Natural Fiber-Reinforced Polymer for Structural Application

Juliano Fiorelli, Nolan Rempe, Julio Cesar Molina and Antonio Alves Dias

Abstract The glued laminated lumber (glulam) beams technique is an efficient process for making sustainable use of wood. Fiber-reinforced polymers (FRPs) associated with glulam provide significant gains in terms of strength and stiffness, as well as modify the rupture mode of these structural elements. Certain natural fibers display sufficient mechanical properties to reinforce the polymer used in the glulam technique. This chapter presents a theoretical analysis considering the behavior of stressed lumber and fibers in glulam beam of *Pinus* sp. and *Eucalyptus* sp. with and without natural fiber-reinforced polymer (NFRP), and a numerical analysis evaluating the stresses and displacements in glulam beams using the finite element method. Curauá, bamboo, and jute fibers were used for reinforcement. NFRP introduced in the tensioned section of glulam beams guaranteed a gain of strength and stiffness in function of the thickness percentage of NFRP used. In terms of maximum stresses and vertical displacement, theoretical and numerical analyses provided analogous results.

Keywords Glulam · Fibers · Polymer · Structural applications

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K. R. Hakeem et al. (eds.), *Agricultural biomass based potential materials,*
DOI 10.1007/978-3-319-13847-3_2

Introduction

The reduced availability of native woods has spurred the development of new techniques for the use of wood from managed forests (Segundinho et al. 2013). Currently, it is not economically viable to use wood from older trees. The use of wood from managed forests is contributing to the spread of the glued laminated timber technique. When used for structural elements, glued laminated lumber (glulam) refers to the material produced by gluing the edges and faces of wood chips together, in flat or curved shapes, with the grains of the sheets parallel to the axis of the larger piece. Longer sheets are obtained by joining boards together longitudinally, gluing them face to face and edge to edge to obtain the desired height and width. The sheets can also be bent to produce a curved shape during gluing. All these factors permit a wide variety of design choices, constrained only by production and/or application costs.

Fiorelli and Dias (2011) evaluated the rupture mode of glulam beams produced with *Pinus* sp. wood and phenol–formaldehyde resin with and without glue-laminated fiber-reinforced polymer (GFRP). The results indicated that beams without reinforcement presented tensile failure beginning in the lower sheet of lumber and spreading to the finger joint. Beams with GFRP reinforcement presented two observed failure stages. The first was a tensile failure in the sheet positioned under the reinforcement layer, while the second occurred as a result of preliminary compression yielding in the upper face of the lumber, followed by both a shear failure at the fiber–lumber interface and a tensile failure in the wood. The use of fiber-reinforced polymers (FRP) to reinforce the underside of beams (last line of glue) ensures improvements in structural strength and stiffness of the element, and alters its mode of rupture.

The use of synthetic FRP to reinforce glulam beams was studied by Triantafillou and Deskovic (1992), Dagher (1999), Lindyberg (2000), Tingley and Kent (2001), Bergmeister and Luggin (2001), Fiorelli and Dias (2006), Kim and Harries (2010), Gentry (2011), Fiorelli and Dias (2011), Garcia et al. (2013), and Yeou-Fong et al. (2014). In recent years, natural fiber-reinforced composites have received significant attention because of their lightweight, nonabrasive, combustible, nontoxic, low-cost, and biodegradable properties. Among the various natural fibers, flax, bamboo, sisal, hemp, ramie, jute, and wood fibers are of particular interest (Kalia et al. 2009).

Composites reinforced with natural fibers are commercially viable only if they have a higher value-in-use in the same application as the incumbent materials which they are going to replace. A new composite part has a better value-in-use than its incumbent counterpart if it has the same functionality but is less costly and more environmentally friendly (Wallenberger 2002). Carvalho (2005) studied the use of sisal fiber-reinforced plastic (SFRP), as an alternative to carbon and glass fibers, for repairing and reinforcing wood structural elements. The results showed that the new SFRP can be used to reinforce timber structures. Kalia et al. (2009) presented a review of pretreated natural fibers for use in polymer matrix-based composites. The effect of surface modification of natural fibers on the properties of fibers and fiber-reinforced polymer composites has also been discussed.

Lee et al. (2005) conducted a study to estimate the strength and elasticity of glued laminated timber beams, considering the modulus of elasticity (MOE) and modulus of rupture (MOR) in bending, obtained in specimens free from defects. The model showed results in accordance with those from tests in rafters performed in this work. Johnsson et al. (2006) studied the reinforcement of glulam beams with pultruded blades made of carbon fiber by analyzing the optimal anchorage length needed. This study concluded that the flexural strength can be modeled similarly to that of reinforced concrete. Plasticizing the compressed region of the beam serves as ductile compression reinforcement in the structural element; the use of reinforcement also alters the mode of rupture, which usually occurs in the region pulled weakly on beams without reinforcement.

Frese et al. (2010) conducted a numerical study to assess the strength of glued wood beams that were tested experimentally. Their model considers the tensile strength of the blades and the tensile strength of the toothed amendments, for slides visually or mechanically sorted. They concluded that these two resistance parameters are not sufficient to ensure the planned mechanical resistance.

Kim and Harries (2010) present a numerical study of three-dimensional finite element modeling, considering the orthotropic properties of wood but not considering the lamination in compression, in order to predict the behavior of glued laminated timber beams reinforced with carbon fibers. In the model, rupture of the wood was considered when the longitudinal strain calculated exceeded the ratio between the MOR and modulus of longitudinal elasticity. The model provides the relative force versus displacement, stress concentrations, and failure modes, allowing for a comparison between the theoretical results and experimental values. The strengthened beams showed an increase in load capacity and energy absorption compared to the beams without reinforcement. According to their findings, with the additional 1.9 % of cross-sectional area from reinforcement, the maximum value of force that the beam supports is reached.

This chapter examines the theoretical strength and stiffness, and provides a numerical evaluation of the stresses and displacements, based on the finite element method, of the natural fiber-reinforced polymer (NFRP)-reinforced glulam beams, where established *Pinus* sp. *and Eucalyptus* sp. sheets reinforced with curauá, bamboo, and jute fibers were fixed along the last line of glue in the tensioned section.

Theoretical Model to Estimate Strength and Stiffness of Glulam Beam

The theoretical deterministic model used in this study considers a realistic behavior for the stressed lumber and fibers. The lumber subjected to compressive loading parallel to its grains exhibits an initial linear elastic behavior, reaching compressive strength parallel to the grains (f_c), followed by decreasing levels of stress as the strain increases, until the material breaks (Buchanan 1990). The lumber subjected to tensile loading parallel to the grains displays a linear elastic behavior until it approaches the rupture point (Fiorelli and Dias 2006). To calculate the bending moment at failure for the timber beams, an elastic–linear model in tension and an elastic–plastic with softening model in compression were considered (Fig. 1). Related to FRP in tension, an elastic–linear model is considered until the point of failure. The bending stiffness was calculated by the transformed section method, in the elastic–linear range, using MOE and thickness of each lumber and fiber reinforcement layer.

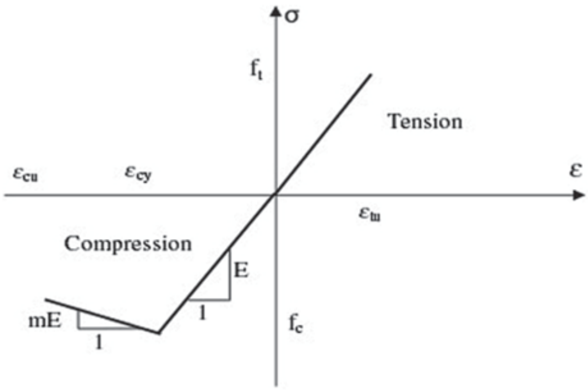


Fig. 1 Stress–strain relation of lumber under compression and tension parallel to the grain. (Source: Fiorelli and Dias 2011)

Software was developed to calculate the bending moment at failure. The position of the neutral axis line (NA) is determined by means of resultant loads of tension and compression equilibrium. By increasing the strain, it is possible to calculate the load on each sheet of lumber on the transversal section of the glulam beam and on the FRP layer, until failure occurs. Failure by tension can occur when the stress reaches the tensile strength, of timber or FRP. In the case of failure by compression, after the stress reaches the value of compressive strength, the section undergoes gradual plastic deformation, reaching the maximum bending moment.

Evaluation of NFRP in Glulam Beam Strength and Stiffness

This section presents information on the theoretical evaluation and numerical simulation performed on glulam beams reinforced with NFRP.

Mechanical Properties

To analyze the efficacy of natural fiber reinforcement in glulam beams, curauá, bamboo, and jute fibers were evaluated. The strength (bending moment failure) and stiffness (moment of inertia) of the glulam beam with NFRP were evaluated. Table 1 indicates the input parameters for analysis of strength and stiffness. Two species of wood were considered for theoretical analysis of reinforced glulam beams (*Pinus* sp. and *Eucalyptus* sp.) as well as three different types of fiber (curauá, bamboo, and jute fiber).

Theoretical Evaluation

For theoretical evaluation of the strength and stiffness of the NFRP-reinforced glulam beams, *Pinus* sp. *and Eucalyptus* sp. sheets were made with curauá, bamboo,

Table 1 Mechanical properties: wood and fiber

	Pinus sp.	*Eucalyptus* sp.	Curauá-fiber-reinforced plastic (CFRP)[a]	Bamboo-fiber-reinforced plastic (BFRP)[b]	Jute-fiber-reinforced plastic (JFRP)[c]
E (MPa)	9868	12,513	31,232	28,200	32,000
f_{c0} (MPa)	42.3	40.3	–	–	–
f_{t0} (MPa)	50.3	70.2	519	564	350

[a] Amaya (2013)
[b] Guimarães (1984)
[c] Beaudoin (1990)

and jute fiber reinforcement fixed along the last line of glue of the tensioned section. The percentage of fiber used was 1–7 % of the height of the beam. The beams had ten 3-cm-thick layers of lumber, for a total nominal section of 7 × 30 × 400 cm.

Tables 2 and 3 show values of bending moment obtained in two ways: considering an elastic–perfectly plastic model (m = 0) of timber in compression, and an elastic–plastic model with softening (m = 0.3), according to Fig. 1.

Numerical Simulation

The numerical evaluation of the stresses and displacements in the glulam beams was performed using the ANSYS commercial software, version 10.0, which is based on the finite element method. For the proposed simulation, the tensile and compressive stresses in the outer grains of the wood (*Pinus* sp.) were evaluated as well as the values of tensile stress in the reinforcement layer (curauá fiber), which was considered in this case with a thickness of 7 % (equal to 2.1 cm). The stress results

Table 2 Theoretical bending moment (M)—m = 0

	Bending moment (kN.cm)					
Reinforcement (%)	Pinus CFRP	Pinus BFRP	Pinus JFRP	*Eucalyptus* CFRP	*Eucalyptus* BFRP	*Eucalyptus* JFRP
0	5180	5180	5180	6492	6492	6492
1	5514	5488	5520	6787	6766	6798
2	5931	5810	5961	7150	7075	7159
3	6268	6185	6285	7425	7371	7439
4	6572	6485	6616	7735	7626	7788
5	6946	6764	7005	8036	7878	8055
6	7277	7038	7305	8295	8132	8317
7	7556	7350	7595	8568	8421	8642

BFRP bamboo-fiber-reinforced plastic, *CFRP* curauá-fiber-reinforced plastic, *JFRP* jute-fiber-reinforced plastic

Table 3 Theoretical bending moment (M)—m=0.3

	Bending moment (kN.cm)					
Reinforcement (%)	Pinus CFRP	Pinus BFRP	Pinus JFRP	*Eucalyptus* CFRP	*Eucalyptus* BFRP	*Eucalyptus* JFRP
0	5146	5146	5146	5902	5902	5902
1	5478	5440	5494	6100	6087	6103
2	5871	5803	5883	6290	6266	6296
3	6161	6098	6176	6474	6442	6482
4	6517	6360	6548	6653	6613	6662
5	6791	6646	6813	6828	6781	6839
6	7064	6946	7124	6998	6945	7011
7	7357	7183	7382	7165	7109	7179

BFRP bamboo-fiber-reinforced plastic, *CFRP* curauá-fiber-reinforced plastic, *JFRP* jute-fiber-reinforced plastic

obtained for the reinforced beam were compared with those of the beam without reinforcement, as shown in Fig. 2. The stresses were obtained for values of applied load at the thirds of span of the beams (four-point flexural testing) which resulted in values for the theoretical bending moment (M) presented in Table 2. For the beam without reinforcement, a theoretical moment (M) of 5180 kN.cm was evaluated, corresponding to an applied force of 38.85 kN, whereas for the reinforced beam (7%) with curauá a theoretical moment (M) equal to 7556 kN.cm was evaluated, corresponding to an applied force of 56.67 kN.

For the discretization of wood layers as well as the curauá fiber layer, the SOLID 45 tool was used, which allows consideration of plasticity effects of the materials. Materials were considered with an isotropic behavior. The constitutive model used for the wood in compression simulates an elastic–perfectly plastic behavior by using a bilinear curve as shown in Fig. 3. To avoid numerical problems in the portion of the curve between ε_y and ε_u, a small slope of E/1000 was considered. In tension, the model adopted for wood as well as curauá fiber simulates an elastic behavior. The mechanical properties of the wood were obtained through experimental tests performed on beams with structural dimensions and properties presented in Table 1.

Results and Discussion

Theoretical Values

Tables 2 and 3 indicated that theoretical model results showed approximately a 5% reduction in value for the elastic–plastic model with softening (m=0.3) when compared to those of the elastic–perfectly plastic model (m=0), for timber in compression. Subsequently, an elastic–perfectly plastic model (m=0) was used for

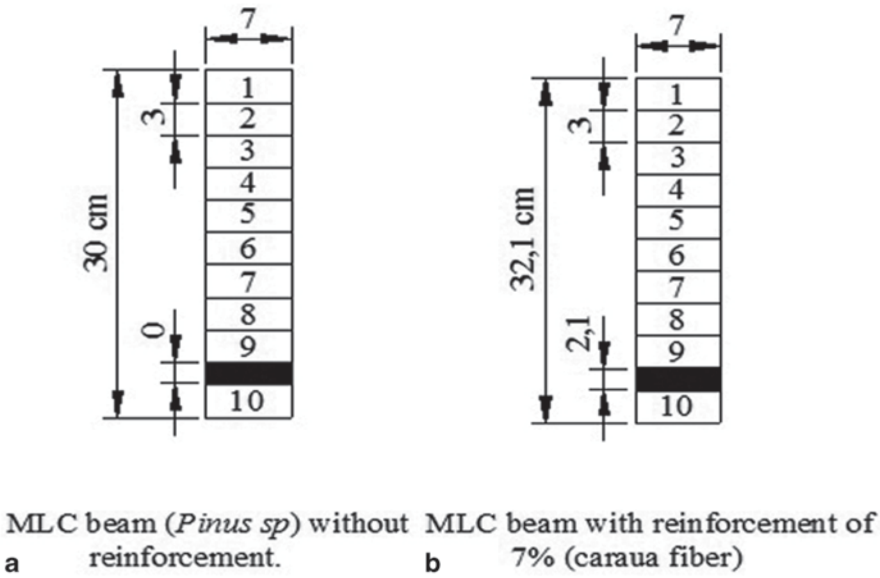


Fig. 2 Configurations of beams evaluated in numerical simulations

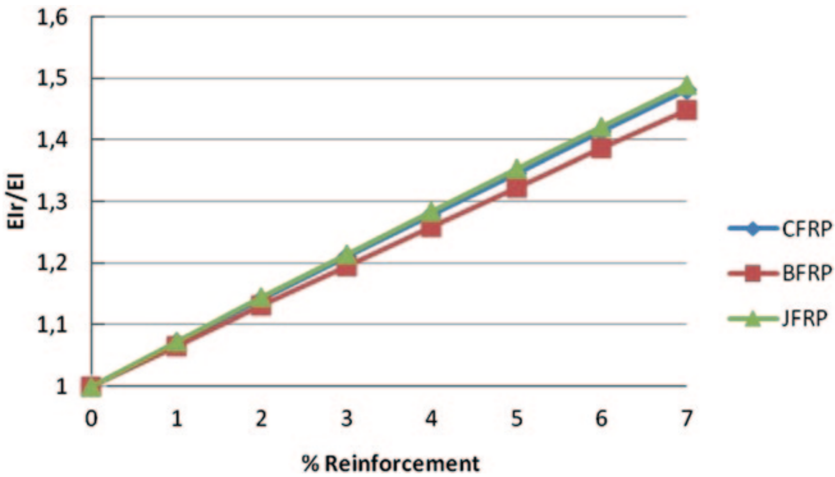


Fig. 3 EI_r/EI versus fiber reinforcement (%)—*Pinus* sp.

the numerical simulation. Table 4 presents the values of bending stiffness calculated on the linear portion of stress × strain curves for various materials.

Figures 3, 4, 5, and 6 present theoretical values of bending stiffness and bending moment of glulam beams (*Pinus* sp. *and Eucalyptus* sp.) reinforced with curauá (CFRP), bamboo (BFRP), and jute (JFRP), obtained according to the sections "Theoretical model to estimate strength and stiffness of glulam beam" and

Table 4 Theoretical bending stiffness (EI)

	EI (10^6 kN.cm^2)					
Reinforcement (%)	*Pinus* CFRP	Pinus BFRP	Pinus JFRP	*Eucalyptus* CFRP	*Eucalyptus* BFRP	*Eucalyptus* JFRP
0	15.54	15.54	15.54	19.71	19.71	19.71
1	16.64	16.56	16.67	20.86	20.77	20.88
2	17.73	17.56	17.77	22.01	21.84	22.06
3	18.81	18.56	18.87	23.16	22.90	23.23
4	19.87	19.55	19.95	24.31	23.98	24.39
5	20.92	20.54	21.02	25.46	25.05	25.56
6	21.97	21.53	22.08	26.61	26.13	26.73
7	23.01	22.51	23.13	27.76	27.22	27.90

BFRP bamboo-fiber-reinforced plastic, *CFRP* curauá-fiber-reinforced plastic, *JFRP* jute-fiber-reinforced plastic

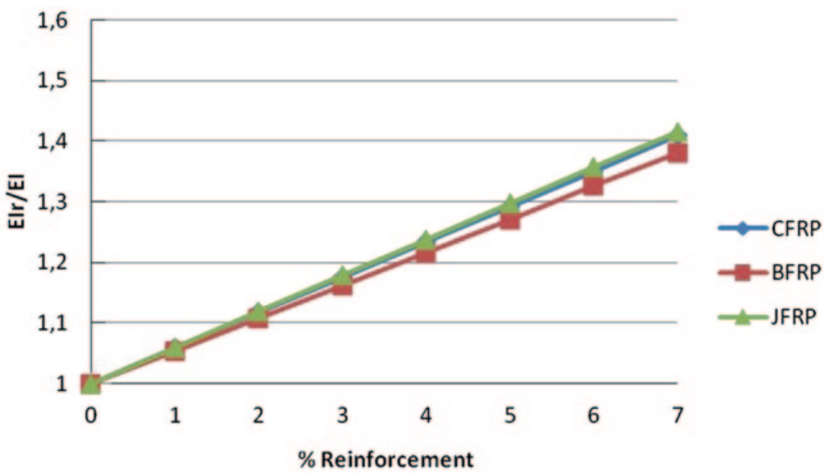


Fig. 4 EI_r/EI versus fiber reinforcement (%)—*Eucalyptus* sp.

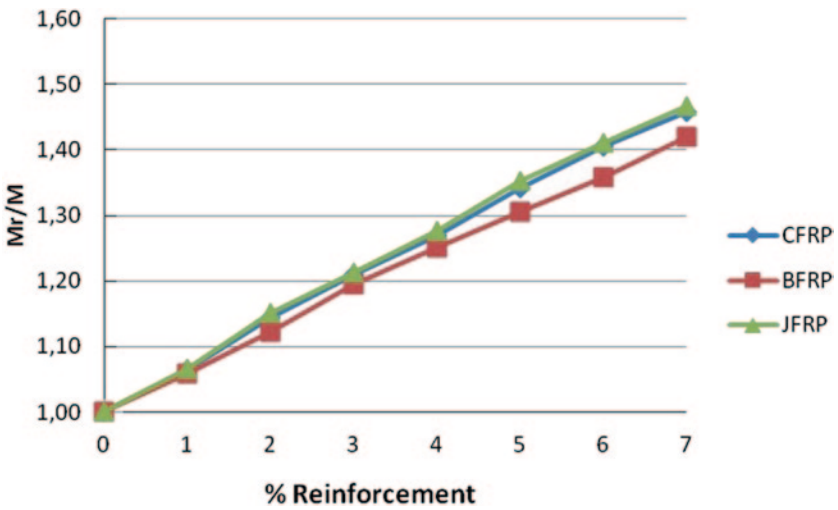


Fig. 5 M_r/M versus fiber reinforcement (%)—*Pinus* sp.

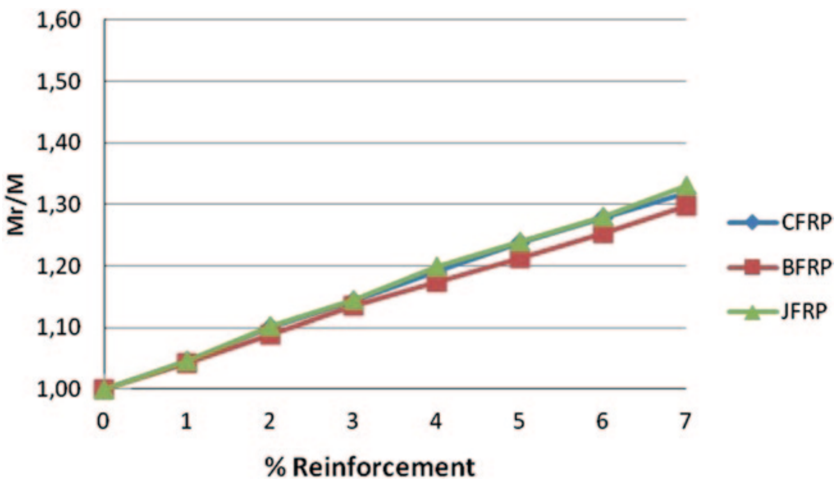


Fig. 6 M_r/M versus fiber reinforcement (%)—(*Eucalyptus* sp.)

"Theoretical evaluation," considering m = 0.0. The increase in strength and stiffness is approximately linear until 7% of fiber reinforcement. As a continuation of this work, experimental tests will be conducted to check the validity of the theoretical data obtained by the theoretical model.

Figure 7 presents stress diagrams created with software for beams without reinforcement, and beams with 7% of fiber reinforcement (curauá, bamboo, and jute) to m = 0.0. The curauá, jute, and bamboo fibers acted as efficient reinforcement for glulam beams, and presented analogous results because of similar values for MOE.

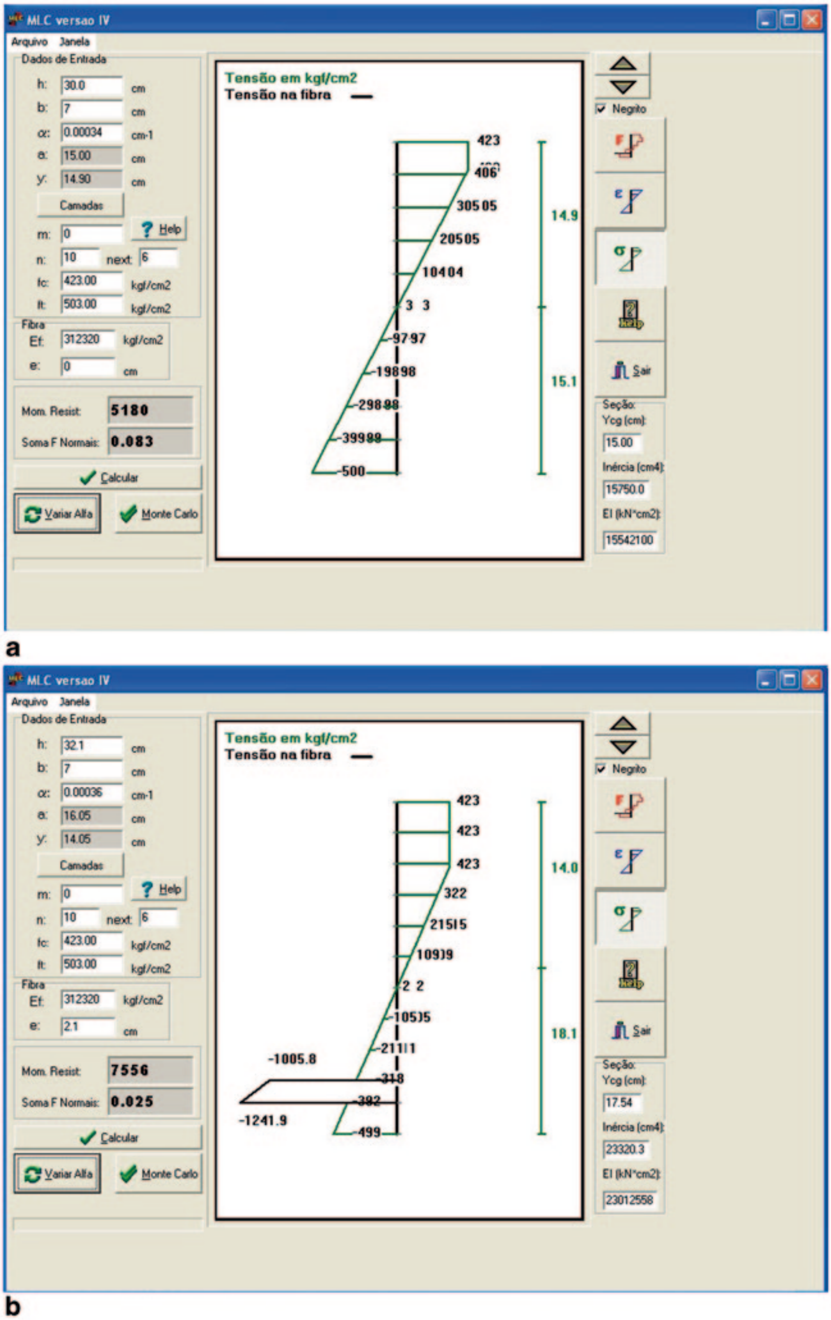
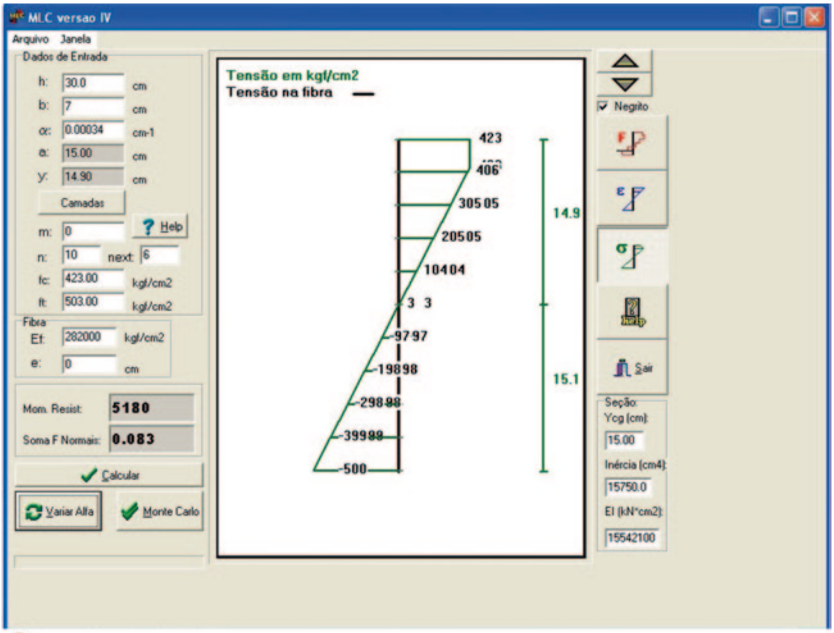
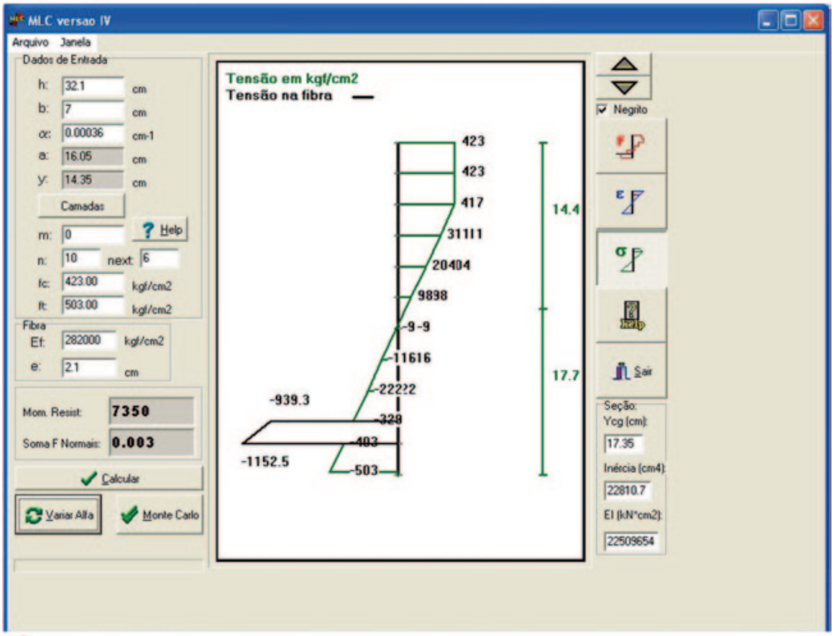


Fig. 7 Glulam beam program—stress diagram: curauá fiber (**a** and **b**), bamboo fiber (**c** and **d**), and jute fiber (**e** and **f**) to *Pinus* sp. glulam beams

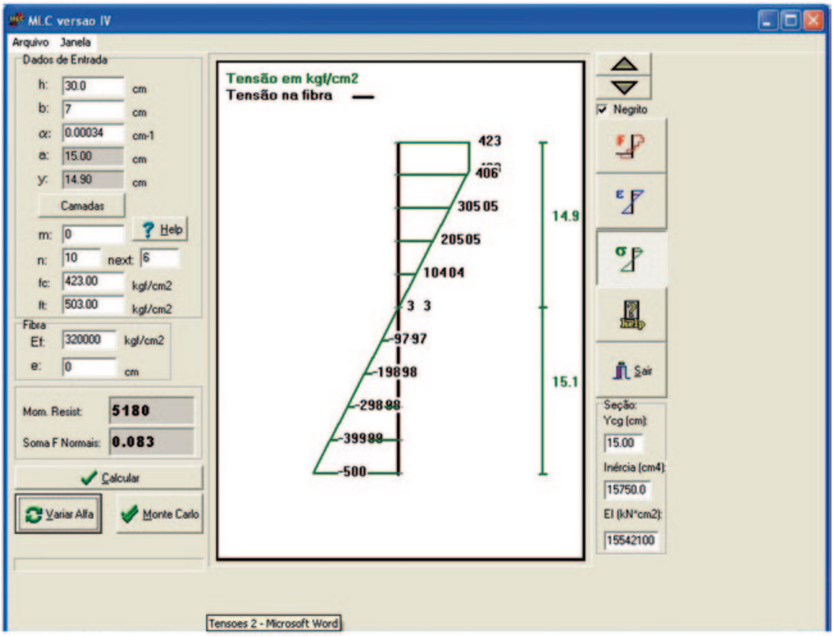


c



d

Fig. 7 (continued)



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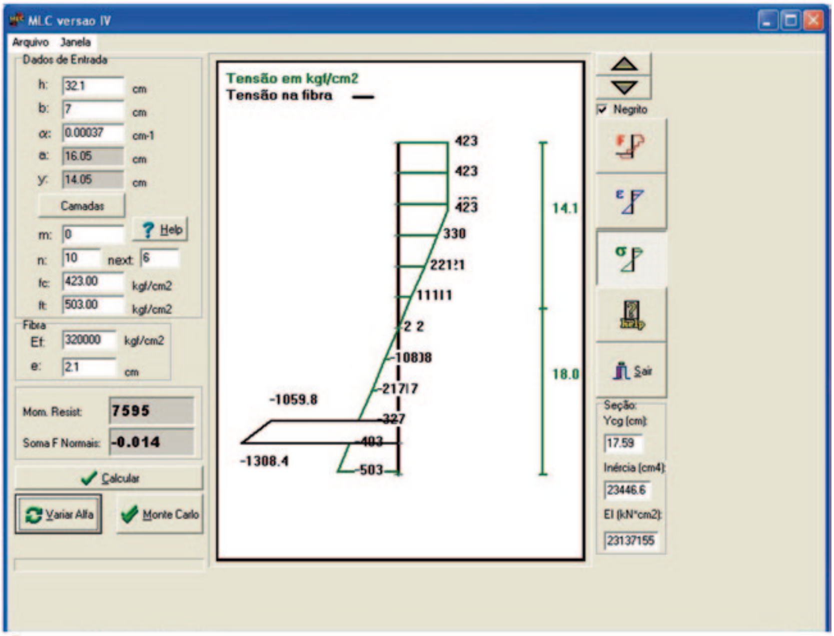

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Fig. 7 (continued)

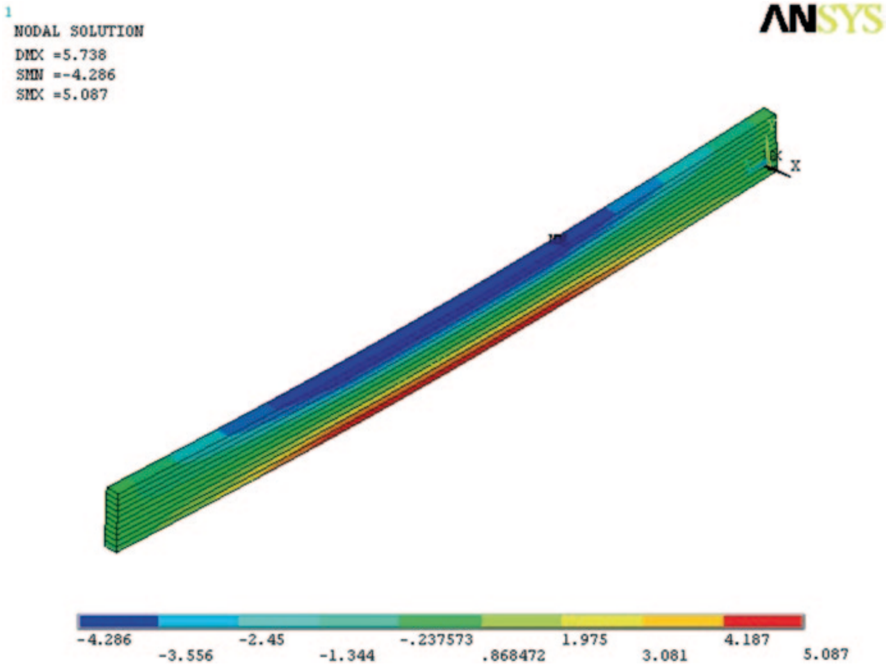

Fig. 8 Stresses (kN/cm2) in the beam (*Pinus* sp.) without reinforcement

The efficacy of these fibers as reinforcement is a result of their stiffness, with values for MOE approximately three times that of wood. The increase in stiffness was of 45–50 % for *Pinus* sp. beams and 40 % for *Eucalyptus* sp. beams, with 7 % of reinforcing fibers. The increase in strength was 40 % for *Pinus* sp. beams and 20 % for *Eucalyptus* sp. beams, with 7 % of reinforcing fibers.

Numerical Values

Figures 8 and 9 show a comparison of the stress values in the z direction obtained for beams with and without reinforcement. The numerical results for stresses and displacement were in accordance with the theoretical results. For the beam without reinforcement, the maximum tensile stress was 5.09 kN/cm^2 and the maximum compressive stress was 4.29 kN/cm^2. The theoretical analysis predicted 5.00 kN/cm^2 as the maximum tensile stress and 4.23 kN/cm^2 as the maximum compressive stress (Fig. 7a). The value of vertical displacement at mid-span corresponding to 40 % of the maximum applied load at the thirds of span was 2.28 cm. Theoretical analysis, using values of bending stiffness from Table 4, predicted a displacement of 2.23 cm.

For the beam with a reinforcement of 7 % (curauá fiber), the maximum tensile stress in the wood was 5.15 kN/cm^2 and the maximum compressive stress was 4.36 kN/cm^2. The maximum tensile stress in the curauá fiber layer was 12.76 kN/

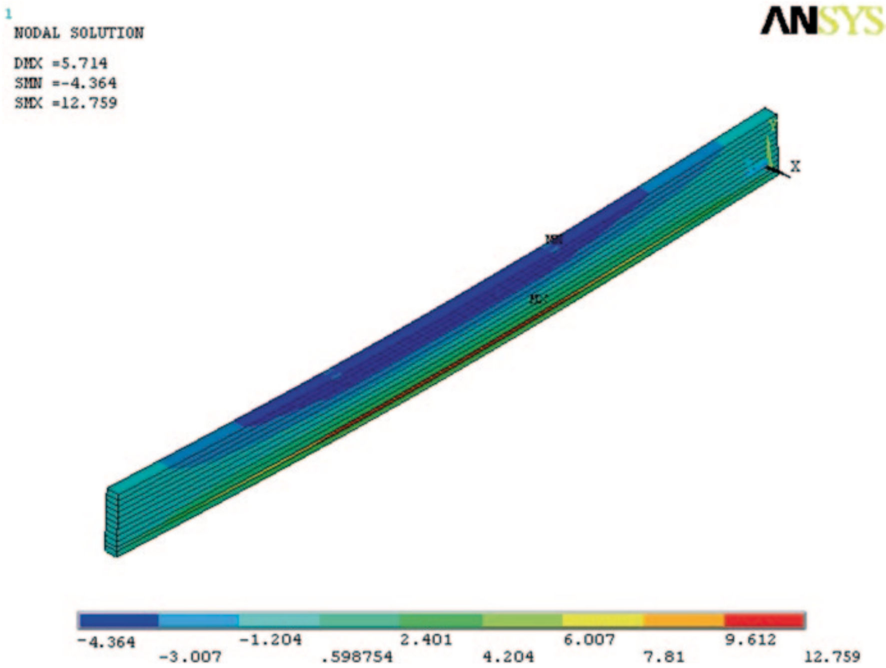

Fig. 9 Stresses (kN/cm2) in the beam (*Pinus* sp.) with reinforcement of 7 % (curauá)

cm^2. The theoretical analysis predicted 4.99 kN/cm^2 as the maximum tensile stress and 4.23 kN/cm^2 as the maximum compressive stress in wood, and 12.42 kN/cm^2 as the maximum tensile stress in the layer of curauá fiber (Fig. 7b). The value of vertical displacement at mid-span corresponding to 40 % of the applied load at the thirds of span was 2.25 cm. Theoretical analysis, using values of bending stiffness from Table 4, predicted a displacement of 2.24 cm.

Conclusion

Based on the current results, it is possible to conclude that the method used to produce glulam beams led to a higher efficiency of the structural elements. The FRP introduced in the tensioned side of glulam beams improved strength and stiffness as the percentage of reinforcement increased.

Reinforced beams have presented two failure stages. The first one was caused by tension in the sheet positioned under the reinforcement layer, while the second occurred as a result of a compression yielding on the upper side of the beam, followed by both a shear failure on the fiber–lumber interface and a tensile failure on the wood.

The maximum stress and vertical displacement calculated by numerical analysis were in good agreement with the values obtained from theoretical analysis.

Acknowledgments Research Foundation of the São Paulo State—FAPESP; National Council for Scientific and Technological Development—CNPq; Financier of Studies and Projects—FINEP and Coordination of Improvement of Higher Education Personnel—CAPES.

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http://www.springer.com/978-3-319-13846-6

Agricultural Biomass Based Potential Materials
Hakeem, K.R.; Jawaid, M.; Alothman, O. (Eds.)
2015, XXI, 505 p. 163 illus., 77 illus. in color., Hardcover
ISBN: 978-3-319-13846-6