10th International Conference on Composite Science and Technology
ICCST/10
A.L. Araújo, J.R. Correia, C.M. Mota Soares, et al. (Editors)

NUMERICAL ANALYSIS OF GLULAM BEAMS WITHOUT AND WITH GFRP REINFORCEMENT

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Key words: Glulam, GFRP reinforcement, Numerical analysis.

Summary: *This work presents a numerical analysis, using the software ANSYS, about glued laminated timber beams (GLULAM) without and with use of a Glass Fiber Reinforced Polymer (GFRP) reinforcement. The beams were composed of six sheets of lumber with a nominal thickness of 3.5 cm. In the case of reinforced beam, the reinforcing layer was positioned between the last and the penultimate lumber sheet at the bottom edge. The thickness of the glass fiber was 7 mm corresponding to about 3% of the beam cross-section. In the performed numerical analysis were obtained the values of the acting stresses on the timber and fibers, the strains, and the vertical displacements at mid-span of the beam, to a load applied at four points. The numerical results were compared with the results obtained by the theoretical analysis and also with the experimental results obtained from prototypes in a natural scale. In the theoretical and numerical analysis were considered the properties of elasticity of each lumber sheet previously evaluated by static bending test. The lumber under compression was considered with a elastic-plastic behavior; lumber under tension and the reinforcement layer were considered with a elastic behavior until failure. The numerical results indicated a good agreement with the theoretical results. Also indicated a good agreement with the vertical displacements obtained experimentally, measured in the linear range. It was observed also a good agreement between the stress values obtained by numerical analysis and those obtained by the theoretical analysis with applied load to failure of the beams*

1 INTRODUCTION

Fiber-reinforced polymers FRP associated with glulam timber beams provide significant gains in terms of strength and stiffness and modify the failure mode in bending of these structural elements. Several researchers had studied glulam timber beams reinforced with FRP, using carbon-fibers, glass fiber or natural fibers.

Dagher [1] studied the reinforcement of glulam timber beams with carbon fiber blades (1.5 mm thick) applied in the bottom glue layer on the tensioned side. When the cross section of the beams had 3.3% of reinforcement it was observed a 60% increase in their strength. Other researchers have found similar results: Lindybeg [2], Romani and Blab [3] and Fiorelli and Dias [4].

Related to the theoretical model to estimate the ultimate bending moment of the reinforced glulam beams, most of researchers have considered Navier/Bernoulli hypothesis (plane sections remain plane after straining). These researchers have considered also a elastic-plastic behavior for FRP and lumber in tension parallel to the grain, but with differences in the constitutive law for lumber in compression parallel to the grain, i.e., some researches considering a elastic-plastic ideal behavior [3,5]; others researchers [2,4] using a constitutive law based in Buchanan [6] that consider a elastic-plastic with softening behavior.

Raftery and Hart [7] discusses the development of a finite element model, which incorporates nonlinear material modeling (including anisotropy) and nonlinear geometry to predict the load–deflection behavior, stiffness, ultimate moment capacity and strain distribution of FRP plate reinforced glued laminated timber beams. In this case, a good agreement was obtained between the predicted behavior and the associated experimental results.

The aim of this work was to compare experimental and theoretical results obtained by Fiorelli [8], who studied glulam timber beams reinforced with glass fiber, with a simplified numerical analysis using the software ANSYS [9]. Most of the proposed simplifications was due to difficulty in obtaining all the properties of wood needed for evaluation that considers its anisotropy.

2 PROCEDURES

2.1 Experimental program

Experimental results were extracted from a PhD Thesis developed by Fiorelli [8]. He studied glulam timber beams made of wood species *Pinus caribea hondurensis* reinforced with fiberglass. Six beams were made with a nominal dimension of 70x210x4100mm. Figure 1 shows finger joints position of the three lumber sheets located at bottom side of these beams.

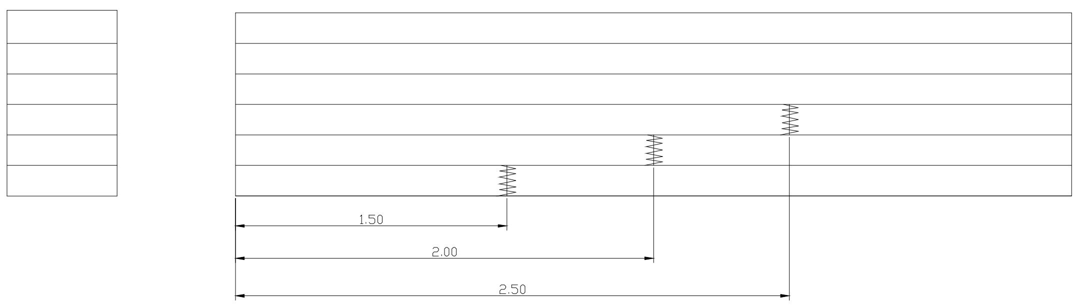


Figure 1: Finger joints positions

Two of these glulam were unreinforced and four were reinforced with a layer of glass fiber reinforced polymer (GFRP), positioned between the last and the penultimate lumber sheet at the bottom edge.

The modulus of elasticity (MOE) of the lumber sheets were previously obtained through bending static tests, and visual graded according to SPIB rules [10].

In this paper were analyzed a unreinforced beam and a reinforced beam, whose lumber sheets properties are showed in Table 1 and Table 2. The values of strength at compression (f_{c0}) and tension (f_{t0}) parallel to the grain were obtained through experimental tests (according to the ABNT NBR 7190:1997 Brazilian standard [11]) of specimens extracted from the top side (compression) and bottom side (tension), after the bending tests of the beams. Table 2 also shows properties of glass fiber reinforcement layer (thickness is related just the glass fiber, without epoxy adhesive).

Visual Grading	Sheet lumber thickness (mm)	MOE (MPa)	Strength (MPa)	Cross Section
Nº2-D	35	14659	f_{c0}=51.4	
Nº3-D	35	14486		
Nº3-ND	35	8733		
SS-ND	34	8001		
SS-D	33	12692		
SS-D	33	14034	f_{t0} = 70.4	

Table 1 - Properties of the unreinforced beam lumber sheets

Visual Grading	Sheet tickness (mm)	MOE (MPa)	Strength (MPa)	Cross Section
SS-ND	35	11942	f_{c0}=50.5	
Nº2-D	35	12400		
Nº3-D	31	11117		
Nº3-ND	30	10867		
Nº1-D	34	12653		
Glass fiber	7	70000		
SS-D	34	13305	f_{t0} = 62.1	

Table 2 - Properties of the reinforced beam lumber sheets and glass fiber layer

Lumber sheets were glued with Phenol–resorcinol adhesive and the polymer used in reinforcement layer was AR-300 epoxy adhesive.

Bending test with two loads applied at one-third intervals along the span (L=4 m) of the beams were made (see Figure 2), according to the ASTM D198:1997 standard [11].

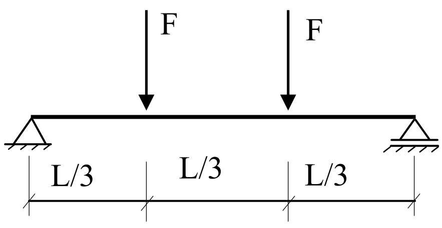


Figure 2: Scheme of the bending test

Vertical displacement and strains were measured at mid-span. Figure 3 shows the positions of strain gages for the reinforced beam. In the case of unreinforced beam, were measured strains at the top and bottom face.

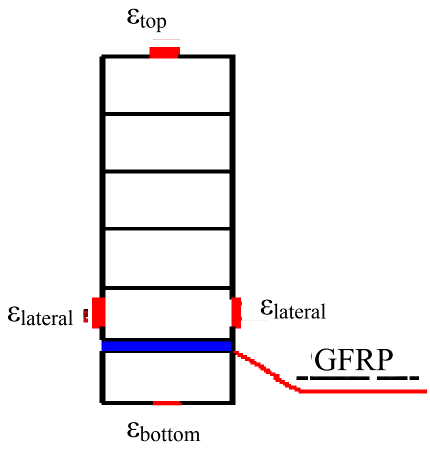


Figure 3: Strain gages positions

Load was applied until failure of the beams, that occurred by tension of the bottom lumber sheet. In the case of reinforced beam, after failure of the lumber sheet located under the GFRP layer was possible to increasing the applied loads (about 28%) until a second stage of failure due shear on the GFRP timber interface and tension in the wood.

2.2 Theoretical analysis

Vertical displacement were calculated in the linear range, considering the properties showed in Table 1 and Table 2.

Ultimate bending moment was determined considering a linear distribution of strains over the beam height. The constitutive law for lumber in compression and tension parallel to the grain is showed in Figure 4. GFRP behavior is considered elastic-linear until failure. This model is based in Lindyberg [2].

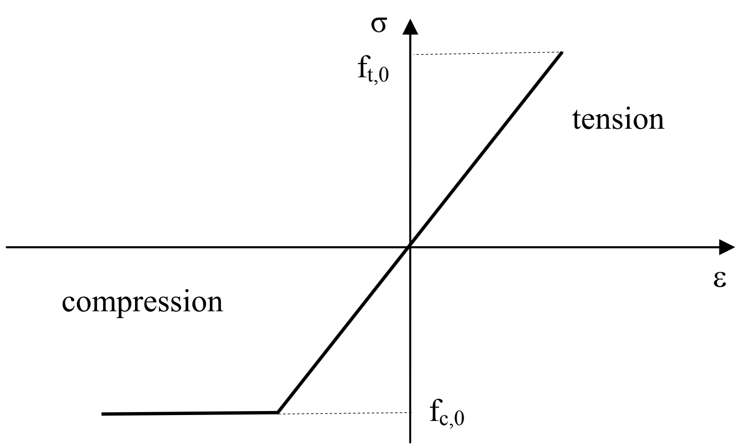


Figura 4: Constitutive law for lumber in compression and tension parallel to the grain

Ultimate bending moment was calculated considering failure in lumber due tension parallel to the grain. The real position of the neutral axis is achieved through an iterative process, taking account that the resultant force due normal stresses in all layers is null. Failure in GFPR was not considered because its maximum tension level is always lower than its strength, in view of the relation of strength and modulus de elasticity for lumber and glass fibers.

2.3 Numerical simulation

Numerical evaluation of the stresses, strains and displacements in the glulam beams was performed using the ANSYS [9] commercial software, version 10.0, based on the finite element method, using SOLID 45 elements.

Wood and GFRP were considered with an isotropic behavior, linear and elastic in tension. The constitutive model used for the wood in compression simulates an elastic–plastic behavior by use of a bilinear curve as shown in Figure 5. To avoid numerical problems in the portion of the curve between εy and εu, a small slope of E/2000 was considered. In the Figure 5, f_y is the strength of wood in compression parallel to the grain and f_u is setting to a arbitrated strain ε_u .

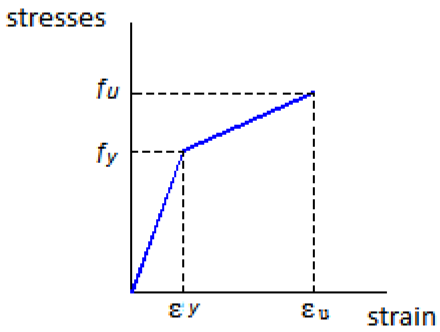
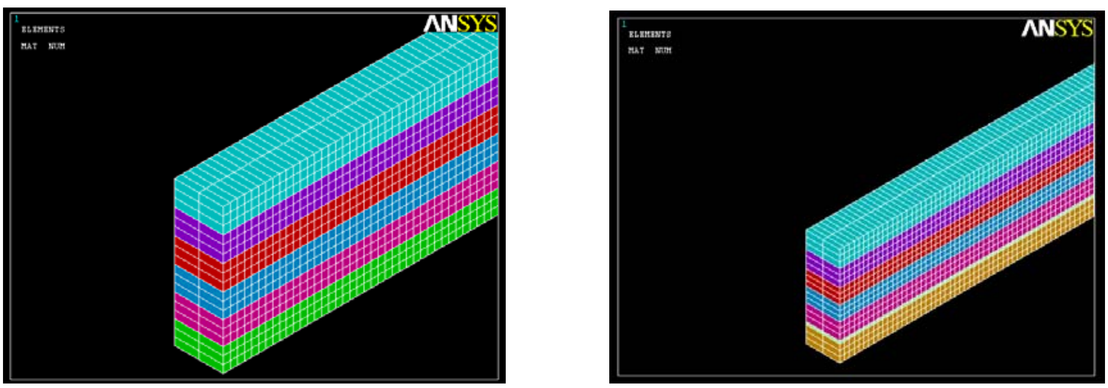


Figure 5: Constitutive model for wood in compression.

In a similar way to that performed in the theoretical analysis, were used the modulus of elasticity of each layer (lumber sheets and GFRP). Poisson ratio for both materials was considered equal to 0.2.

Figure 6 shows the mesh used in numerical simulation.



(a) (b)

Figure 6: Mesh used in numerical simulation: (a) unreinforced beam (b) reinforced beam.

3 RESULTS AND ANALYSIS

Table 3 and Table 4 show the theoretical and numerical results, and experimental results obtained by Fiorelli (2005). The results showed are stresses, strains and the vertical displacements at mid-span of the beams. For each beam, the results are showed for 4 load levels (F is the value of each load applied at one-third of the beam span) related to:
F_1 : last experimental measurement of vertical displacement;
F_2 : last experimental measurement of strains;
F_3 : experimental failure of the beam;
F_4 : theoretical failure of the beam, considering experimental strength in tension parallel to the grain.

Results	F_1 = 5,68 kN			F_2 = 15,15 kN			F_3 = 17,05 kN		F_4 = 23,63 kN	
	Exp.	Theor.	Num.	Exp.	Theor.	Num.	Theor.	Num.	Theor.	Num.
Strain (με) bottom face	1170	1156	1162	3350	3083	3098				
Strain (με) top face	-1180	-1100	1080	-3590	-2934	-2881				
Displacement (mm)	18.65	18.75	18.78							
Stress (MPa) bottom face							48.7	48.9	70.4	70.7
Stress (MPa) top face							-48.4	-47.5	-51.4	-51.4

Table 3: - Results - unreinforced beam

Results	F_1 = 6,50 kN			F_2 = 18,40 kN			F_3 = 19,21 kN		F_4 = 25,61 kN	
	Exp.	Theor.	Num.	Exp.	Theor.	Num.	Theor.	Num.	Theor.	Num.
Strain (με) bottom face	1150	1124	1130	3620	3182	3200				
Strain (με) top face	-1480	-1357	-1365	-5000	-3842	-3860				
Strain (με) lateral faces	480 450	435	508	1420 1260	1232	1440				
Displacement (mm)	21.10	21.18	20.22							
Stress (MPa) bottom face							44.2	44.4	62.1	62.5
Stress (MPa) top face							-47.9	-48.2	-50.5	-50.5
Stress (MPa) GFRP							147.5	148.3	204.9	206.0

Table 4: - Results - reinforced beam

For both beams, the values of vertical displacements (experimental, theoretical and numerical), which were obtained in the linear range, had a very good agreement, as well as for the strains. Based on these results, it can be concluded that a simple calculation, taking into account the materials with linear elastic behavior, can be used in the case of serviceability limit states.

To the load level F_2, which is near failure, it can be observed a very good agreement between the theoretical and numerical values of strains, but the experimental values are higher. One explanation for this behavior is that the constitutive law for wood in compression, used in the theoretical and numerical models, consider elastic behavior until the beginning of plastic stage. Then, estimated values of strains are lower that the real strains and, consequently, a lower position of neutral axis that increases tension in bottom face. Probably best results will be obtained using a constitutive law that represents the real behavior of wood in the compression until the beginning of plastic stage.

The load level equal to F_3, related to the experimental failure, was reached with compression and tension levels estimated by theoretical and numerical analysis with good agreement, but lower than the strength in compression and tension for both beams. The value of tension calculated using theoretical and numerical analysis were about 70% of the strength of wood in tension, for both beams. On the other hand, this value approximately corresponds to the strength of the finger joints.

In the case of load level equal to F4, it can be observed that the strength in compression and tension were reached, with good agreement between theoretical and numerical results. These analyzes provide a good evaluation of load at failure if is used a strength in tension parallel to the grain considering the finger joints.

4 CONCLUSIONS

Theoretical and numerical analysis had a good agreement with experimental results, in the linear range. To evaluate vertical displacements (serviceability limit states) a simple calculation based on the classical theory of strength of materials, considering the materials with linear elastic behavior can be used. This calculus must consider the real properties of each layer of the glulam timber beam.

For load level near failure, theoretical and numerical analysis underestimated the values of experimental strains. It is suggested the use of a constitutive law that represents in a better way the behavior of wood in the compression until the beginning of plastic stage.

Results obtained from the numerical analysis proposed had a very good agreement with the theoretical results for all load level evaluated. These analyzes can provide a good evaluation of load at failure if is used the strength of finger joints.

ACKNOWLEDGEMENT

The authors thank CNPq (National Council of Technological and Scientific Development) and FAPESP (Foundation for Research Support of São Paulo State) for financial support.

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