Bamboo Engineering (structural design methods, analysis and calculations)

EXPERIMENTAL STUDY ON BENDING PERFORMANCE OF CONFINED GUADUA BAMBOO LAMINATE (CGBL) WITH RADIATA PINE.

Alfonso Cruz, *Civil Engineer. Spc and Msc of Structures.*
Ph.D. Student, Universidad Nacional de Colombia, Bogotá, Colombia.
acruzg@unal.edu.co

Vivian Kandia
Civil engineering Student, Universidad Nacional de Colombia, Bogotá, Colombia
vpkandiar@unal.edu.co

Oscar Pabón
Civil engineering Student, Universidad Nacional de Colombia, Bogotá, Colombia
ofpabonc@unal.edu.co

Caori Takeuchi, *Ph.D.*
Professor, Universidad Nacional de Colombia, Bogotá, Colombia
Research Group: Análisis, Diseño y Materiales GIES
cptakeuchit@unal.edu.co

Abstract

The constructive technique called Confined Guadua Bamboo Laminate (**CGBL**) is an improvement of the mechanical properties of wood with low specifications, by means of the reinforcement of laminates of *Guadua angustifolia* Kunth Bamboo. The CGBL is composed by softwood that confines laminates of guadua. Thus, wood of low mechanical specification can be used for structural constructions with the CGBL technique. Bending tests were carried out for radiata pine, laminates of *Guadua angustifolia* Kunth bamboo and composites of pine and guadua bamboo laminates, to demonstrate the advantages of the CGBL construction technique. The density was determined for each material and also the moisture content at the end of the tests. The apparent modulus of elasticity in bending (E_b), the maximum load ($P_{máx}$), the load that corresponds to the proportionality limit (P_{LP}) and the distance between the neutral axis and the end compression fiber (Y_c) were obtained with the graphs: load (P) vs vertical displacement (δ) at the middle of the span (L) and moment (M) vs strain in the end compression fiber (ε_c). The composite had a bamboo laminate percentage of 37%. The results of the tests are outstanding; the composite behaviour was similar to the guadua bamboo laminates although the resistance of the radiata pine is lower, demonstrating the efficiency of the CGBL constructive technique. Wood from reforestation and fast-growing processes, with the CGBL construction technique, can accomplish structural requirements and become an alternative to hardwood with high mechanical resistance but longer growing time. In this way, not only the selection processes of structural elements for constructions in wood are favoured, but also the environment.

Keywords:

Bamboo, wood, laminates, modulus of elasticity, bending, compression, Eco construction

INTRODUCTION

Wood with the quality and mechanical properties needed for construction has an environmental and economic cost. The radiata pine has a low cost and is easy to work, however, its mechanical properties are low compared to other woods (Palermo 2013).

Alternative materials such as bamboo have advantages due to their low environmental cost and fast growth (Wong et al. 2011) and laminated guadua bamboo has greater mechanical properties than pine (López & Correal 2009), however, the production cost is high.

Different authors have studied the bending properties for alternative materials . For example, in bamboo laminates, the maximum stress MOR values range on average from 87.98 MPa to 128.78 MPa, and the apparent flexural elastic modulus, MOE, is 12,472 MPa (Montoya 2014). In the case of radiata pine, the bending strength is low and presents sudden failure, the maximum stress value is approximately 63.25 MPa and the apparent flexural elastic modulus is 9,698 MPa (Barker 1989).

Preliminary tests of compression parallel to the fibre in Confined Guadua Bamboo Laminate (CGBL), show significant increments of the resistance and the elastic modulus (Cruz Guzmán 2017). The difference between Poisson coefficient (ν) of laminated bamboo, ν approx. 0.50 (Takeuchi 2014), and pines, ν approx. 0.30 (United States Department of Agriculture Forest Service 2010), in this composite section produces stresses in the confined bamboo improve strength and stiffness. The resulting stresses in bending mechanical are a combination of compressive, tensile and shear stresses. In consequence, the location of guadua bamboo laminates improves the compression resistance, which positively affects the results of the bending tests of CGBL This document presents the flexural behaviour of the CGBL with a laminated bamboo percentage of 37%.

MATERIALS AND METHODS

This section explains the methodology of laboratory tests and numerical analysis of pine samples, bamboo guadua laminates and CGBL.

Materials

Bamboo guadua

Bamboo guadua used in this research were extracted from Armenia (Quindío – Colombia). Two hundred strips of laminate bamboo guadua with 120 cm length, 2.2 cm width, and 0.5 cm thickness were used.

Radiata pine.

The specimens of pine and composites used in this research were taken from three commercial units of radiata pine with 490 cm length, 14 cm width and 3.2 cm thickness.

Laboratory assemble and testing

Pressing process

There were two stages of pressing: first, to manufacture bamboo laminated boards and second, to assemble blocks of guadua laminates with sheets oriented in one direction, or blocks of pine and bamboo laminates. The applied pressure ranged between 0.6MPa and 0.7MPa in normal temperature conditions for a minimum time of 12 hours.

Glue

Melamine formaldehyde urea (MUF 1242 resin and catalyst) was used

Test specimens

For each type of specimens five samples numerated consecutively from one (1) to five (5) were tested. The first one of each type was tested to calibrate the test.

The average dimensions of the test pieces of pine were 995.58 mm length, 39.40 mm width and 39.70 mm thickness and for the guadua bamboo laminates specimens were 999.76 mm length, 39.72 mm width and 39.45 mm thickness. The specimens of composites of pine and bamboo had average dimensions of 38.67 x 37.09 x 997.57 mm and were formed by one piece of bamboo laminate of average thickness 14.46 mm confined by blocks of pine.

Strain gages were used in the specimens identified in **Table 1** and the position is showed in **Figure 1**. All the test pieces were measured using a calliper of 0.01mm precision and weighed with a digital balance of 0.01 gr precision. The vertical displacement ***(δ)*** at the centre of the span ***(L)*** was measured in the samples 2 to 5, using a deflectometer. The application speed of the load was 0.01 mm/s.

Bamboo guadua Specimens	Radiata pine Specimens	Composite section Specimens
3, 4, 5	3, 4, 5	3, 4, 5

Table 1. Instrumented specimens

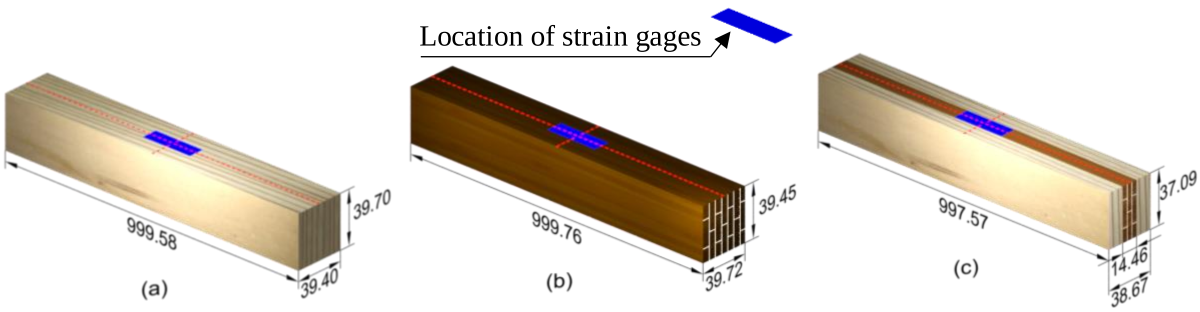

Figure 1. Location of strain gages and average dimensions in the test specimens. Guadua Bamboo Laminated. (b) Radiata Pine. (c) Material composite.

Test assembly

The tests were carried out with the assembly presented in the Figure 2, according with the Colombian Technical Standard NTC 5279 and the ASTM D198.

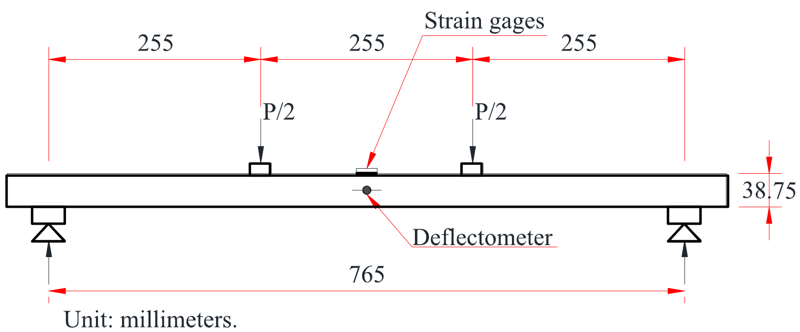

Figure 2 Assembly of tests

CALCULATIONS

Scope

The apparent elastic modulus was evaluated with the ASTM D198 standard (Table x2.1), which means that the shear deflection component was not considered.

Calculation

In general terms, for a simply supported beam with equal loads of ***P/2*** in the thirds

$$P = \frac{1296}{23}\frac{EI}{L^3}\delta \quad (1)$$

where ***E*** is the modulus of elasticity and ***I*** is the inertia

In consequence, the stiffness ***EI*** is equals to:

$$EI = \frac{23}{1296}L^3 m_1 \quad (2)$$

where m_1 is the slope of the ***P*** vs δ graph in the elastic range

The materials under study are anisotropic, in this case the modulus of elasticity at compression and tension are different and the neutral axis is displaced from the geometric centre. (See Figure 3).

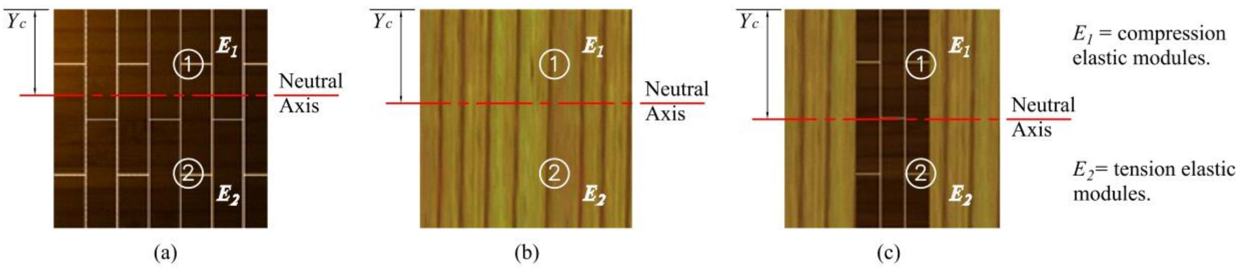

Figure 3 Neutral of a cross section with different tension and compression modulus of elasticity. (a) Guadua Bamboo Laminated. (b) Radiata Pine. (c) Material composite.

In the elastic range:

$$\sigma_1 = E_1 * \epsilon_1 \quad (3)$$

$$\sigma_1 = \frac{M * Y_c E_1}{E_1 * I_1 + E_2 * I_2} = \frac{M * Y_c E_1}{E * I} \quad (4)$$

$$M = \frac{EI}{Y_c} * \epsilon_1 \quad (5)$$

where E_1, E_2 and I_1, I_2 are the modulus of elasticity and the inertia respect to the neutral axis of each part of the section and Y_c the distance between the neutral axis an the end compression fibre.

Then, knowing ***EI*** the position of the neutral axis could be found as:

$$Y_c = \frac{EI}{m_2} \tag{6}$$

where m_2 is the slope of the M *vs* ε graph in the elastic range

Is possible to determine E_1 and E_2, considering first, that the stiffness ***EI*** is equivalent to:

$$EI = E_1 I_1 + E_2 I_2 \tag{7}$$

$$EI = \frac{E_1 b (Y_c)^3}{3} + \frac{E_2 (h - Y_c)^3}{3} \tag{8}$$

Where the variables b and h used to replace the inertia of each material are the average dimensions (width and length) of the specimens.

And second, that the first area moment of the cross section is equal to zero, so:

$$E_1 \int_1 Y dA + E_2 \int_2 Y dA = 0 \tag{9}$$

Where:

$$E_1 \frac{(Y_c)^2}{2} b - E_2 \frac{(h - Y_c)^2}{2} b = 0 \tag{10}$$

Then, it is possible to calculate the compression and tension modulus of elasticity E_1 and E_2, with the equations (8) and (10).

RESULTS AND DISCUSSION.

Bamboo laminates results and failure mode

The behaviour of the bamboo laminates until they reach the bending resistance are shown in **Figure 4**, **Table 2, Figure 5** and **Table 3**, corresponding respectively to the graph P vs δ with its results summary table and the graph M vs ε with its results summary table. In the following figures: P is the vertical load (N), δ is the vertical displacement in the middle of the span (mm), M is the acting moment (N-m), ε is the strain (mm/mm), E_{bb} is the bamboo apparent modulus of elasticity in bending (MPa), Y_c is the distance between the neutral axis and the end fibre compression and ρ_b is the bamboo density (g/cm^3).

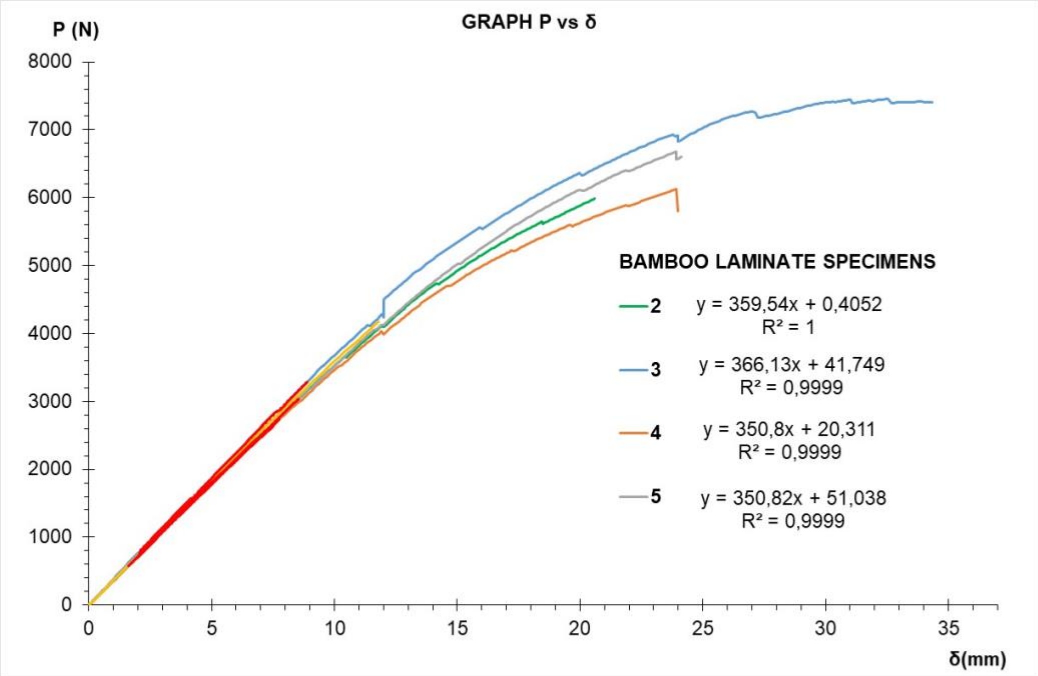

Figure 4 Graph ***P*** vs ***δ*** bamboo laminate specimens

Bamboo Specimens	$P_{máx}$	P_{LP}	δ_{LP}	**Apparent modulus of elasticity in bending**			ρ_b
	N	**N**	**mm**	E_{bb} **(MPa)**	E_{bb}**I (MN*m²)**	**Correlation coefficient**	**g/cm³**
2	6282,9	2513,2	7,02	14258,2	2.86E-03	1,0000	0,677
3	7913,3	3165,3	8,58	14328,7	2.91E-03	0,9999	0,705
4	6816,7	2726,7	7,76	13739,7	2.79E-03	0,9999	0,661
5	7572,1	3028,9	8,52	13478,7	2.79E-03	0,9999	0,714
Average	7146,3	2858,5	7,97	13951,3	2.84E-03	0,9999	0,689
s	637,1	254,8	0,64	355,2	5.12E-05	0,00	0,02
c.v	0,0892	0,0892	0,0799	0,0255	0,0181	0,0000	0,0274

Table 2. Results of the maximum load ($P_{máx}$), the proportionality limit load (P_{LP}), the modulus of elasticity of bamboo laminated (E_{bb}), coefficients of linear regressions and density of bamboo laminate specimens

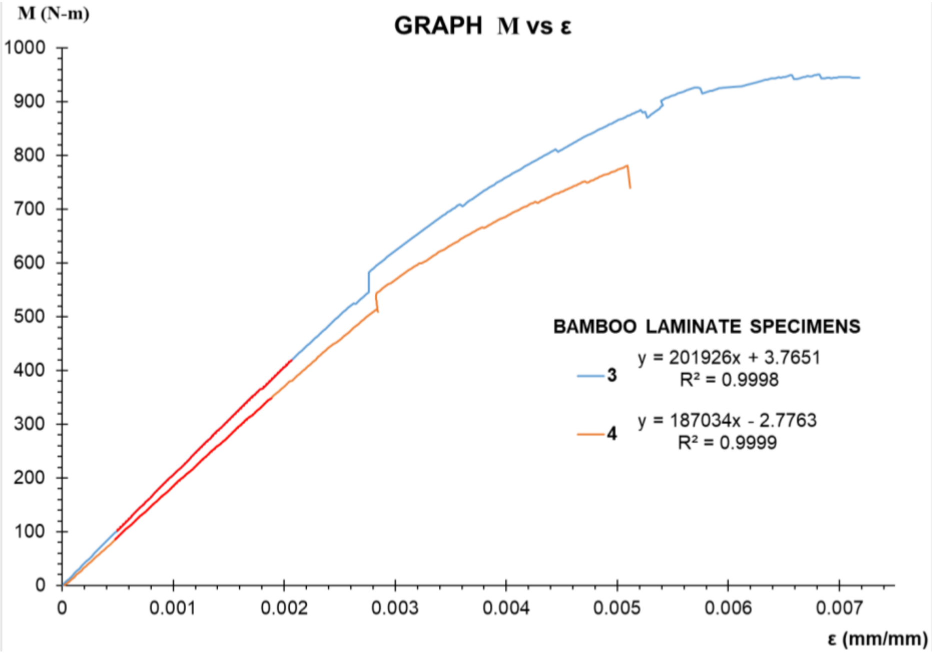

Figure 5 Graph $\boldsymbol{M}$. vs ε bamboo laminate specimens

Bamboo	$\boldsymbol{M}_{máx.}$	$\boldsymbol{M}_{LP}$	**Neutral Axis**		ρ_b
Specimens	**N-m**	**N-m**	$\boldsymbol{Y}_c$ (mm)	**Correlation coefficient**	**g/cm³**
3	1008,94	403,58	14,4	0,9998	0,705
4	869,13	347,65	14,9	0,9999	0,6612
5*					
Average	939,04	375,61	14,7	0,9999	0,683
s	69,90	27,96	0,2	0,00	0,02
c.v.	0,0744	0,0744	0,0169	0,0000	0,0322

Note: The strain gages in specimen 5 were damaged and data collection was not possible

Table 3. Results of the maximum moment ($\boldsymbol{M}_{máx}$), the moment in proportionality limit ($\boldsymbol{M}_{LP}$), the distance between neutral axis and end compression fibre ($\boldsymbol{Y}_c$), coefficients of linear regressions and density of bamboo laminate specimens.

The failure of the bamboo laminate specimens was ductile (Figure 12) with high resistance to bending and degradation without breaking. Failure in bamboo laminates occurred in the end compression fibre. In Figure 6, the loading system and a top view of the upper compression fibres of a bamboo laminate specimen after the test, are shown.

Figure 6 Bending test – bamboo laminate specimen.

Radiata Pine results and mode of failure

The elastic behaviour of the radiata pine is represented in **Figure 7**, **Table 4, Figure 8** and **Table 5**, corresponding respectively to the graph $\boldsymbol{P}$ vs $\boldsymbol{\delta}$ with the results summary table and the graph $\boldsymbol{M}$ vs $\boldsymbol{\varepsilon}$ with its results summary table. In the following figures: $\boldsymbol{P}$ is the vertical load (N), $\boldsymbol{\delta}$ is the vertical displacement in the middle of the span (mm), $\boldsymbol{M}$ is the acting moment (N-m), $\boldsymbol{\varepsilon}$ is the strain (mm/mm), $\boldsymbol{E_{bp}}$ is the pine apparent modulus of elasticity in bending (MPa), $\boldsymbol{Y_c}$ is distance between neutral axis and the end compression fiber and ρ_p is the pine density (g/cm^3).

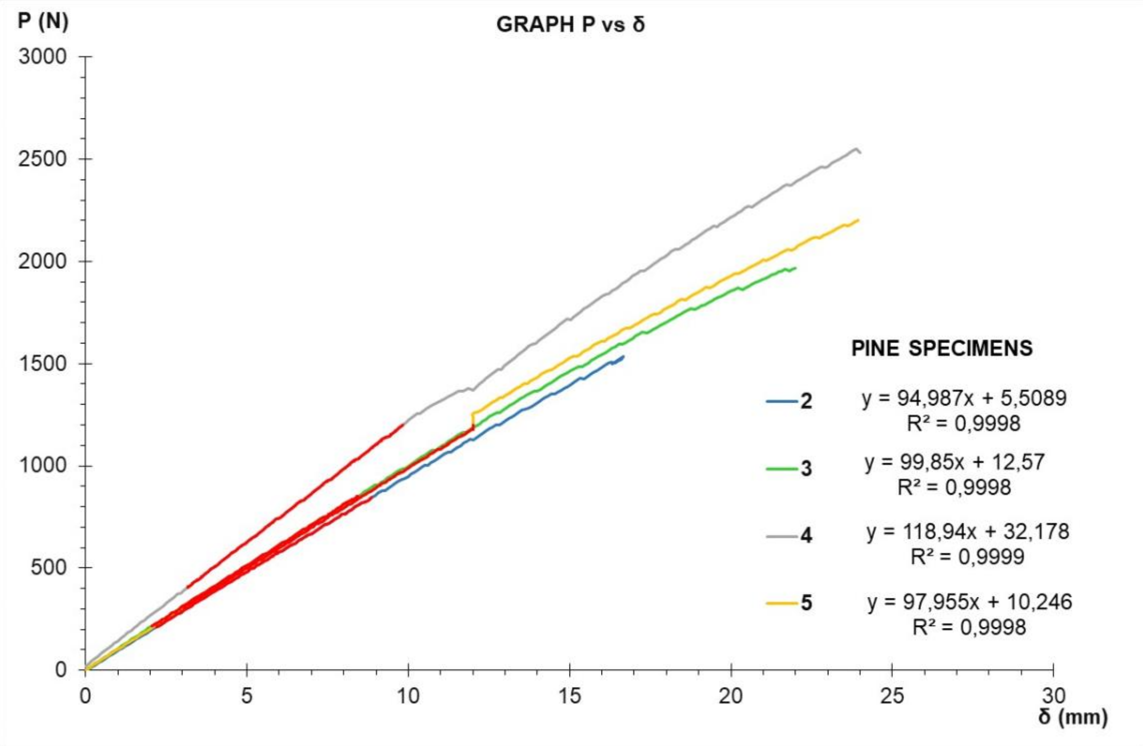

Figure 7 Graph $\boldsymbol{P}$ vs $\boldsymbol{\delta}$ radiate pine specimens

Pine Specimens	P_{max}	P_{LP}	δ_{LP}	Apparent modulus of elasticity in bending			ρ_p
	N	N	mm	E_{bp} (MPa)	E_{bp}I (MN*m²)	Correlation coefficient	g/cm³
2	2103,32	841,33	8,87	3686,74	7.56.E-04	0,9998	0,409
3	2154,01	861,60	8,53	3823,11	7.95.E-04	0,9998	0,388
4	4039,32	1615,73	14,06	4568,79	9.47.E-04	0,9999	0,481
5	3126,13	1250,45	12,00	3719,91	7.80.E-04	0,9998	0,382
Average	2855,69	1142,28	10,87	3949,64	8.20E-04	0,9998	0,415
s	795,70	318,28	2,29	360,98	7.49E-05	0,0000	0,039
c.v.	0,2786	0,2786	0,2105	0,0914	0.0913	0,0000	0,0946

Table 4. Results of $\boldsymbol{P_{máx}}$, $\boldsymbol{P_{LP}}$, apparent modulus of elasticity in bending of pine ($\boldsymbol{E_p}$), coefficients of linear regressions and density of radiate pine specimens

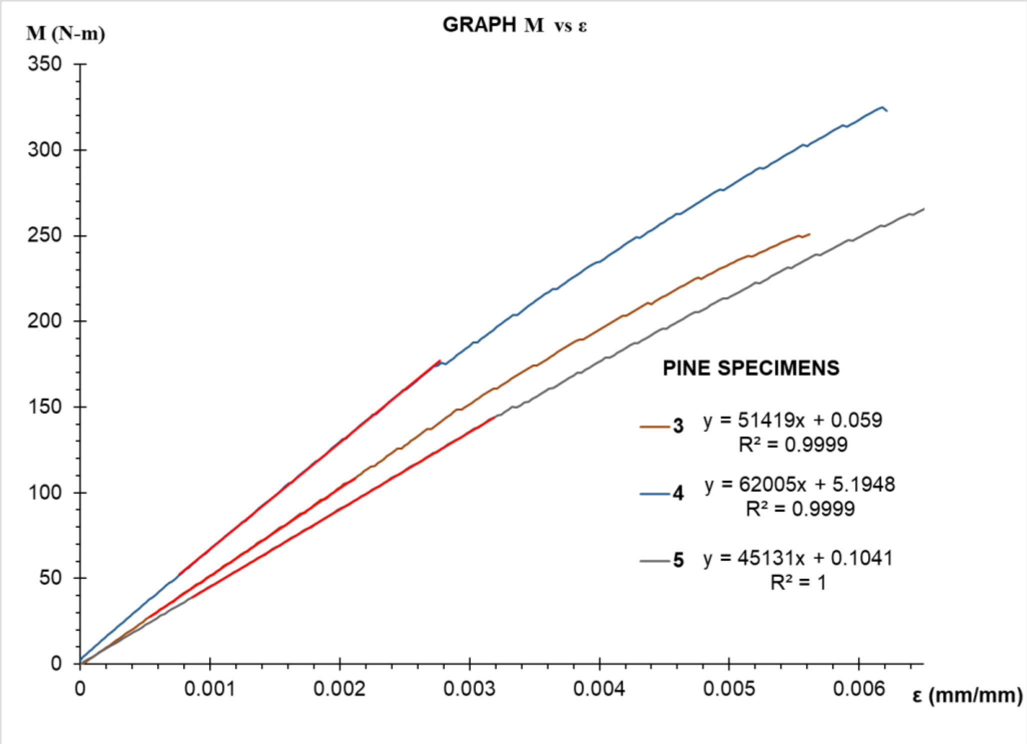

Figure 8 Graph ***M*** vs *ε* radiate pine specimens

Pine Specimens	$M_{máx.}$	M_{LP}	Neutral Axis		ρ_g
	N-m	**N-m**	Y_c (mm)	**Correlation coefficient**	**g/cm³**
3	274,64	109,85	15,46	0,9999	0,388
4	515,01	206,01	15,28	0,9999	0,481
5	398,58	159,43	17,29	1,0000	0,382
Average	396,08	158,43	16,01	0,9999	0,417
s	98,15	39,26	0,90	0,0000	0,045
c.v.	0,2478	0,2478	0,0566	0,0000	0,1084

Table 5. Results of maximum moment ($M_{máx}$), moment in proportionality limit (M_{LP}), distance between neutral axis and the end compression fiber (Y_c), coefficients of linear regressions and density of radiate pine specimens.

Pine specimens presented sudden failure (Figure 12), the maximum load was low (2855,69 N - average) and the deformation was higher than the one presented in the bamboo laminate (see. Table 4). The pine specimens failed by tension in the lower fibres. In Figure 9, the loading system and the fragments of a pine specimen after the test are shown.

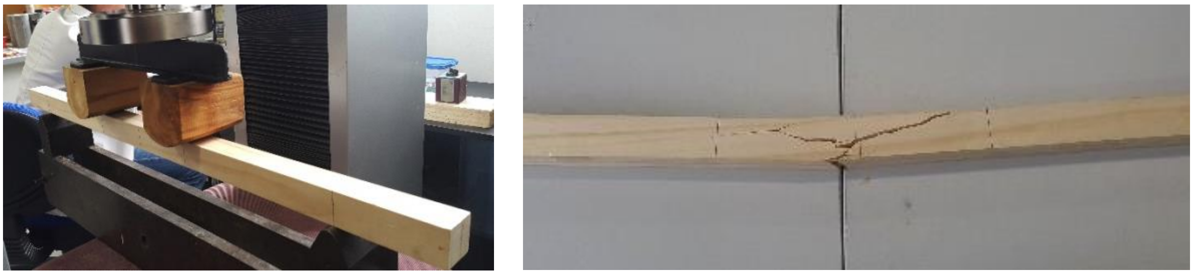

Figure 9 Bending test – radiate pine specimen.

Results and mode of failure of the composite section of pine and bamboo laminates

The results of the composite section in the load range is represented in **Figure 10**, **Table 6, Figure 11** and **Table 7**, corresponding respectively to graph ***P*** vs ***δ*** with the summary table of results and graph ***M*** vs ***ε*** with its results summary table. In the following figures: ***P*** is the vertical load (N), ***δ*** is the vertical displacement in the middle of the span (mm), ***M*** is the acting moment (N-m), ***ε*** the strain (mm/mm), E_{bc} is the apparent modulus of elasticity in bending of the composite section (MPa), Y_c is distance between neutral axis and the end compression fiber and ρ_b is the bamboo density (g/cm^3).

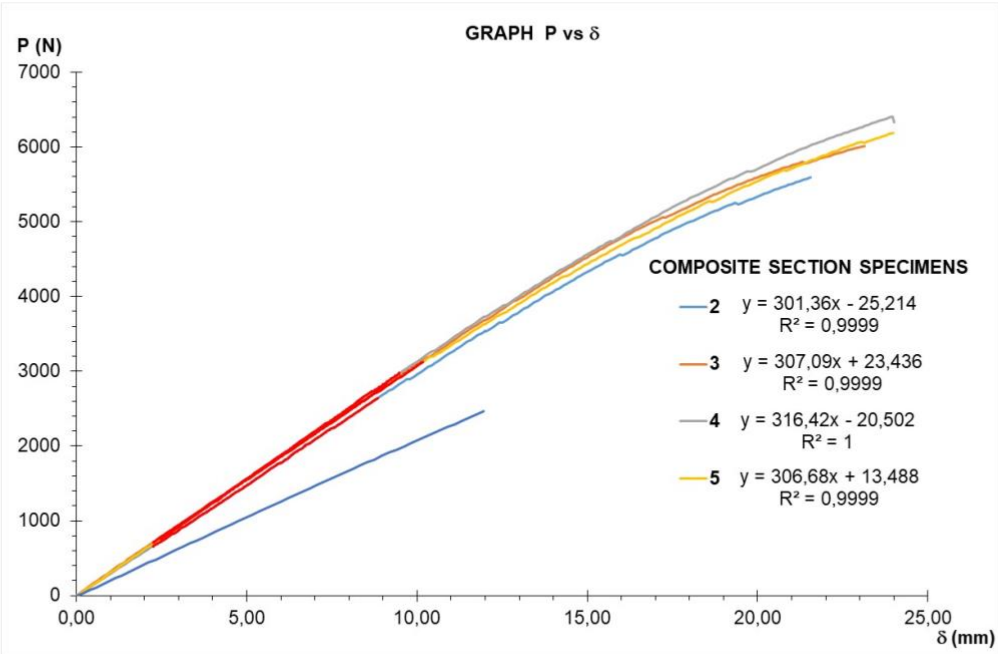

Figure 10 Graph ***P*** vs ***δ*** composite section specimens

Composite	$P_{máx.}$	P_{LP}	δ_{LP}	Apparent modulus of elasticity in bending			ρ_{cs}
Specimens	**N**	**N**	**mm**	E_{bcs} (MPa)	$E_{bsc}I$ (MN*m²)	**Correlation coefficient**	**g/cm³**
2	6623,3	2649,3	8,85	13281,3	2.39.E-03	0,9999	0,613
3	7092,7	2837,1	9,10	13935,1	2.44.E-03	0,9999	0,602
4	7468,4	2987,4	9,38	14086,5	2.51.E-03	1,0000	0,632
5	7807,7	3123,1	10,16	18951,8	2.44.E-03	0,9999	0,626
Average	7248,0	2899,2	9,37	15063,7	2.45.E-03	0,9999	0,619
s	440,54	176,22	0,49	2265,1	4.31.E-05	0,00	0,02
c.v.	0,0608	0,0608	0,0525	0,1504	0.0176	0,0000	0,0346

Table 6. Results of $P_{máx}$, P_{LP}, apparent modulus of elasticity in bending of the composite section (E_{bcs}), coefficients of linear regressions and density of composite section specimens

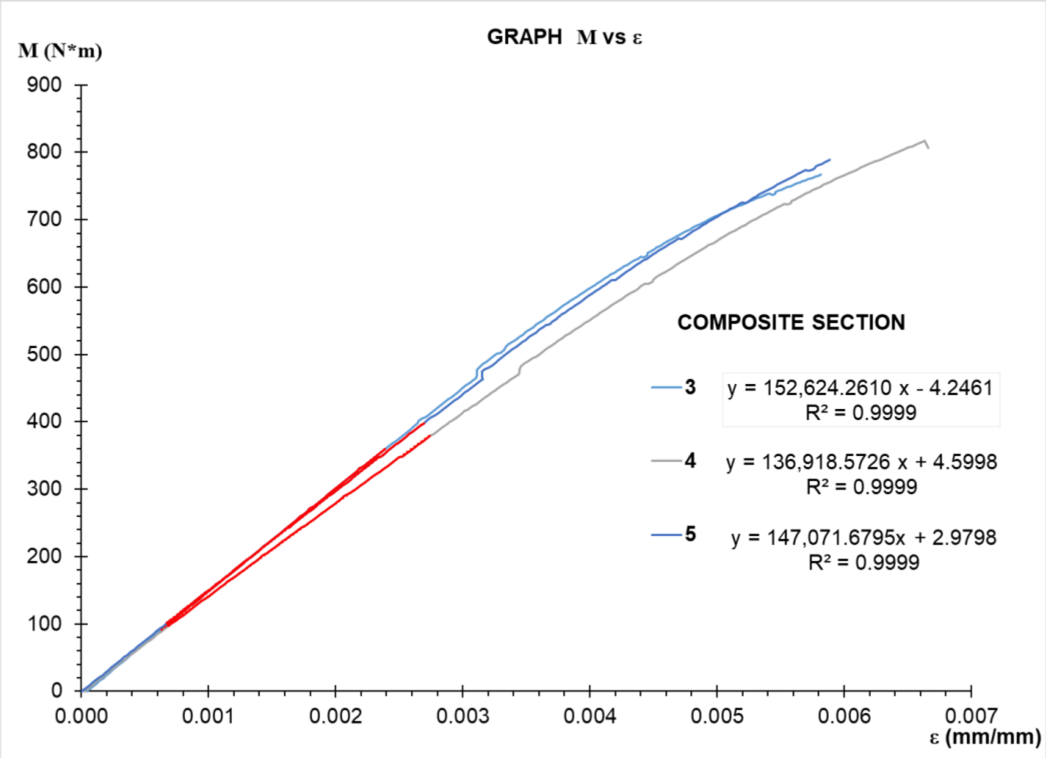

Figure 11 Graph ***M*.** vs *ε* composite section specimens

Composite	$M_{\text{máx.}}$	M_{LP}	Neutral Axis		ρ_g
Specimens	**N-m**	**N-m**	Y_c (mm)	**Correlation coefficient**	**g/cm³**
3	904,3	361,73	15,99	0,9999	0,602
4	952,2	380,89	18,36	0,9999	0,632
5	995,5	398,19	16,57	0,9999	0,626
Average	950,7	380,27	16,97	0,9999	0,620
s	37,24	14,89	1,00	0,00	0,01
c.v.	0,0392	0,0392	0,0596	0,0000	0,0208

Table 7. Results of maximum moment ($M_{máx}$), moment in proportionality limit (M_{LP}), distance between neutral axis and the end compression fiber (Y_c), coefficients of linear regressions and density of composite section specimens

Composite section didn't has sudden failure. The failure happened in the tension zone with the breakage of one of the two faces of the pine, after a small loss of resistance, the tension is redistributed, and the specimen began to resist more load until the other side of the pine failed and the element had excessive deformation and lost its ability to resist the load. (See Figure 12).

The Figure 12 shows the behaviour of specimen No.1 of each type of material in flexion until failure and represents the general behaviour presented by the specimens of each type.

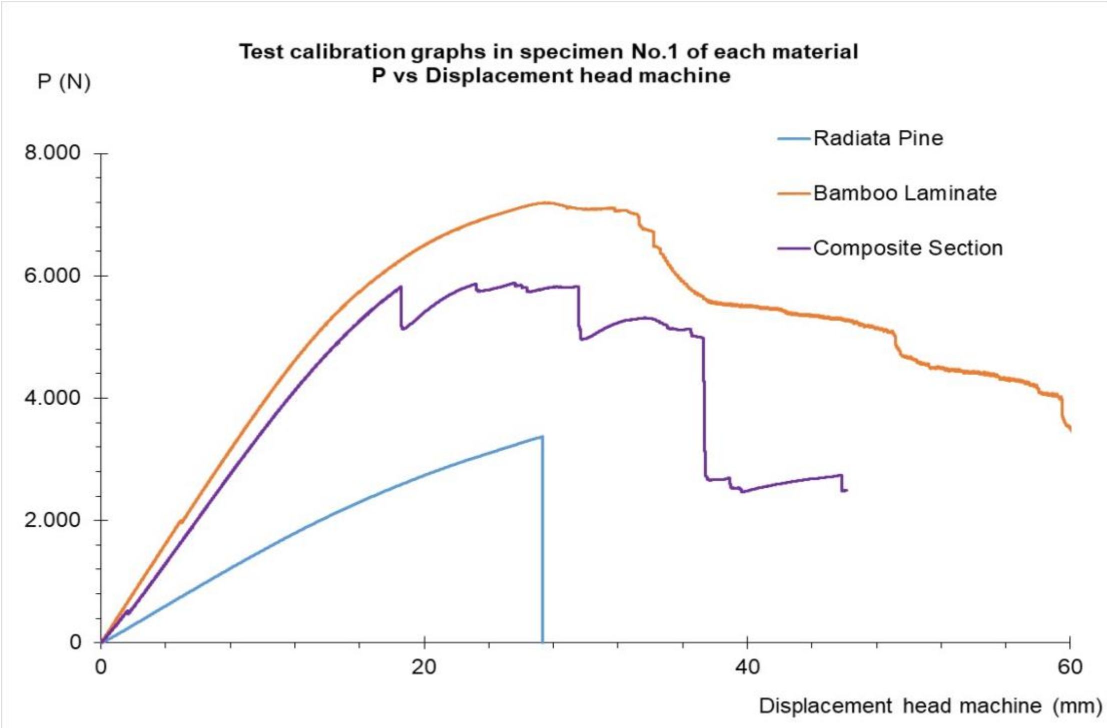

Figure 12 Graph ***P*.** vs ***δ*** Displacement head machine by test calibration graphs in specimen No.1 of each material

Moisture Content

The moisture content of each sample in the moment of test was determined in accordance with NTC 206-1 on a section taken from the specimen once the test finished, the results are summarized in Table No.8.

	Bamboo			**Pine**			**Composite sectión**		
Specimen	**Wet weight (g)**	**Dry weight (g)**	**Moisture (%)**	**Wet weight (g)**	**Dry weight (g)**	**Moisture (%)**	**Wet weight (g)**	**Dry weight (g)**	**Moisture (%)**
1	55,20	51,40	7,39	54,40	50,90	6,88	44,50	41,60	6,97
2	60,10	55,90	7,51	39,90	37,30	6,97	51,20	47,80	7,11
3	49,10	45,90	6,97	32,70	30,80	6,17	49,80	46,90	6,18
4	48,60	45,40	7,05	34,90	32,80	6,40	41,80	39,30	6,36
5	64,70	60,50	6,94	29,40	27,40	7,30	37,40	31,20	19,87

Table 8. Results of moisture content

Compression and tension modules of elasticity.

Using the equation (8) and (10) the tension and compression modulus of elasticity for each material were determined. The table 9 summarizes the tension and compression modulus of elasticity and stresses and strains.

Variables	Specimens		
	Bamboo	**Pine**	**Composite**
E_1 **(MPa)**	25162.19	6136.03	23951.22
σ_{1max} **(MPa)**	122.13	47.46	166.61
ε_{1max}	0.004854	0.007735	0.006956
σ_{1LP} **(MPa)**	48.85	18.99	66.65
ε_{1LP}	0.001941	0.003095	0.002783
E_2 **(MPa)**	8874.2	2802.94	7724.34
σ_{2max} **(MPa)**	72.89	32.08	63.68
ε_{2max}	0.008214	0.011445	0.008244
σ_{2LP} **(MPa)**	29.16	12.83	25.47
ε_{2LP}	0.003286	0.004577	0.003297

Table 9. Tension and compression modulus of elasticity, stresses and strains for each material

CONCLUSIONS

Beams with solid sections of bamboo laminate are not mechanically efficient because the tension stiffness is lower than the compression stiffness and consequently these laminates will fail by compression in the corresponding end fibres due to two reasons: the compression stress is higher than the tension stress and there are not transverse fibres and neither confinement that prevent the local buckling of fibres due to compression. The main advantage of the bamboo laminated is its tensile strength that is higher than the compression strength (Lopez & Correal 2009) (Takeuchi 2014), but in the bending tests carried out the tension zone do not reach its capacity because first the beam fails by compression.

In the case of radiata pine, the sudden failure to bending is due to its low tensile strength (σ_{2max} = 32.08MPa). However, the tension strain is noteworthy (ε_{2max} = 0.01145 mm/mm).

In the bending test of the composite section the pine goes well with the bamboo providing it a confinement that increases its compression strength and reduces deformation. The possibilities of success of the proposed composite material are high, as shown in Figure No.12. A section composed by radiata pine and bamboo laminates with a percentage of 37% behaves very similar to an equivalent section of only laminates of bamboo.

Sections composed of fast growing materials, confined bamboo laminates and pine, are an alternative to achieve a new material with capabilities equivalent to hardwoods, that require many years of cultivation and that deforestation processes degrade our environment.

REFERENCES

López, L.F. & Correal, J.F., 2009. Estudio exploratorio de los laminados de bambú Guadua angustifolia como material estructural. *Maderas. Ciencia y tecnología*, 11, pp.171–182. Available at: http://www.scielo.cl/scielo.php?script=sci_arttext&pid=S0718-221X2009000300001&nrm=iso.

Palermo, A., 2013. Compressive strength and stiffness of Radiata Pine laminated veneer lumber. , pp.795–804.

Takeuchi, C.P., 2014. *Caracterización mecánica del bambú guadua Laminado para uso estructural*. Universidad Nacional de Colombia.
United States Department of Agriculture Forest Service, 2010. *Wood Handbook - Wood as an Engineering Material*, Madison, Wisconsin.
Wong, M., Jiang, P. & Zheng, S., 2011. Dynamics of Carbon Accumulation During the Fast Growth Period of Bamboo Plant. , pp.287–295.

LIST OF FIGURES

pág.

LIST OF TABLES

pág.

LIST OF CHARACTERS

c.v	Coefficient of Variation
CGBL	Confined Bamboo Guadua Laminate.
E	Modulus of Elasticity
E_1	Compression elastic modules
E_2	Tension Elastic Modules
E_b	Apparent modulus of Elasticity
E_{bb}	Apparent modulus of Elasticity in bending of Bamboo
E_{bcs}	Apparent modulus of Elasticity in bending of Composite Section
E_{bp}	Apparent modulus of Elasticity in bending of Pine
ρ_b	Bamboo Density
ρ_{cs}	Composite Section Density
ρ_p	Pine Density
M	Moment
M_{LP}	Moment in Proportionality Limit
$M_{máx}$	Maximum Moment
P	Load
P_{LP}	Proportionality Limit Load
$P_{máx}$	Maximum Load
s	Standard Deviation
Y_c	Distance Between Neutral Axis and the end compression fiber
δ	Vertical Displacement in the middle of the span
ε	Strain
ε_1	Strain in the end compression fiber
ε_{1LP}	Strain at end compression fiber in Proportionality Limit.
ε_{1max}	Maximum Strain in the end compression fiber
ε_{2LP}	Strain at end Tension Fibre in Proportionality Limit.
ε_{2max}	Maximum Strain in the end Tension Fibre
ε_c	Strain in the end compression fiber
σ_1	Compression elastic modules
σ_{1LP}	Maximum Compression stress in Proportionality Limit.
σ_{1max}	Maximum Compression stress
σ_{2LP}	Maximum Tension Stress in Proportionality Limit.
σ_{2max}	Maximum Tension Stress