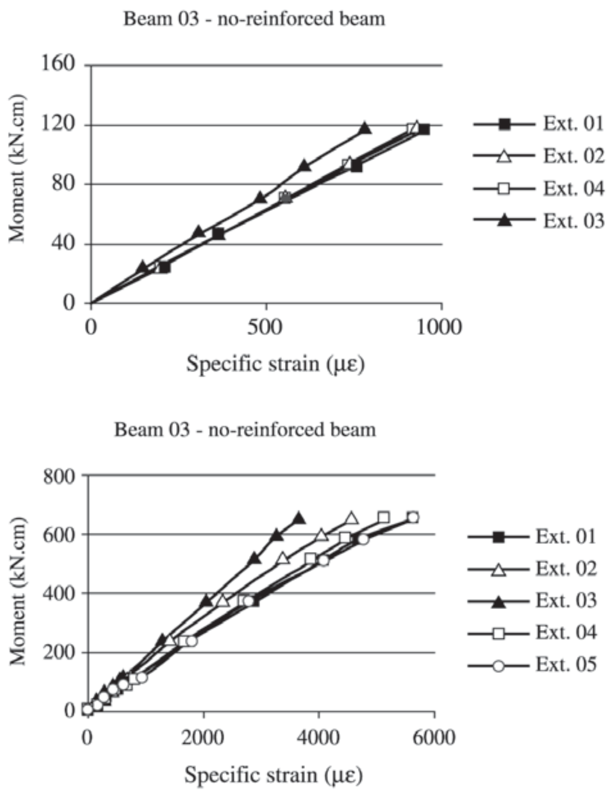

Figure 5. Moment x specific strain - Pinus beam 03 with section (6 × 12 cm).

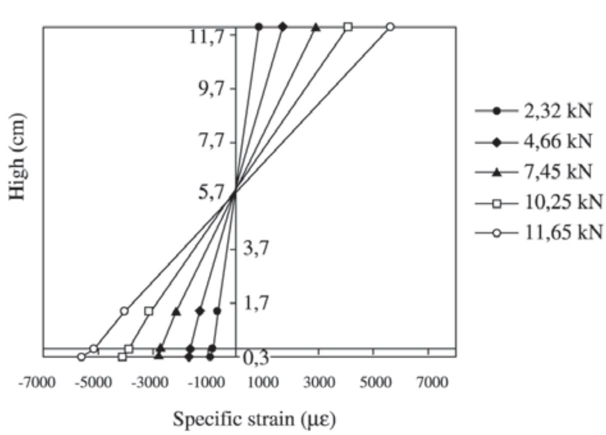

Figure 6. Variation of the strain in cross section - Pinus beam 03 section (6 × 12 cm).

To verify the service limit state, the vertical displacements are determined based on bending stiffness and are evaluated according to a linear elastic calculation model (transformed section method).

To determine the ultimate bending moment, the model is similar the developed by Triantafillou & Deskovic (1992)[1] and by Lindyberg (2000)[3] with simplification of the model and it was considered elastic plastic behavior to wood subjected compression loads and the fragile elastic behavior of reinforcement fibers and of timbers subjected to tension. The evaluation of strength to shear stress will disregard the contribution of the fiber, considering the timber as solely responsible for total absorption of the load.

6.1.1 Evaluation of the Stiffness of Fiber-Reinforced Beams

The stiffness of timber beams reinforced with FRP will be by transformed section analysis.

6.1.2 Analysis of the Failure Moment in FRP Reinforced Beams

This item presents the calculation model for evaluation of the ultimate moment of fiber-reinforced beams. The model is based on the hypothesis of Navier/Bernoulli (plane sections remain plane after being strained) and considers the limit states of the timber's tension and compression failure.

The theoretical model stabiles that the timber presents an elastic-plastic behavior in parallel compression. The relation among the plastic strain (ε_2) and elastic strain (ε_1) was determined experimentally with compression test it using small size simple of dimensions (3 × 3 × 9 cm) and

Table 4. Mean strength and modulus of elasticity values.

Beam	*Pinus Caribea var. Hondurensis*			
	Strength (MPa)		Elasticity Modulus (MPa)	
	f_{c0}	f_{t0}	E_{c0}	E_{t0}
01	36	73	12,410	12,109
02	45	69	15,087	12,771
03	41	62	10,492	8,002
04	48	68	13,044	13,442
05	38	42	11,841	9,426
06	40	56	10,995	8,702
07	42	65	11,921	12,458
08	34	44	10,685	10,835
09	39	59	12,446	14,194

deflection velocity same the 0.002 mm/min.

Figure 7 presents one of the tests that were carried out, illustrating the stress versus strain diagram. The relation between the total strain (ε_2) and the strain in the elastic phase of the plastic elastic model (ε_1) is represented by "k".

A fragile elastic behavior is considered for the tensioned wood and for the fiber reinforcement, assuming that the timber's maximum specific strain is equal to that of the fiber. Thus, the relation between the maximum tension acting on the fiber and the maximum tension acting on the timber is equal to the relation between the modulus of elasticity of the fiber and the timber. Because this relation is always much lower than the ratio found for the fiber's and the timber's

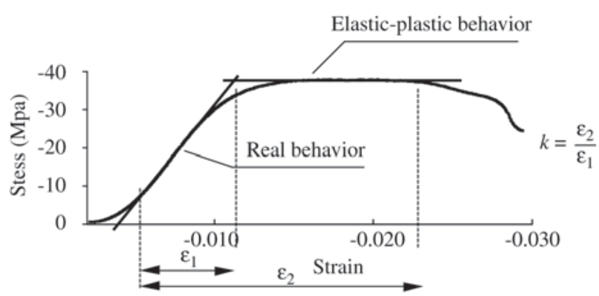

Figure 7. Stress *vs.* strain in compression parallel to grain.

tensile strength, one can conclude that failure by tension will always occur in the timber.

Figure 8, present the graphics of stress × strain of the compression testing parallel to grain of the wood, used to determined "k".

The value of "k", for the species Pinus caribea var. hondurensis, is same the 3. The following considerations were made for the two evaluations (failure by compression or by tension). For $\varepsilon_1 \leq \varepsilon \leq \varepsilon_2$, the compression stress of the timber is equal to:

$$\sigma_c = f_{c0} \quad (5)$$

The strain in the fiber was equal to the maximum strain in the timber, disregarding the strain along the thickness of the fiber. The following denominations were established:

h = beam height; t = fiber thickness;

f_{c0} = compression strength parallel to the timber's grain;

$$s = \frac{f_{c0}}{E_c \cdot m}\ ;\ p = \frac{f_{t0}}{E_t \cdot m}\ ;$$

f_{t0} = tensile strength parallel to the timber's grain;

E_c = modulus of elasticity to parallel compression on the timber;

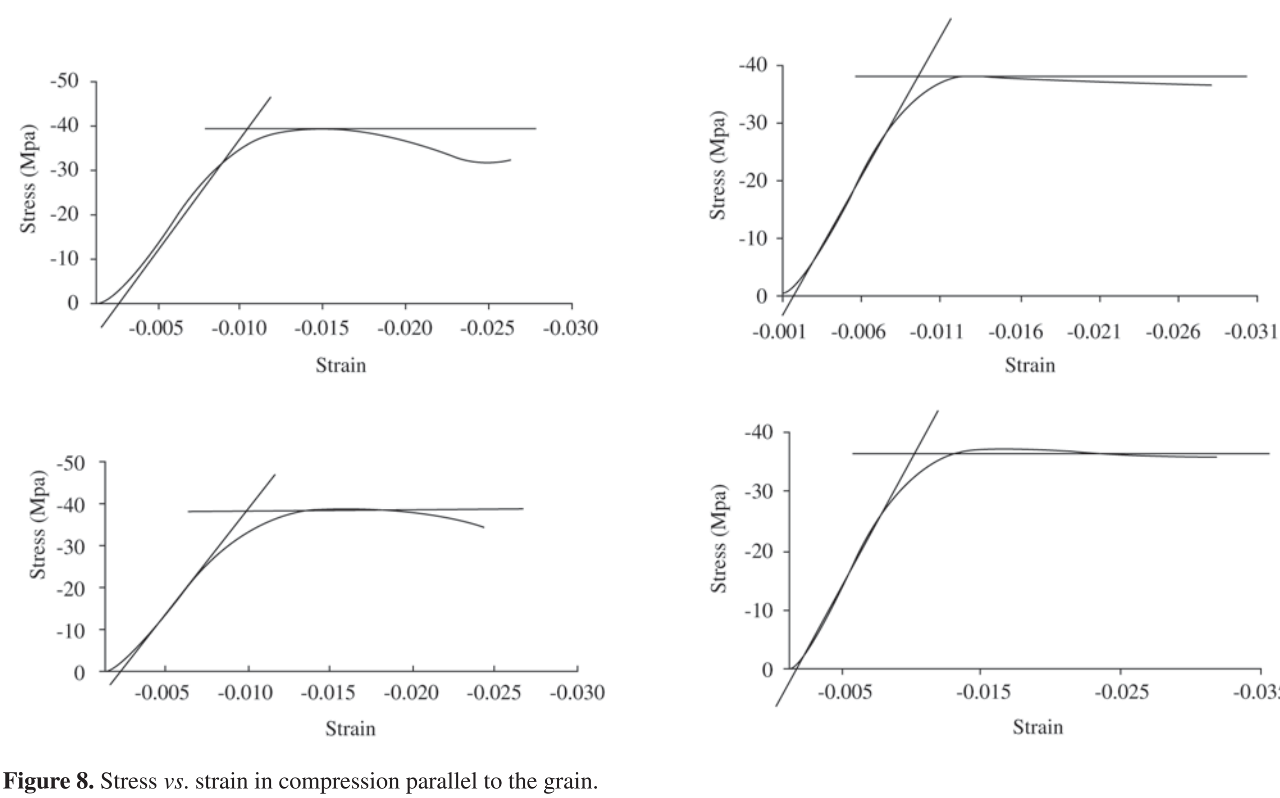

Figure 8. Stress *vs.* strain in compression parallel to the grain.

E_t = modulus of elasticity to parallel tension in the timber;
E_f = modulus of elasticity to tension of the fiber.

6.1.3 Failure Mode: Compression

The ultimate state of compression is considered to have been attained when the maximum strain in the compressed part reaches the value of ε_2. Based on the relations established between stresses and strains, Fig. 9 shows the distribution of stresses when that limit is reached, as well as the forces resulting from those stresses and their positions.

Starting from the condition of equilibrium of the horizontal forces and a rearrangement of the terms, one has:

$$m^2 \cdot (h^2 E_t E_c^2 + 2E_c^2 E_f th) + m(-2hE_t kf_{c0} E_c - 2E_c tE_f kf_{c0}) + (k^2 f_{c0}^2 E_t - 2E_c f_{c0}^2 (k-1) - (E_c f_{c0}^2) = 0 \tag{6}$$

$$M_c = \left[b \cdot \frac{f_{c0}^2}{E_c \cdot m} \cdot (k-1) \right] \cdot \left[(\frac{f_{c0}}{E_c \cdot m} + (\frac{f_{c0}}{E_c \cdot m} \cdot (k-1)) \right] + \left[(\frac{f_{c0}^2 \cdot b}{2 \cdot E_c \cdot m}) \cdot (\frac{2}{3} \cdot \frac{f_{c0}}{E_c . m}) \right] + \left[\frac{b}{2} \cdot (h - \frac{k \cdot f_{c0}}{E_c \cdot m}) \right] \cdot \left[E_t \cdot (mh - \frac{kf_{c0}}{E_c}) \cdot \frac{2}{3} \cdot (h - \frac{kf_{c0}}{E_c \cdot m}) \right] + \left[b \cdot t \cdot E_f \cdot (mh - \frac{kf_{c0}}{E_c}) \cdot (h + \frac{t}{2} - \frac{kf_{c0}}{E_c \cdot m}) \right] \tag{7}$$

6.1.4. Failure Mode - Tensile

The timber's tensile limit state is considered to have been attained when the maximum tensile stress is equal to its tensile strength. Based on the relations established between the stresses and the strains, Fig. 10 illustrates the distribution of stresses when this limit state is attained, as well as the forces resulting from these stresses and their positions.

Based on the relations established between the stresses and the strains. Based on the condition of equilibrium of forces, one has:

$$m = \frac{f_{t0}^2 \cdot E_c + 2 \cdot E_t \cdot f_{c0}^2 + 2 \cdot E_c \cdot f_{c0} \cdot f_{t0} - f_{c0}^2 \cdot E_t}{2 \cdot f_{c0} \cdot h \cdot E_t \cdot E_c - 2 \cdot E_c \cdot e \cdot E_f \cdot f_{t0}} \tag{8}$$

$$M_t = f_{c0} \cdot b \cdot \left[(h - \frac{f_{co}}{E_{cm}} - \frac{f_{t0}}{E_t \cdot m}) \cdot (\frac{f_{c0}}{E_c \cdot m} + (\frac{h}{2} - \frac{f_{t0}}{2 \cdot E_t \cdot m} - \frac{f_{c0}}{2 \cdot E_c \cdot m}) \right] + \left[(\frac{f_{c0}^2 \cdot b}{2 \cdot E_c \cdot m}) \right] \cdot \left[(\frac{2}{3} \cdot \frac{f_{c0}}{E_c \cdot m}) \right] + \left[(\frac{f_{to}^2 \cdot b}{2 \cdot E_t \cdot m}) \cdot (\frac{2 \cdot f_{t0}}{3 \cdot E_t \cdot m}) \right] + \left[(\frac{b \cdot t \cdot E_f \cdot f_{t0}}{E_t}) \cdot (\frac{f_{t0}}{E_t \cdot m}) \right] \tag{9}$$

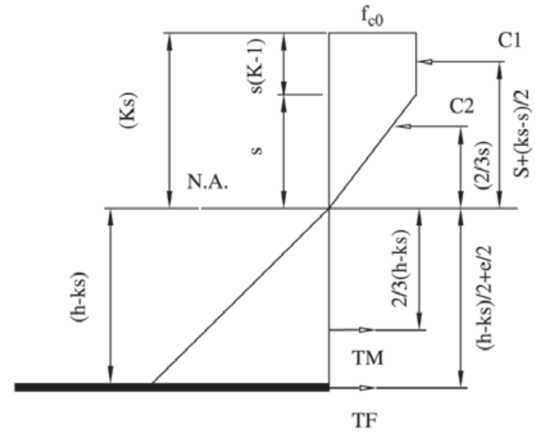

Figure 9. Distribution of stresses in the transversal section (failure by compression).

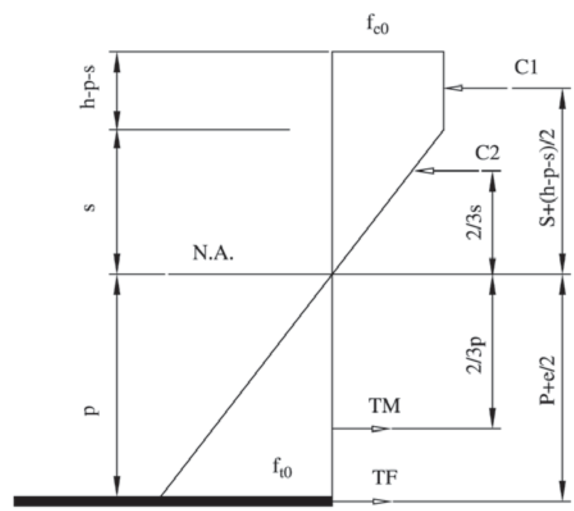

Figure 10. Distribution of stresses in the transversal section (failure by traction in the wood).

6.2 Comparison Between Experimental and Theoretical Results

The results presented below were obtained both experimentally and theoretically, based on the theoretical models presented earlier herein. The Tables 5 and 6 present the experimental and theoretical values of bending stiffness (EI) and moment of failure.

EI_{exp} = experimental value of bending stiffness of the beam no-reinforced;

$EI_{r,exp}$ = experimental value of bending stiffness of the beam reinforced;

EI_r = theoretical value of bending stiffness of the beam reinforced.

The values obtained experimentally had a good agreement with the theoretical (Table 6). The increase in the stiff-

Table 5. Experimental and theoretical values bending stiffness.

Reinforcement	Beam	$EI_{exp.}$(exp.)	$EI_{r,exp}$(exp.) kN.cm^2	EI_r(theoretical)	$EI_{r,exp.}/EI_{r\ theor.}$	EI_r/EI_{exp}
Glass fiber	1	556,371	711,534	645,390	1.10	1.28
	2	958,128	1,081,958	1,073,103	1.01	1.13
Carbon fiber	3	705,910	914,934	847,092	1.08	1.30
	4	1,054,281	1,236,808	1,222,966	1.02	1.17
Glass fiber	5	1,303,614	1,463,894	1,473,084	0.99	1.12
	6	1,450,813	1,669,113	1,653,927	0.99	1.15
Carbon fiber	7	1,999,199	2,279,938	2,239,103	1.02	1.14
	8	1,389,845	1,611,869	1,570,524	1.03	1.16
Glass fiber	9	913,062	1,440,282	1,396,985	1.03	1.58

Table 6. Experimental and theoretical moment of failure.

Reinforcement	Beam	Experimental moment of failure (kN.cm)	Theoretical moment of failure (kN.cm)	Relation $M_{exp.}/M_{theor.}$
Glass fiber	1	920	871	1.05
	2	1051	938	1.12
Carbon fiber	3	978	934	1.04
	4	1072	935	1.14
Glass fiber	5	1094	1085	1.00
	6	1301	1400	0.93
Carbon fiber	7	1491	1474	1.01
	8	1060	1144	0.93
Glass fiber	9	1118	1056	1.06

ness varied from 15 to 30% in beams reinforced with 1.0% of glass fiber and/or with 0.4% of carbon fiber. In the case of beam 09, which was reinforced with 3.0% of glass fiber, the increase in stiffness was significant, i.e., approximately 60%.

The theoretical values of the failure moment were determined by failure tensile, more critic situation. Table 6 presents a good relation among experimental and theoretical values. These results indicate the validated of the theoretical model.

The bending stiffness (EI) and moment of failure determined experimentally were higher than the theoretical values, thus ensuring structural safety. Another important observation is that the use of reinforcement led to an increase of the ductility in the failure phase. The reinforced beams first displayed bearing of the upper fibers by compression, causing an increase in the beams' strength, followed by tensile failure close to the glue line, as presented in Fig. 11.

It was concluded that the proposed calculation model is valid for the evaluation of fiber-reinforced timber beams.

The results of these tests demonstrated the good performance of this reinforcement technique, evidenced by the increase in strength and stiffness of the reinforced beams.

The strain, presented in Fig. 5 and 6, indicates that the section plane sections remained plane after being strained. This situation indicates that the hypothesis of the theoretical model is correct. The Fig. 12 presents a comparison among experimental and theoretical values of strains of the beam 03 of section 6 × 12 cm reinforced with 1.0% of glass fibers. To determine the values of the deformation it was used the theoretical model presented on item 6.1. The results indicate that experimental values are close to the theoretical values (Fig. 12). The behavior of the other beams is similar to the behavior of the beam 03.

7. Conclusions

The theoretical model presented, that is a simplification of other models, led to satisfactory values compared to those obtained experimentally, thus demonstrating their validity.

An important factor is observed in the failure mode of the composite: in the first moment occurs the crush of the timber in the compression region of the cross section, above the neutral axis. In the second moment occurs the failure for tensile stress and/or shear stress in the timber.

In this case the timber beams reinforced with fibers presented significant gain in ductility, in comparison with not-reinforced beams. This situation is positive to the structural behavior.

In view of the comments and conclusions presented throughout this paper, the application of glass and carbon fibers was found to be viable in the reinforcement and recovery of timber beams. This technique is not only easy but also confers greater strength and stiffness of reinforced structural elements. It also renders the system more reliable, reducing the possibility of tensile failure caused by defects.

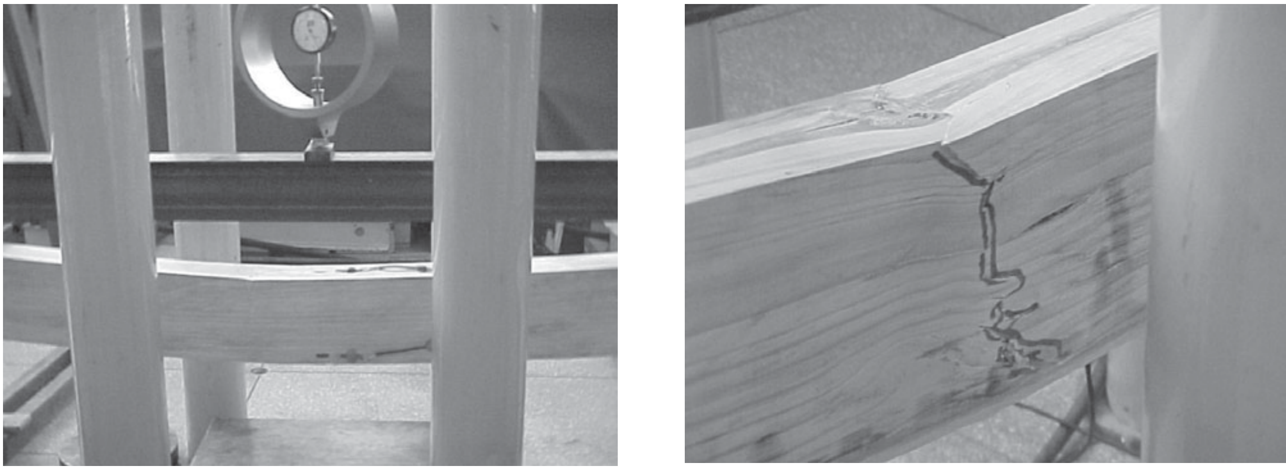

Figure 11. Deflection, followed by tensile failure of the beam.

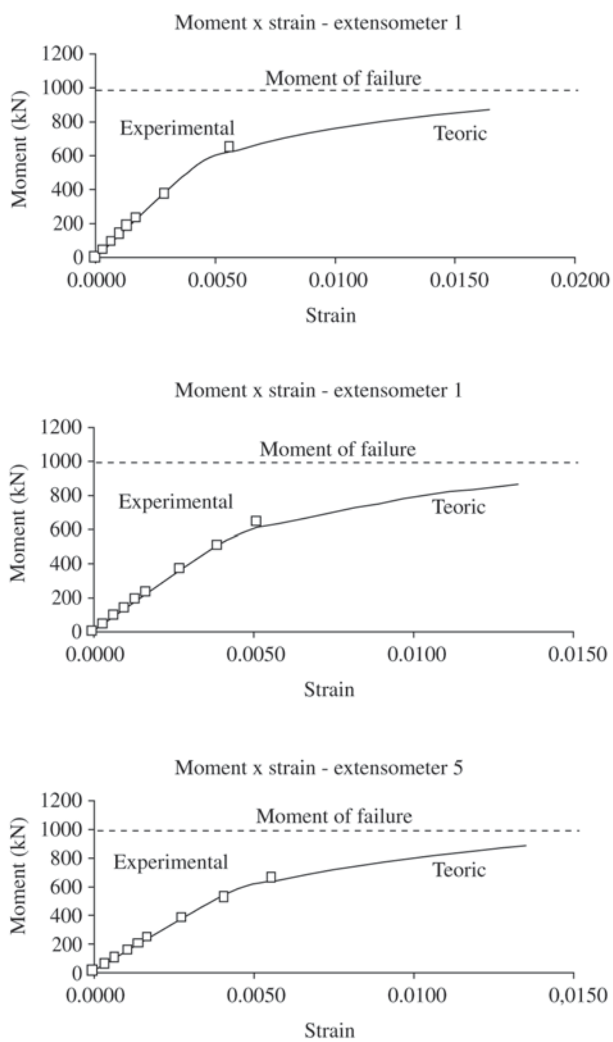

Figure 12. Moment × strain - Pinus beam 03 section (6 × 12 cm).

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