Glued Laminated Timber Beams Using Castor Oil Adhesive

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Abstract

Glued laminated timber (glulam) is composed of visually graded lumber, which has smaller dimensions in relation to the final dimensions of the structural element, allowing a better placement of the graded material to obtain a final product with the best rigidity and strength characteristics. This work evaluated a new polyurethane adhesive based on castor oil in the production of glulam beams, using the wood species Pinus Sp. The pieces of lumber with nominal dimensions of 4.0 x 8.0 x 410 cm were graded visually, processed in the nominal dimensions of 3.5 x 7.5 x 400 cm, and then mechanically graded through bending tests. Two series of six beams of structural sizes were produced, the first one with nominal dimensions of 7x20x400 cm composed of 6 lams, and the second one with nominal dimensions of 7x30x400 cm composed of 9 lams. The rigidity and strength of the specimens were evaluated through static bending tests using four-point loading. The experimental and theoretical results were compared using the transformed section method, considering the modulus of elasticity of each lam. The obtained results showed a good performance of the tested adhesive.

Keywords: Pinus Sp, strength and rigidity of beams, transformed section method

Introduction

This work evaluated a new polyurethane adhesive based on castor oil in the production of glulam beams. Twelve beams of structural sizes were produced and tested through static bending tests using four-point loading.

Experimental Procedures

Materials

Pieces of lumber (*Pinus sp* species) with nominal dimensions of 4.0 x 8.0 x 410 cm were dried until 12% of moisture content. A new polyurethane adhesive based on castor oil (*Ricinus communis*) made by Industry Kell was used.

Methods

Visual and mechanical grading

The pieces of lumber with nominal dimensions of 4.0 x 8.0 x 410 cm were graded visually, processed in the nominal dimensions of 3.5 x 7.5 x 400 cm, and then mechanically graded through bending tests. The pieces were graded visually, according CARRERA (2003): Select Structural (SS), number 1 (N1), number 2 (N2), number 3 (N3), and dense (D) or no dense (ND). The Young's modulus (flatwise) was obtained through three-point loading bending tests.

Production of glulam beams

Glue was applied through painting, and manual press (around 1 MPa) was used during about 24 hours (figure 1). After that, the beams were processed laterally. Two series of six beams of structural sizes were produced, the first one with nominal dimensions of 7x20x400 cm composed of 6 lams, and the second one with nominal dimensions of 7x30x400 cm composed of 9 lams.

Figure 1- Production of glulam beams

Static Bending tests of glulam beams

Test procedures were made according ASTM D19 [3] to determinate experimental bending stiffness (EI_{exp}) and ultimate load (F_{ult}). Figure 2 shows test arrangement, using four-point loading, and clear span between suports L= 380 cm.

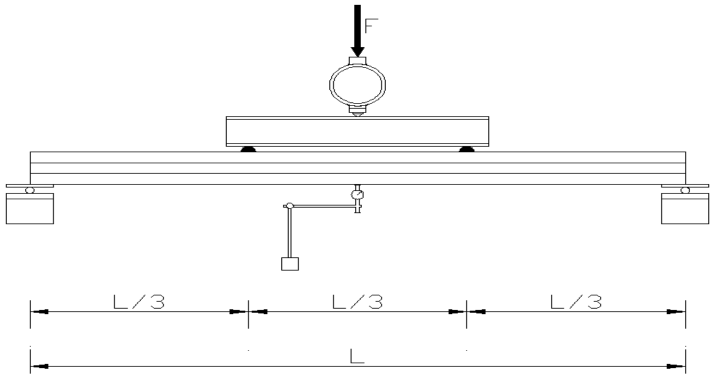


Figure 2 – Test arrangement

The deflection at center span was measured until L/200, and the test were made until beam failure (figure 3).

Figura 3 – Failure of beam 2

Small clear specimen tests

After beams bending tests, small clear specimens from beams tests were tested. The following testes were made: compression parallel to grain; tension parallel to grain; static bending; shear parallel to grain; shear in the glue; moisture content; density. The tests were made according "NBR 7190 (1997) – Projeto de Estruturas de Madeira". For each test were used 2 specimens. Specimens for tension and bending tests were extracted from the bottom side of the beam, and for compression tests from top side. Specimens for shear tests (wood and glue) were obtained from the central portion of the beam.

Results

Grading and distribution of lams

"Table 1" shows results obtained in visual grading, Yong's modulus (E) and thickness (h_i) of lams. The position of each lam in the "Table 1" corresponds to the position in the beam. "Table 1" presents also dimensions of the beams (depth and width).

Table 1a – Lams properties and distribution of them in each beams 1-6

Beam 1				Beam 2				Beam 3			
Lam	Grade	E (MPa)	h_i (mm)	Lam	Grade	E (MPa)	h_i (mm)	Lam	Grade	E (MPa)	h_i (mm)
2	SS-ND	10497	34.8	28	N1 - ND	11464	35.3	30	N1 - ND	11351	35.6
44	N2-ND	10205	35.4	54	N2 - ND	10077	34.8	13	SS - ND	9473	35.1
14	SS-ND	8212	33.6	8	SS - ND	8076	35.2	38	N1 - ND	8643	34.8
90	N3-ND	8415	35.3	85	N3 - ND	8390	35.0	96	N3 - ND	8178	35.2
71	N3-ND	7804	34.3	77	N3 - ND	7903	34.3	84	N3 - ND	7766	34.3
31	N1-ND	7866	34.4	1	SS - ND	7752	33.8	11	SS - ND	7737	34.6
12	SS - ND	8609	35.7	10	SS - ND	8587	34.7	18	SS - ND	8400	34.7
117	N2 - ND	14083	35.4	45	N2 - ND	11599	35.5	37	N2 - ND	11398	35.0
3	SS - ND	13316	34.1	5	SS - ND	12902	34.4	9	SS - ND	13097	35.0
		depth (mm)	312.9			depth (mm)	313.0			depth (mm)	314,3
		width (mm)	69.7			width (mm)	65.0			width (mm)	69.3

Beam 4				Beam 5				Beam 6			
Lam	Grade	E (MPa)	h_i (mm)	Lam	Grade	E (MPa)	h_i (mm)	Lam	Grade	E (MPa)	h_i (mm)
49	N2 - ND	17040	35.6	58	N2 - ND	18435	34.0	47	N2 - D	16883	34.9
108	N2 - ND	9940	35.2	116	N2 - ND	9898	35.9	17	SS - ND	8846	34.4
33	N2 - ND	8400	34.5	42	N2 - ND	8192	34.4	39	N2 - ND	8071	35.0
88	N3 - ND	8095	34.3	113	N2 - ND	7995	35.4	16	SS - ND	7739	34.9
120	N2 - ND	7683	32.4	110	N2 - ND	7347	36.0	93	N3 - ND	7687	35.4
98	N3 - ND	7975	35.7	87	N3 - ND	7829	34.5	7	SS - ND	7377	34.5
21	SS - ND	8393	34.8	52	N2 - ND	8986	35.3	107	N2 - ND	8669	36.2
41	N2 - ND	11856	34.5	48	N2 - ND	11640	35.6	112	N2 - ND	11167	35.4
15	SS - ND	10774	35.0	25	N1 - ND	13081	34.0	20	N1 - ND	13824	34.8
		depth (mm)	312.0			depth (mm)	315.0			depth (mm)	315.5
		width (mm)	70.1			width (mm)	68.5			width (mm)	66.6

Table 1b – Lams properties and distribution of them in each beams 7-12

Beam 7				Beam 8				Beam 9			
Lam	Grade	E (MPa)	h_i (mm)	Lam	Grade	E (MPa)	h_i (mm)	Lam	Grade	E (MPa)	h_i (mm)
56	N2 - ND	12374	35.7	51	N2 - ND	13251	35.5	50	N2 - ND	12910	34.6
70	N3 - ND	10919	35.0	78	N3 - ND	13700	34.5	73	N3 - ND	12381	34.3
79	N3 - ND	8666	350	81	N3 - ND	8428	35.6	86	N3 - ND	8580	34.9
89	N3 - ND	26617	34.7	91	N3 - ND	9374	34.2	76	N3 - ND	8980	35.5
32	N2 - ND	11251	34.2	118	N2 - ND	10973	34.8	111	N2 - ND	10155	35.8
29	N1 - ND	12639	35.3	19	N1 - ND	12591	34.8	23	N1 - ND	12728	34.7
depth (mm)			209.9	depth (mm)			209.5	depth (mm)			209.9
width (mm)			70.4	width (mm)			70.5	width (mm)			68.3

Beam 10				Beam 11				Beam 12			
Lam	Grade	E (MPa)	h_i (mm)	Lam	Grade	E (MPa)	h_i (mm)	Lam	Grade	E (MPa)	h_i (mm)
103	N2 - ND	14449	35.7	63	N2 - ND	12106	34.9	106	N2 - ND	13719	36.1
72	N3 - ND	11685	35.0	74	N3 - ND	11090	34.8	75	N3 - ND	11052	34.2
99	N3 - ND	8837	35.0	92	N3 - ND	8648	34.8	82	N3 - ND	8414	35.5
95	N3 - ND	8983	34.7	34	N2 - ND	8708	34.9	57	N2 - ND	8871	35.7
36	N2 - ND	10249	35.2	46	N2 - ND	10368	35.6	40	N2 - ND	10238	35.5
22	N1 - ND	12563	35.3	27	N1 - ND	12251	35.4	24	N1 - ND	11543	35.2
depth (mm)			210.9	depth (mm)			210.5	depth (mm)			212.1
width (mm)			70.0	width (mm)			69.9	width (mm)			68.9

Static Bending tests of glulam beams

Linear relationship between applied force (F) and deflection (v) was obtained (v = constant + **k**.F). Experimental bending stiffness (EI_{exp}) was calculated using "Equation (1)", not considering shear influence:

$$EI_{exp} = \frac{23 \cdot L^3}{1296 \cdot k} \qquad (1)$$

"Table 2" shows experimental bending stiffness (EI_{exp}), ultimate load (F_{ult}) and ultimate bending moment. Figures 4 and 5 show glulam beams with 9 lams and 6 lams after failure.

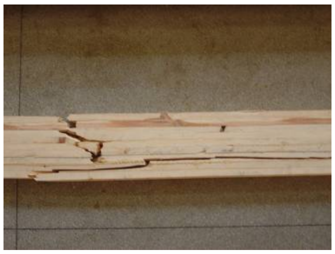
Table 2 – Results obtained in static bending tests – glulam beams

beam	1	2	3	4	5	6	7	8	9	10	11	12
EI_{exp} (kN.m^2)	1877	1750	1877	2019	2127	2150	651	634	582	653	582	619
F_{ult} (kN)	74,7	96,3	90,4	89,8	103,9	81,7	48,7	42,2	40,5	48,7	48,8	34,6
M_{ult} (kN.cm)	4730	4387	5723	5689	6580	5175	3084	2673	2567	3084	3093	2193


Beam 1


Beam 2


Beam 3

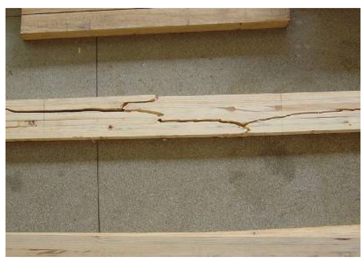

Beam 4


Beam 5


Beam 6

Figura 4 – Failure detail of beams with 9 lams


Beam 7


Beam 8


Beam 9


Beam 10


Beam 11


Beam 12

Figure 5 – Failure detail of beams with 6 lams

Small clear specimen tests

"Table 3" shows the results, strength (f) and modulus of elasticity (E), obtained from small clear specimen tests (mean values of 2 specimens), mean values and coefficient of variation (CV) for each propertie.

Table 3 - Results obtained for specimens

Beam	Compression parallel to grain		Tension parallel to grain		Static Bending		Shear		Moisture Content (%)	Density (g/cm^3)
	$f_{c,0}$ (MPa)	$E_{c,0}$ (MPa)	$f_{t,0}$ (MPa)	$E_{t,0}$ (MPa)	f_M (MPa)	E_M (MPa)	$f_{v,wood}$ (MPa)	$f_{v,glue}$ (MPa)		
1	40.8	9841	59.8	9766	74.5	10859	11.8	10.3	12.4	0.56
2	39.5	8514	60.1	9616	67.9	10951	10.6	10.0	11.2	0.55
3	33.6	6024	60.7	12866	80.2	9139	12.1	12.8	11.7	0.59
4	52.5	13262	48.8	7368	75.4	8939	12.0	10.5	12.3	0.76
5	51.6	10987	57.8	8559	85.4	11053	11.0	11.5	11.5	0.66
6	46.9	10499	78.7	9458	97.7	11509	13.0	10.8	12.0	0.64
7	41.4	9135	50.5	6137	84.3	11742	8.5	9.4	11.5	0.57
8	44.6	9793	87.8	13472	76.6	10432	110	6.3	11.5	0.48
9	43.4	9735	75.9	9269	57.6	10918	11.4	8.9	11.3	0.49
10	46.5	10479	50.5	12808	83.2	12440	9.3	82	12.3	0.60
11	40.9	9085	57.7	8657	97.8	12432	9.1	7.9	11.2	0.52
12	41.8	9740	70.8	11135	78.9	9606	10.4	10.7	11.1	0.51
Mean Values	**41.7 (22%)**	**9758 (21%)**	**63.3 (22%)**	**9.926 (26%)**	**80.0 (21%)**	**10835 (16%)**	**10.9 (14%)**	**9.8 (20%)**	**11.6 (5%)**	**0.57 (15%)**

Analysis

The experimental and theoretical results for stiffness were compared using the transformed section method, considering the modulus of elasticity of each lam (E_i) from "Table 1". The theoretical value of stiffness is calculated by "Equation (2)":

$$EI_{theo} = E_c \cdot I' = E_c \cdot b \cdot \sum_{i=1}^{n} \left(\frac{E_i \cdot h_i^3}{E_c \cdot 12} + \frac{E_i \cdot h_i \cdot y_i'^2}{E_c} \right) \qquad (2)$$

Where:
E_c = modulus of elasticity of lam located in the bottom side of the beam, used for homogenized beam section;
I' = moment of inertia of homogenized beam section;
b = width of beam
h_i = thickness of lam "i" (from "Table 1");
y_i' = distance to neutral axis of homogenized section from center of lam "i";

The section modulus (W') used to calculate tension in extreme fiber at bottom side of beam is given by "Equation (3)":

$$W' = \frac{I'}{y'_{bot}} \qquad (3)$$

y'_{bot} = distance to neutral axis of homogenized section from bottom of beam

"Table 4" shows geometric properties of homogenized section and a confrontation between experimental and theoretical values for stiffness. The obtained results were satisfactory, because the efficiency was superior to 90% in all the cases. If shear effect is considered the efficiency would increase around 5%.

Table 4 – Geometric properties (homogenized section) and confrontation between experimental and theoretical stiffness

Beam	y'_{bot} (mm)	$I'(mm^4)$	W' (mm3)	EI_{exp} ($kN.m^2$)	EI_{teo} ($kN.m^2$)	$EI_{exp.}/EI_{teo}$
1	147	150735071	1025409	1877	2007	0,94
2	152	142900342	940134	1750	1844	0,95
3	152	150725345	991614	1877	1974	0,95
4	164	197864032	1206488	2019	2132	0,95
5	163	176131990	1080564	2127	2304	0,92
6	159	157850877	992773	2150	2182	0,99
7	101	52690572	521689	651	666	0,98
8	107	54042170	505067	634	680	0,93
9	107	50583242	472741	582	644	0,90
10	109	55085858	505375	653	692	0,94
11	106	51723014	487953	582	634	0,92
12	110	56621881	514744	619	654	0,95

Usually, except beam number 3, failure began at the bottom side of center span, due to tension stress, which is more critical than shear for beams tested. Then, we must evaluate the adhesive efficiency through confrontation between shear strength in wood and glue from values showed in "Table 3". Only beam number 8 presents glue shear strength smaller than 75% of wood shear strength. Mean value shows that glue shear strength is about 90% of wood shear strength. This fact confirms the good performance of adhesive.

"Table 5" shows experimental and theoretical values for ultimate bending moment (M_{ult}). Theoretical values are obtained using tension and bending strength from "Table 3" (and section modulus from "Table.4". Analyzing the two last columns of "Table 5" can be observed that bending strength gave results with smaller variation than tension strength.

Tabela 5 – Experimental and theoretical values for ultimate bending moment

Beam	M_{ult} (kN.m)			(I)/(II)	(I)/(III)
	Experimental (I)	Theoretical			
		W'. $f_{t,0}$ (II)	W'. f_M (III)		
1	47,297	61,325	76,405	0,77	0,62
2	43,871	56,521	63,812	0,78	0,69
3	57,234	60,176	79,525	0,95	0,72
4	56,892	58,928	90,913	0,97	0,63
5	65,803	62,486	92,287	1,05	0,71
6	51,750	78,147	96,951	0,66	0,53
7	30,843	26,334	43,972	1,17	0,70
8	26,733	44,345	38,708	0,60	0,69
9	25,669	35,876	27,231	0,72	0,94
10	30,843	25,538	42,038	1,21	0,73
11	30,926	28,168	47,734	1,10	0,65
12	21,932	36,436	40,619	0,60	0,54
			Mean value	0,88	0,68

Conclusions

The obtained results showed a good performance of the adhesive based on Castor Oil. The experimental stiffness of the twelve glulam beams tested were superior to 90% of theoretical stiffness calculated using the transformed section method, considering the modulus of elasticity of each lam. Except beam number 3, failure began at the bottom side of center span, due to tension stress; the glue shear strength was sufficient to prevent horizontal shear failure between lams. Shear tests using small clear specimens obtained from the beams show that glue shear strength is about 90% of wood shear strength. Finally, we suggest the use of 60% bending strength value (small clear specimen) to evaluate ultimate bending moment.

References

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS (1997). NBR 7190 - Projeto de estruturas de madeira. ABNT. Rio de Janeiro.

CARRERA, M.R. (2003). Critérios para classificação visual estrutural de peças de pinus spp. Dissertação de Mestrado, 182p, - Escola de Engenharia de São Carlos, Universidade de São Paulo. São Carlos, SP.

AMERICAN SOCIETY for TESTING and MATERIALS (1984). ASTM D198 - Standard Methods of Static Test of Timber in Structural Sizes. ASTM, EUA.

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