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AXIAL STRESS-STRAIN CURVES FOR TWO BAMBOO SPECIES (*GUADUA ANGUSTIFOLIA KUNTH* AND *BAMBUSA OLDHAMII*)

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— Abstract—

In this paper, experimental stress-strain curves of tensional and compressional tests carried out in Mexico for two bamboo species (*Guadua Angustifolia Kunth* and *Bambusa Oldhamii*) as wells as a comparison with those obtained in Ecuador and Colombia, are evaluated. For the *Guadua Angustifolia Kunth*, similar curve shapes for Mexican, Colombian and Ecuadorean bamboos were observed, despite variations in the test conditions, physic and geometric specimen properties, and original specimen position in the bamboo culm. Next, through a least square analysis, characteristic equations for these stress-strain curves were obtained. *Bambusa Oldhamii* species always showed higher tensile and compressive strengths (273.3 MPa and 56.1 MPa). Stress-strain curves for these bamboo species were favorable compared with that of unreinforced concrete. Then, for the building construction is adequate material.

Keywords

Bamboo, Angustifolia, Oldhamii, Relationship, tension, compression.

Guerrero, Oaxaca, and Chiapas have a high seismic hazard. Coincidentally it is also the area of least social-economic development in the country. This situation is reflected in the poor quality of materials and inadequate construction processes. The combination generates a high seismic risk for society. For this reason, it is necessary to propose lightweight, low cost, and resistant construction materials that can replace traditional materials (masonry and reinforced concrete). By considering the weather characteristics, bamboo is a biomaterial that could be used. It has shown adequate behavior under seismic forces (Camacho & Páez, 2002; González, 2006).

A parameter that defines an adequate seismic behavior is the ratio of compressive strength to unit weight of the material. The ratio are: a) 1042 m for compressive strength concrete, f'_c = 25 MPa (CDMX Government, 2017); b) 3373 m in A-36 steel with yield stress f_y = 248.2 MPa (Mexican Institute of Steel Construction, 2014); c) 8664 m for the *Bambusa Oldhami* species. Additionally, the ratio of the tensile to the compressive strength of bamboo is from 2.8 to 4.9 (Álvarez, 2012). For unreinforced simple concrete, it does not exceed 0.10 (Gonzales and Robles, 2005). The low unit weight of bamboo reduces the seismic design forces to values of 13% compared to those obtained in traditional masonry systems (Kakkad & Sanghvi, 2011). Regarding the mechanical properties, the tensile stress and elastic modulus are in the ranges 193 MPa - 340 MPa and 18 GPa - 25.6 GPa, respectively (Dixon & Gibson 2014). In compression, stress ranges from 25.9 MPa to 33.5 MPa (Sánchez *et al*., 2016).

After the Bhuj earthquake (India, 1999), constructions with double masonry walls and vertical bamboo reinforcement instead of the reinforcing steel where built, the cost relation between both materials was 55% (Sreemathi, 2002). In the city of Chilpancingo (Mexico), a one-level house was built, where the cost of bamboo walls represented 60% of that assessed with confined masonry walls (Ascencio, 2010).

In Mexico, there are few technical references about the characteristics and design of bamboo. For example, the mechanical and physical properties of three Mexican species were studied to encourage their use in construction (Ordoñez-Candelaria & Bárcenas-Pazos, 2014). Besides, frames with bamboo trusses 6.0 m length adequately supported the vertical and lateral loads generated by seismic forces in low-income housing (Barragán-Trinidad *et al*., 2014).

On the other hand, the mechanical characterizations of materials in small specimens under several solicitations (tension-compression, and flexural stresses) are essential to define the behavior of a structure constructed with these materials. Thus, bilinear masonry behavior laws have been proposed based on wall tests (Sánchez *et al*., 2010).

II. OBJECTIVES

The objectives are:

1. Compute the axial stress vs. strain relationship of *Guadua Angustifolia Kunth* and *Bambusa Oldhamii* species planted in Veracruz, Mexico.
2. Obtain the equation of axial stress vs. strain relationship of the *Bambusa Oldhamii* species tested in Mexico and of the *Guadua Angustifolia Kunth* tested in Mexico, Colombia and Ecuador.

III. MATERIALS AND METHODS

III.1. Carried out tests in Mexico

The culms of both species were cured before the test. Tests performed on 16 specimens with compression parallel to the fiber are shown in Table 1. To the *Guadua Angustifolia Kunth* species, only noded specimens were tested.

Table 1
Compression-tested specimens

Species	With node	Without node
Bambusa Oldhamii	4	6
Guadua Angustifolia Kunth	6	-

The mean slenderness ratio (height/outside diameter, *RE*) in the compression specimens was 1.9. In order to measure the axial strain, the system shown in Image 1 was implemented, it was recorded in increments of 9.81 KN. Moisture content and density tests were also performed.

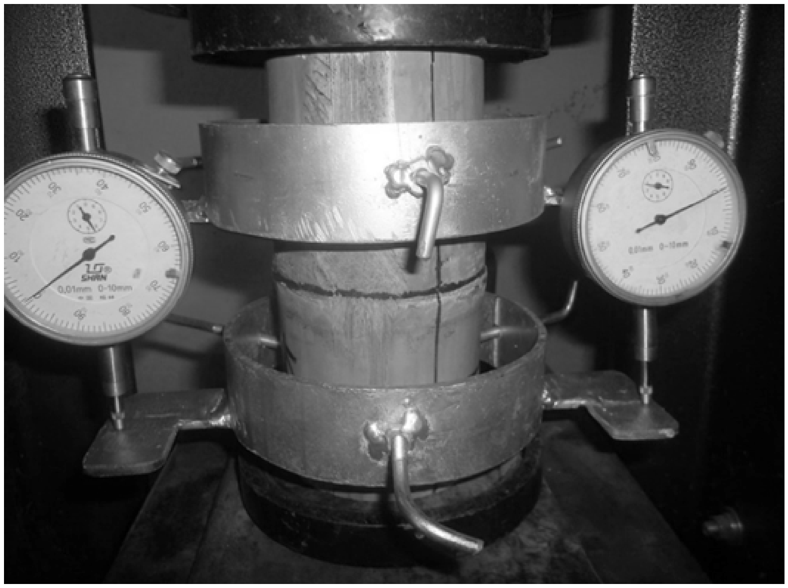


Image 1. Strain measurement system in compression test

Regarding tensile tests, Mendoza (2014) reports results of nine specimens of the species *Bambusa Oldhamii*, obtained from pieces with 0.90 m length. Figure 2 shows the geometry and final shape of the samples.

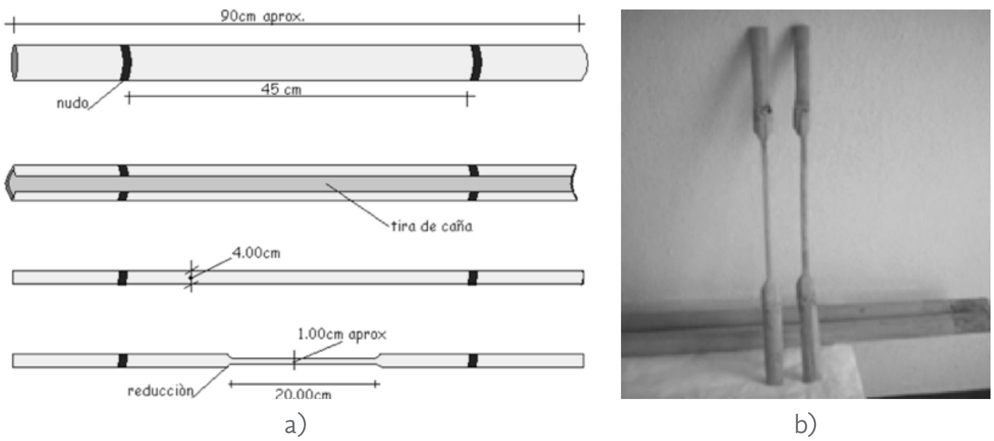


Image 2. A) Extraction and geometry, b) Sample of specimens under tension. (Mendoza, 2014)

On the other hand, there are no Mexican standards for the testing of bamboo specimens. Then, the ISO 22157-1: 2004 standard was used as a guide (International Organization for Standardization, 2004). However, the instrumentation of the compression specimens was done with analog dial indicator according to the testing procedure of compression concrete cylinders. It is opposed to the use of strain gauges proposed in the ISO standard: In Colombia, specimens were also instrumented with analog dial indicator (González, 2006). Concerning the tensile tests, strain measure was performed with a linear displacement transducer (LDVT) attached to the specimen (Mendoza, 2014).

III.2. Data obtained in Ecuador

In Ecuador, extensive experimental work was developed for calculating the mechanical and structural properties of the *Guadua Angustifolia Kunth* species, to propose values to design constructions. The information used in this document corresponds to 11 stress-strain curves recorded in compression tests parallel to the fiber in specimens with a slenderness ratio equal to 2.0. Also, ten tensile stress-strain curves were used. The instrumentation was performed with strain gauges; see Image 3 (Córdoba, 2014).

Image 3. Tension specimens after the test (Córdoba, 2014)

III.3 Data obtained in Colombia

Studies were carried out in Colombia to evaluate the density, moisture content, compressive strength and elastic modulus of the *Guadua Angustifolia Kunth* species. The culms were collected in two departments of Colombia (Quindío and Caldas). From this document, 20 compressive stress-strain curves were used, which were obtained in specimens with an average slenderness ratio of 2.0, density equal to 0.59 and moisture content of 12.76%. The specimens were instrumented with strain gauges. The load was applied with a speed of 0.01mm/s (González, 2006).

III.4. Proposal for the evaluation of the average curve of a series of experimental curves

In the literature no procedure was found for the calculation of the average curve from experimental curves. For this reason, the authors developed the proposal presented here. Image 4a presents a series of experimental curves (curves 1, 2, and 3) on which it is required to draw control lines (cc1 y cc2), with intersection points P1 to P3 on the line cc1 and P4 to P6 on the line cc2 In these graphs, strain and stress are the abscissa and the ordinates, respectively. The coordinates of the midpoint P_i ($\boldsymbol{\varepsilon}_{cci}$, $\boldsymbol{\sigma}_{cci}$) of the three experimental curves intersected by the line cc1 are defined by equations (1) and (2).

$$\varepsilon_{cc1} = (\varepsilon_1 + \varepsilon_2 + \varepsilon_3)/3 \quad (1)$$

$$\sigma_{cc1} = (\sigma_1 + \sigma_2 + \sigma_3)/3 \quad (2)$$

Image 4b represents curve 2 and control line cc1. The points c22 and c33 belong to the experimental curve, point P2 is between them, which is the intersection with the experimental curve and unknown coordinates. Considering that the control line cc1 is proposed, the angles Θ_1 to Θ_3, as well as the coordinates of c22, c23 and P0 are known; whereby it is possible to define equation (3). According to Image 4c, equation (4) is obtained.

$$V = L\sin(\theta_1 - \theta_3)/\sin(180 - \theta_1) \quad (3)$$

$$Z = V\sin\theta_1/sin(180 - \theta_1 - \theta_2) \quad (4)$$

The variation of stress and strain concerning to point c22 is evaluated by equations (5) and (6), Image 4d. The coordinates of point P2 are defined with equations (7) and (8), identically; the coordinates of points P1 and P3 are obtained.

$$\Delta\varepsilon = Z\,cos\,\theta_2 \quad (5)$$

$$\Delta\sigma = Z\,sin\,\theta_2 \quad (6)$$

$$\varepsilon_2 = \varepsilon_{C22} + \Delta\varepsilon \quad (7)$$

$$\sigma_2 = \sigma_{C22} + \Delta\sigma \quad (8)$$

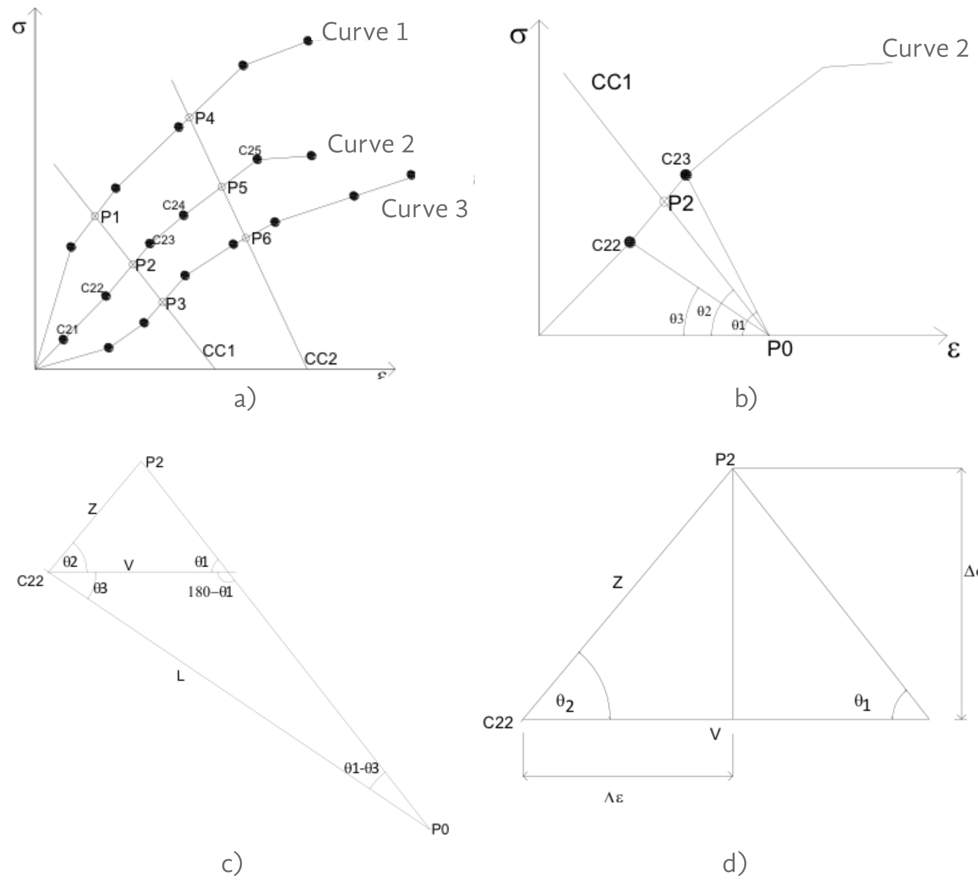


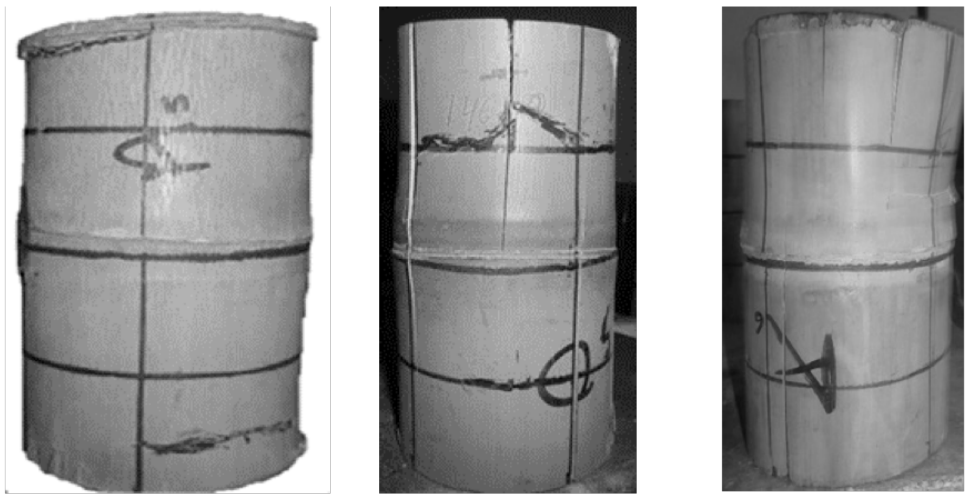
Image 4. Proposal to evaluate the average curve of three experimental curves

Finally, having the coordinates of points P1, P2 and P3 and using equations (1) - (2), the coordinate of the midpoint of all experimental curves intercepted by the control line CC1 is evaluated. The procedure is repeated with the CC2 control line (Image 4a), until the length of the experimental curves is covered. This process was automated through an algorithm developed in free software (Scilab Enterprises, 2014).

IV. RESULTS

IV.1. Tests in Mexico

Table 2 presents the results of moisture content, compressive strength, and density of the specimens. The average value of moisture content (*MC*) was 9.5% for the *Bambusa Oldhamii* species and 7.8% for the *Guadua Angustifolia Kunth* species. The average values of compressive stress ($\boldsymbol{\sigma}_{mc}$ and density (*D*) are: a) 56.1 MPa and 0.66 for *Bambusa Oldhamii*, b) 49.1 MPa and 0.55 for *Guadua Angustifolia Kunth*, respectively. The last column of Table 2 indicates the three types of failure: a) Crushing (C), b) Shearing (S), c) Combined shearing and crushing (SC), Image 5 present each of these. Image 6 shows ten curves of compression tests of *Bambusa Oldhamii*. The mean elastic modulus (E_{mc}) measured at 20% and 80% of the maximum stress was 24.6 GPa with a coefficient of variation (CV) of 32%. In Image 7, six compression curves of the *Guadua Angustifolia Kunth* are presented, where an mean value of E_{mc} = 18.4 GPa was recorded.



a) b) c)

Image 5. a) Crushing failure (C) in *Guadua Angustifolia Kunth*, b) Shearing failure (S) in *Bambusa Oldhamii*, c) Crushing and shearing failure (CS) in *Guadua Angustifolia Kunth*

Table 2

Results of compression and physical tests

#	S	RE	MC %	σ_{mc} MPa	*D*	*Failure*
1	*Bambusa Oldhamii Without node*	1.6	16.5	50.0	0.47	S
2		2.0	8.7	53.0	0.46	S
3		1.8	8.3	65.5	0.60	S
4		1.9	8.8	61.0	0.80	S
5	*Bambusa Oldhamii With node*	2.0	9.6	61.0	0.79	CS
6		1.8	9.7	66.0	0.71	CS
7		1.9	8.9	40.0	0.64	C
8		2.0	9.9	65.5	0.84	S
9		1.9	9.7	59.0	0.72	C
10		2.0	4.6	40.5	0.58	CS
11	*Guadua Angustifolia Kunth*	1.9	8.9	53.0	0.31	C
12		1.9	8.4	41.0	0.64	CS
13		1.9	8.0	68.0	0.84	S
14		1.9	8.3	45.5	0.51	C
15		1.8	8.8	46.0	0.52	C
16		1.8	4.1	51.0	0.51	S

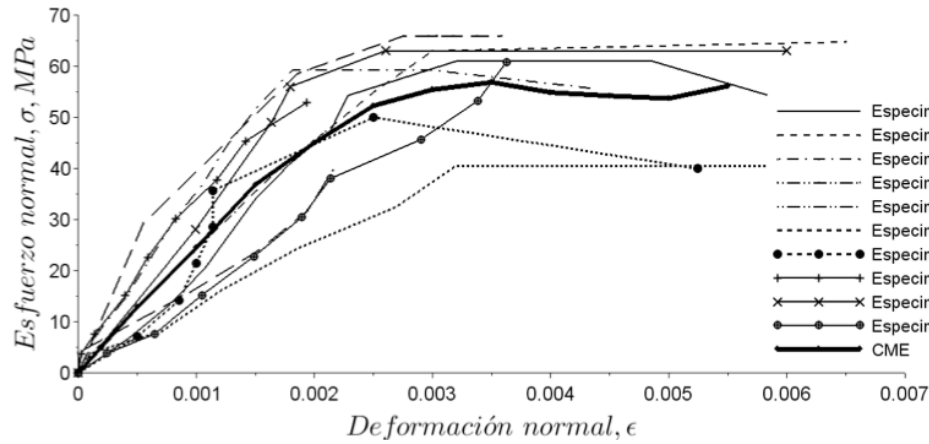


Image 6. Axial compressive stress-strain curves (Bambusa Oldhamii, Mexico)

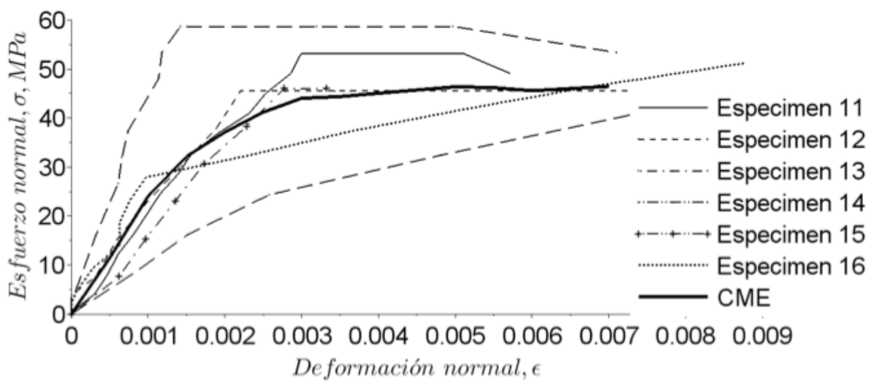


Image 7. Axial compressive stress- strain curves (Guadua Angustifolia Kunth, Mexico)

The experimental mean curve (EMC) of the ten experimental curves of *Bambusa Oldhamii* was obtained, Image 6. The calculation was made at each $\Delta\boldsymbol{\varepsilon}$=0.0005, from $\boldsymbol{\varepsilon}$ = 0.0005 to $\boldsymbol{\varepsilon}$ = 0.0055, according to the process defined in II.4. The last line of control intersects at least four experimental curves. Then, by using a least-squares analysis was obtained the equation (9), which defines the proposed mean curve (PMC). In it, two parts are distinguished; if the strain $\boldsymbol{\varepsilon} \leq 0.0035$, a second-degree equation is established, otherwise it has a first-degree equation. This process is repeated for the *Guadua Angustifolia Kunth* data, see Image 7 and equation (10), for which the maximum strain proposed was 0.007.

$$\sigma = \begin{cases} -3797030.80\varepsilon^2 + 29819.41\varepsilon \;\; si\; 0 \leq \varepsilon \leq 0.0035 \\ -864.92\,\varepsilon + 54.83 \;\; si\; 0.0035 < \varepsilon \leq 0.0055 \end{cases} \tag{9}$$

$$\sigma = \begin{cases} -4322731.30\,\varepsilon^2 + 27500.32\,\varepsilon \;\; si \leq 0.0\,\varepsilon \leq 0.0030 \\ 601.79\,\varepsilon + 42.56 \;\; si\; 0.0030 < \varepsilon \leq 0.007 \end{cases} \tag{10}$$

Regarding the tensile test, Image 8 contains nine experimental curves of the *Bambusa Oldhamii* species, the experimental mean curve (EMC) is also presented. The average value of the elastic modulus measured at 50% of the maximum stress was E_{mt} = 14.92 GPa with a CV = 39%. The average value of the maximum stress of the nine samples reached $\boldsymbol{\sigma}_{mt}$= 273.30 MPa and CV = 14.4%, which was associated with a strain $\boldsymbol{\varepsilon}$ = 0.0197. Equation (11) represents the PMC of the axial stress-strain relationship, in this case $\boldsymbol{\varepsilon}_1$ = 0.01. Image 9 shows the final state of a specimen after testing.

$$\sigma = \begin{cases} 14553.86\,\varepsilon \quad si\ 0.0\ \varepsilon \le 0.010 \\ 8\,111.07(\varepsilon - \varepsilon_1) + 145.54 \quad si\ 0.010 < \varepsilon \le 0.024 \end{cases} \tag{11}$$

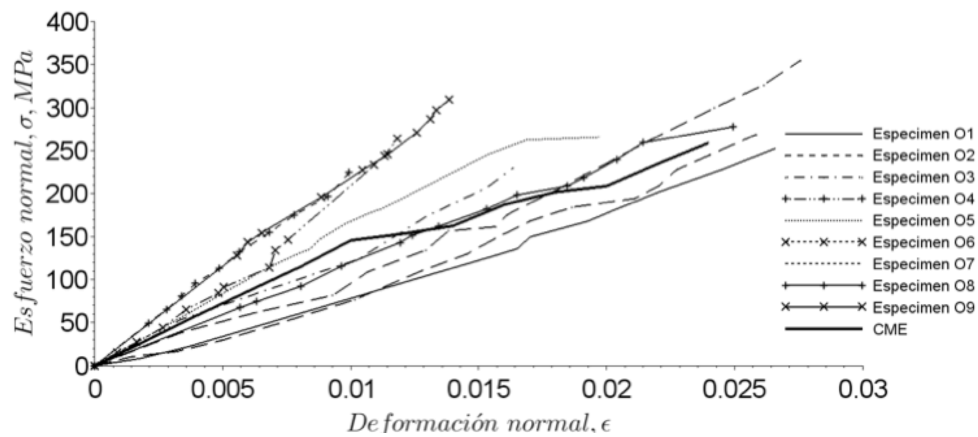


Image 8. Axial tensile stress-strain curves for *Bambusa Oldhamii* Mexico (Mendoza, 2014)

IV.2. Experimental mean curves and proposals for the Guadua Angustifolia Kunth species from Ecuador and Colombia

Following the methodology presented, the experimental (EMC) and proposed (PMC) mean curves of the axial compressive stress-strain were obtained. In the case of Ecuador, equation (12) represents the PMC obtained from the experimental mean curve and is valid for strain $\boldsymbol{\varepsilon} \le 0.0035$. In the Colombian tests, equation (13) of parabolic type was proposed up to $\boldsymbol{\varepsilon} \le 0.0040$ and linear from this point to $\boldsymbol{\varepsilon}$ = 0.0070, see Images 10 and 11.

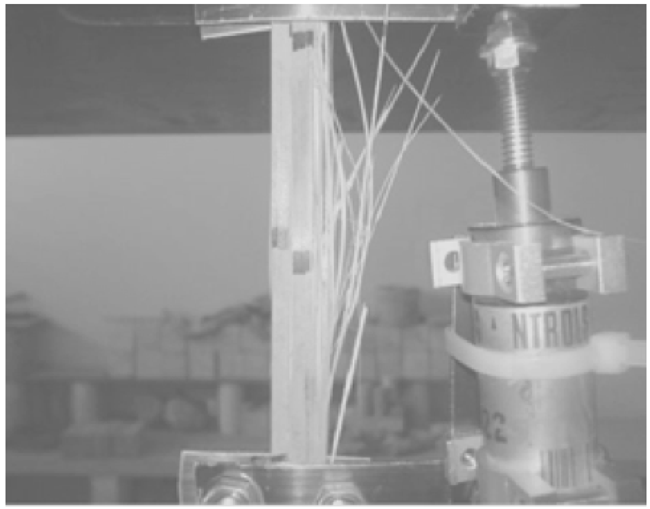


Image 9. Failure in tension test (Mendoza, 2014)

The mean value of compressive stress in Ecuador was $\boldsymbol{\sigma}_{mc}$= 48.9 MPa and CV = 10.7%, while the elastic compressive modulus registered E_{mc} = 25.5 GPa with CV = 21%. In the case of Colombia, the mean compressive stress value was $\boldsymbol{\sigma}_{mc}$ = 52.31 MPa with CV =16.2%, modulus of elasticity E_{mc} = 17.8 GPa and CV = 42%.

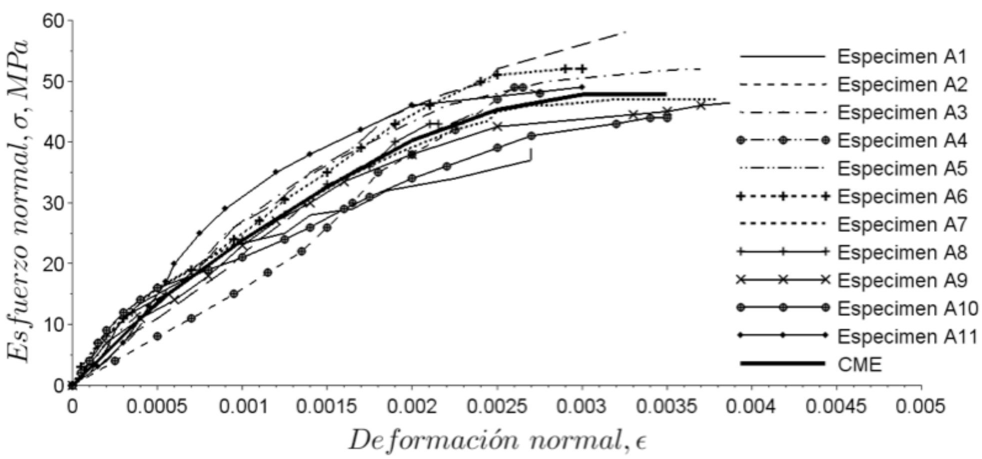


Image 10. Axial compressive stress- strain curves of Guadua Angustifolia Kunth, Ecuador (Córdoba, 2014)

$$\sigma = -4186304.80\,\varepsilon^2 + 28423.46\,\varepsilon \quad si\ 0 \le \varepsilon \le 0.0035 \tag{12}$$

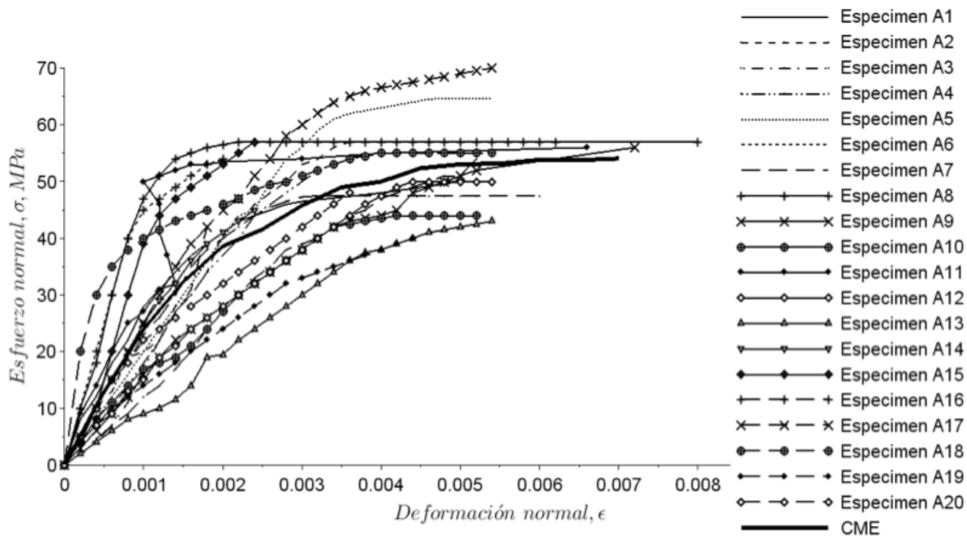


Image 11. Axial compressive stress-strain curves of Angustifolia Colombia (González, 2006)

$$\sigma = \begin{cases} -2817267\,\varepsilon^2 + 24243.87\,\varepsilon \quad si\ 0 \le \varepsilon \le 0.0040 \\ 721.42\,\varepsilon + 49.01 \quad si\ 0.0040 < \varepsilon \le 0.007 \end{cases} \tag{13}$$

Image 12 presents the tensile curves of ten tests performed in Ecuador, as well as the experimental average curve. The PMC is defined with equation (14), for this case ε_1=0.007. The average value of tensile stress was σ_{mt} =136.0 MPa and *CV* =7.5%. The elastic modulus was E_{mt} = 18.4 GPa with a coefficient of variation *CV* = 26%.

$$\sigma = \begin{cases} 16120.18\,\varepsilon \quad si\ 0 \le \varepsilon \le 0.007 \\ 8177.15\,(\varepsilon - \varepsilon_1) + 112.84 \quad si\ 0.0070 < \varepsilon \le 0.009 \end{cases} \tag{14}$$

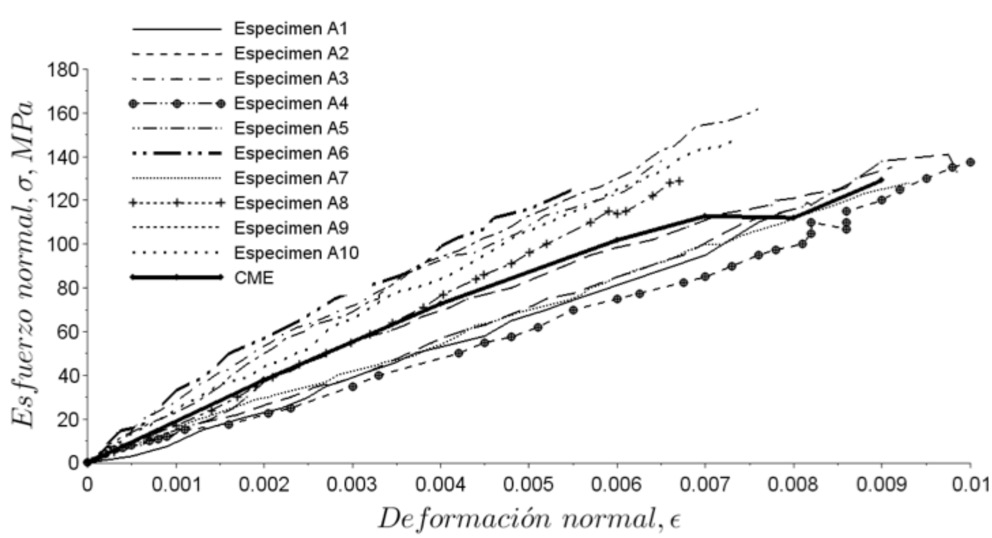
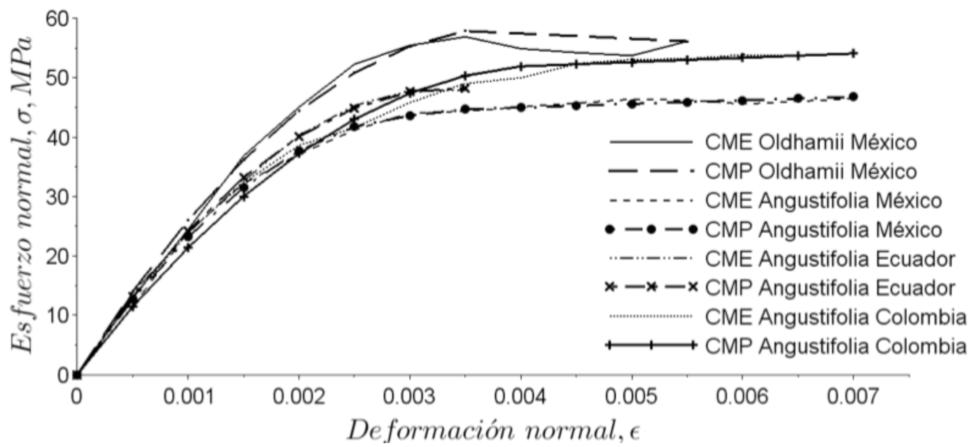
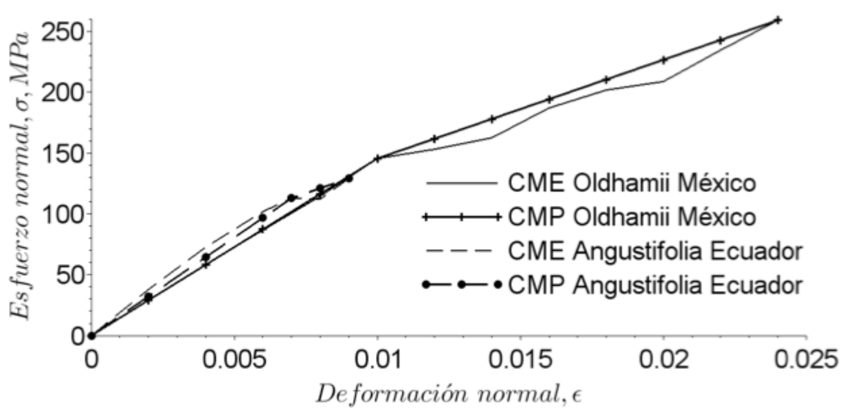


Image 12. Axial tensile stress-strain curves of *Guadua Angustifolia* Ecuador (Córdoba, 2014)

Image 13 shows the experimental (EMC) and proposed (PMC) mean compressive and tensile stress vs. strain curves, while Image 14 presents the complete proposed curves for *Bambusa Oldhamii* (Mexico) and *Guadua Angustifolia Kunth* (Ecuador). The negative part is tension defined by equations (11) and (14); the positive part represents compression obtained by plotting equations (9) and (12). An unreinforced concrete curve obtained in the compression test was added (Sánchez *et al*., 2011)



a) Compression



b) Tension

Image 13. Comparison of experimental and proposed curves

V. DISCUSSION

Tables 5 and 6 present the summary of mechanical and physical properties of the specimens tested. Regarding density (D), *Guadua Angustifolia Kunth* registered similar values for the cases of Mexico and Colombia.

Concerning the moisture content (*MC*), the specimens tested in Mexico were drier (7.8% vs. 12.7%). About the compressive strength (σ_{mc}), the species *Bambusa Oldamii* has the highest value with 56.1 MPa and the compressive strength of *Guadua Angustifolia Kunth* is similar in the three studies. The elastic modulus in compression of *Guadua Angustifolia Kunth* (E_{mc}) obtained in Ecuador was higher, with a lower value of strain (ε_{mc} =0.0035) to the mean stress. The strain values to the mean stresses obtained in Mexico and Colombia are similar.

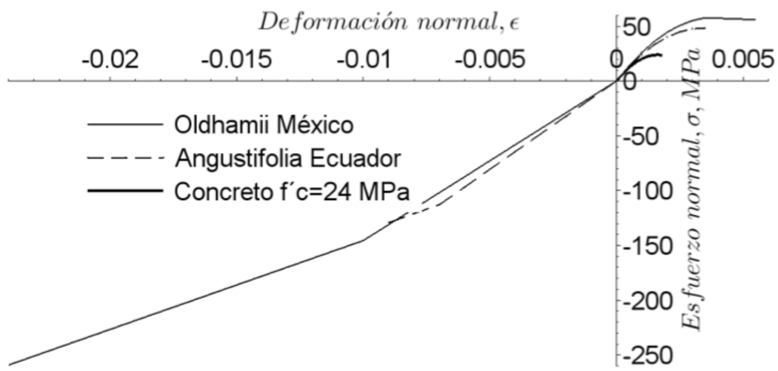


Image 14. Proposed behavior curves for monotonous load in tension-compression

In the tensile tests, again *Bambusa Oldhamii*-Mexico registered the highest stress (σ_{mt} = 273.3MPa) while *Guadua Angustifolia Kunth*-Ecuador only reached 49% of this value (136.0 3MPa). The situation was inverted for the elastic modulus (E_{mt}), *Bambusa Oldhamii*-Mexico reached 81% (14.92 GPa) of the value registered by *Guadua Angustifolia Kunth*-Ecuador.

Table 3

Average values of physical properties

Species/ Origin	Propiedades físicas	
	MC (%)	*D*
Bambusa Oldhamii/México	9.5	0.66
Guadua Angustifolia Kunth/México	7.8	0.55
Guadua Angustifolia Kunth/Colombia	12.7	0.59

Table 4
Mean values of mechanical properties

Species/ Origin	Mechanical properties					
	Compression			*Tension*		
	σ_{mc} (MPa)	E_{mc} (GPa)	ε_{mc}	σ_{mt} (MPa)	E_{mt} (GPa)	ε_{mt}
Bambusa Oldhamii/México	56.1	24.6	0.0055	273.3	14.9	0.0197
Guadua Angustifolia Kunth/México	12.7	0.59				
Guadua Angustifolia Kunth/Ecuador	48.9	25.5	0.0035	136.0	18.4	0.008
Guadua Angustifolia Kunth/Colombia	52.3	17.8	0.0057			

Tables 5 and 6 show: *MC*, moisture content; *D*, density; σ_{mc}, mean compressive stress; E_{mc}, modulus of elasticity in compression; ε_{mc}, strain to mean compressive stress; σ_{mt}, mean tensile stress; E_{mt}, modulus of elasticity in tension; ε_{mt}, strain to mean tensile stress.

There is no failure pattern in compression tests. However, four *Bambusa Oldhamii* without node specimens failed by shearing (S), where a negative effect on the compressive strength was observed.

The proposed mean compression curves (PMC) are, in most cases, parabolas and straight lines; the first end with deformations between 0.0030 and 0.004. Then, there is a linear behavior with decrease in stiffness. Image 13a shows a similar behavior of the *Guadua Angustifolia Kunth* species in the three countries, regardless of the test parameters, geometry, and physical characteristics of the specimens, as well as the position of the specimen on the bamboo cane. Thus, the initial slope in the three curves is similar up to deformations between 0.0035 and 0.004, and then the material is plasticized.

For tensile tests, the proposed mean curve (PMC) of *Bambusa Oldhamii* shows stiffness degradation starting from ε = 0.01. In contrast, in *Guadua Angustifolia Kunth* it starts with ε = 0.007. In the same order, the ratio of tensile to compressive stress is 4.87 and 2.78, respectively, with a higher ultimate strain in *Bambusa Oldhamii*.

Image 14 shows the proposed curves of both species in tension and compression recorded in Mexico and Ecuador under monotonic loading, which indicates the structural advantage of bamboo over unreinforced concrete. In this case, the maximum strength of the concrete is 20 MPa. At the same time, the *Bambusa Oldhamii* species reaches values close to 60 MPa, with similar slenderness ratios in the tests of both materials (2 for the concrete and 1.9 for the bamboo specimen). On the tensile stress, concrete does not exceed 10% of the compressive strength (2.0 MPa), while *Bambusa Oldhamii* reaches up to 250 MPa.

VI. CONCLUSIONS

The experimental axial compressive stress-strain mean curves of *Guadua Angustifolia Kunth* obtained in Mexico, Ecuador and Colombia have the same shape. The maximum compressive strength of 60 MPa recorded in *Bambusa Oldhamii* would correspond to a high strength concrete.

In both bamboo varieties, the axial tensile stress-strain curves show elastoplastic behavior. In the *Bambusa Oldhamii* species the slope of the plastic section is 55% of the slope of the elastic part. The ratio decreases to 51% in the *Guadua Angustifolia Kunth* species.

The mean curves in compression tests of *Guadua Angustifolia Kunth* obtained in the three countries, regardless of the test procedure or the characteristics and origin of the specimens, have the same shape. Then, the characterization of the behavior of the material is possible, like that made for concrete or steel. Thus, the compressive/tensile stress- strain curves can be used in the analysis of structures made with this material.

Under certain conditions, the bamboo has a better behavior that the one registered in the unreinforced concrete. However, the disadvantages of the material should be reviewed, specifically the durability and fire resistance, which can reduce the design service life of this structures. Another problem in the design phase is the a priori ignorance of the geometric properties of the culms, unlike steel profiles, concrete elements or wood, where the cross sections are known.

Finally, this biomaterial would be a construction option in Guerrero, Oaxaca, and Chiapas It can reduce the lack of housing, to diminish the risk of the society caused by natural phenomena, and to reduce the costs of the construction.

V. REFERENCES

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VIII. LIST OF ACRONYMS AND SYMBOLS

C,	Crushing failure
MC,	Moisture content in %
EMC,	Experimental mean curve
PMC,	Proposed mean curve
PS,	Parallel shear failure
PSC,	Parallel shear and crushing failure
CV,	Coefficient of variation
D,	Dimensionless density
E_{mc},	Average modulus of elasticity at compression, GPa
E_{mt},	Mean compressional modulus of elasticity, GPa
LDVT,	Linear displacement transducer
RE,	Slimness ratio
ε,	Normal dimensional strain
ε_1,	Normal tension elastic strain
σ,	Normal stress
σ_{mc},	Average compression stress, MPa
σ_{mt},	Average stension stress, MPa