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VARIATION OF MODULUS OF ELASTICITY OBTAINED THROUGH THE STATIC BENDING METHOD CONSIDERING THE *S/h* RATIO

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ABSTRACT

This study aimed to determine the influence of *S/h* ratio on the apparent longitudinal elastic modulus in static bending obtained experimentally by plateau response, applying linear and non-linear regression models. This study employed specimens with 5 x 5 x 140 cm randomly extracted from beams made of three wood species: 144 from Peroba Rosa (*Aspidosperma polyneuron*), 72 from Eucalyptus (*Eucalyptus tereticornis*) and 72 from Jatobá (*Hymenaea courbaril* L.). In total were 288 specimens tested. Loads were applied tangentially and perpendicularly to the growth rings of the wood specimens, with moisture content above fiber saturation. The *S/h* ratios chosen for the static bending tests were 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, and 26. It was concluded that the *S/h* equal to 21 ratio (which is currently recommended in the NBR 7190 (1997) Brazilian standard for wooden structure projects) can be reduced to *S/h* equal to 19 without compromising safety for loads applied tangentially and the *S/h* equal to 14 ratio recommended by ASTM D 143 (2009) for bending to occur with shearing deformations. All adjusted mathematical models appear to be adequate, however the exponential model 1 with plateau is recommended because of its practical use, since it directly provides the maximum values of *S/h* and E_a.

KEYWORDS: Static bending; non-linear regression; plateau response; quadratic model; exponential model.

INTRODUCTION

According to Mascia and Nicolas (2013), Brazil has vast timber producing forests of a variety of species that are used in civil construction. The use of wood in the manufacture of structural elements, especially construction beams and columns, has increased the demand for efficient and reliable geometric properties that generate cost-effective solutions, in addition to improving the mechanical properties of these elements. In Brazil, wooden structural elements are designed from a combination of permanent and variable actions in view of their ultimate limit state and service limit state. Elements such as wooden beams are generally stronger and more stable when made of solid timber, but the mechanical properties of solid timber can also be found in wood-based products that use binding agents or other types of connectors, e.g., nails, screws, or staples.

Adopted upon dimensioning supported structural wooden elements subjected to bending efforts, the geometric parameter relates the length of the span between supports to height in the case of sawn pieces or span to diameter in the case of logs. This parameter is important in that it enables designers to choose whether or not to take shearing deformations into account when estimating vertical displacement, according to Chui et al. (1999), who employed the Bernoulli beam model allowing for the taper of logs after they found that the span/diameter ratio of the logs was greater than 20. The model proposed by Timoshenko cited in Brancheriau and Baillere (2002) admits that the span/height ratio of the beam is relatively small and takes into account the deformation caused by shearing strength in addition to inertia to cross-section rotation.

Rocco Lahr (1983) recommended S/h equal to 21, where S and h are the cross-section span and height, respectively. Thus, shearing deformations are assumed not to have an effect on the estimation of vertical displacements of structural elements and the apparent elastic modulus E_a remains constant, thereby enabling more accurate assessment of performance of wooden elements subjected to static bending. The three-point static bending tests of specimens were conducted according to ASTM D 143 (2009), which recommends a ratio S/h equal to 14, i.e., a value lower than the real longitudinal elastic modulus value in static bending.

In Brazil, characterization of wood with regard to static bending is conducted according to NBR 7190 (1997), i.e., the Brazilian standard for designing wooden structures, which follows the suggestions in Rocco Lahr (1983). It recommends the conduction of three-point static bending test on 5 x 5 x 115 cm defect-free specimens as well as on structural elements subjected to static bending. In this test, the specimen must be connected to two mobile articulated supports, with span between supports equal to or longer than 21 h (105 cm) to prevent the apparent longitudinal elastic modulus from being influenced by shearing deformations. According to Carreira (2012), in the case of wooden logs, shear strength can be disregarded when estimating the dynamic elastic modulus by means of transversal vibration testing of logs in free suspension for $S/D_{midpoint}$ equal to or longer than 21, where S is the span and $D_{midpoint}$ is the diameter measured at midpoint lengthwise.

According to Eq. 1, the estimation of vertical displacement at midpoint under a load P applied at this point takes into account beam deformations because of the stretching of strained fibers and shortening of compressed fibers (first part of the equation). It also accounts for the effect of deformation due to shearing caused by shear strength acting in the beam (second part of the equation), which can be technologically disregarded from the S/h ratio, considering an apparent longitudinal elastic modulus E_a close to the actual value, as given by Eq. 2.

$$\delta = \frac{W \cdot S^3}{48 \cdot E \cdot I} + \frac{3 \cdot W \cdot S}{10 \cdot Z \cdot G} \qquad (1)$$

where: E - longitudinal elastic modulus (MPa);
G - transversal elastic modulus (MPa);
W- load increase (N);
S- distance between supports (mm);
δ- vertical displacement due to applied load (mm);
I- moment of inertia of cross-section (mm^4);
Z- section modulus (mm^3).

$$E_a = \frac{W \cdot S^3}{48.\delta.I} \qquad (2)$$

where: E_a- apparent longitudinal elastic modulus under static bending (MPa);
W- load increase (N);
S-distance between supports (mm);
δ- vertical displacement due to applied load (mm);
I- moment of inertia of cross-section (mm^4).

This study aimed at assessing the influence of the *S/h* ratio on apparent longitudinal elastic modulus E_a obtained experimentally in static bending. To this end, the plateau response technique was employed by means of segmented regression models. A quadratic polynomial model and two non-linear regression models with plateau response were compared.

MATERIAL AND METHODS

The material tested consisted of specimens drawn randomly from beams of three wood species: 144 Peroba Rosa (*Aspidosperma polyneuron*), 72 Eucalyptus (*Eucalyptus tereticornis*), and 72 Jatobá (*Hymenaea* sp.). Specimens measuring 5 x 5 x 140 cm were tested in static bending under loads tangential and perpendicular to the growth rings, moisture content above that of fiber saturation. The *S/h* ratios selected for the tests were 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, and 26. In total were 288 specimens tested.

Static bending test

The static bending tests were conducted on wood specimens to determine the apparent longitudinal elastic modulus E_a under loads tangential and perpendicular to growth rings. The tests were performed at three points of specimens of the aforementioned wood species, i.e., load concentrated at span midpoint of specimens simply supported, at 10 $MPa.min^{-1}$ speed and vertical displacement up to 70 % of the average tensile strength value of the wood species in question. The apparent longitudinal elastic modulus in static bending E_a is given by Eq. 2. The study employed a thoroughly randomized design with 12 treatments (12 *S/h* ratios) and 12 repetitions for Peroba Rosa and 6 for both Eucalyptus and Jatobá.

Statistical models

In order to adjust the plateau response models investigated, the PROCNLIN procedure was employed - SAS Institute NLIN (2004). The models studied are described below.

Quadratic polynomial model with plateau response (QPM)
The following models were considered:

$$y = a + bx + cx^2 + e \quad \text{if} \quad x < x_0 \quad \text{(quadratic)} \tag{3}$$

$$y = p + e \quad \text{if} \quad x \geq x_0 \quad \text{(plateau)} \tag{4}$$

where: y -the apparent longitudinal elastic modulus E_a for the *S/h* ratio.

Thus, for x smaller than x_0, the model describing the response y is a quadratic function, and for x equal to or greater than x_0 the equation is a constant or plateau. In order to estimate the parameters, the model must present appropriate mathematical properties, i.e., it must be a continuous function and differentiable in x_0. This condition implies that $x_0=-b/2c$ and $p=a-(b^2/4c)$,

where: x_0 - the maximum *S/h* ratio estimator, for a maximum apparent longitudinal elastic modulus E_a and the point of intersection of two lines,
p -the plateau, in which
a, b, and c - the model parameters to be estimated.

Non-linear exponential model 1 with plateau response (NLEM1)
The following models were considered:

$$y = a \cdot exp\left[-c\left(x-b\right)^2\right] + e \quad \text{if} \quad x < x_0 \quad \text{(exponential)} \tag{5}$$

$$y = p + e \quad \text{if} \quad x \geq x_0 \quad \text{(plateau)} \tag{6}$$

Like Models 3 and 4, when y is derived in x:

$$\frac{\partial y}{\partial x} = \frac{\partial\left\{a \cdot exp\left[-c\left(x-b\right)^2\right]\right\}}{\partial x} = a \cdot exp\left[-c\left(x-b\right)^2\right] \cdot \left[-2c\left(x-b\right)\right] \tag{7}$$

Equating the derivation result to zero and solving the equation for x=x_0, one get s$x_0=b$. By replacing x with x_0 in the initial equation, we obtain $p=f(x_0)=a.exp[c(b-b)^2]$, which results in $p=a$,

where: x_0 -the maximum *S/h* ratio estimator, for a maximum apparent longitudinal elastic modulus E_a;
p -the plateau estimator;
a, b, and c -model parameters to be estimated.

Non-linear exponential model 2 with plateau response (NLEM2)
The following models were considered:

$$y = a \cdot exp\left(bx - cx^2\right) + e \quad \text{if} \quad x < x_0 \quad \text{(exponential)} \tag{8}$$

$$y = p + e \quad \text{if} \quad x \geq x_0 \quad \text{(plateau)} \tag{9}$$

As in previous models (3) and (4), when y is derived in x:

$$\frac{\partial y}{\partial x}=\frac{\partial\left[a\cdot exp\left(bx-bx^2\right)\right]}{\partial x}=a\cdot\left(b-2cx\right)\cdot exp\left(bx-cx^2\right) \tag{10}$$

By equating the derivation result to zero and solving the equation for $x=x_0$, we obtain $x_0=b/2c$. Replacing x with the value of x_0 in the initial equation, we get $p=f(x_0)=a.exp[b^2/2c-c(b^2/4c^2)]$, which results in $p=a.exp(b_2/4c)$,

where: x_0 - the maximum S/h ratio estimator for a maximum apparent longitudinal elastic modulus E_a, the point where the two lines intersect;
p -the plateau response estimator;
a, b, and c - the model parameters to be estimated.

Determination coefficient (R^2)

R^2 was estimated by means of the following expression: $R^2=\left(r_{y\hat{y}}\right)^2$

where: (y) -the square correlation observed among the treatments in question and
$(\hat{y})$ - the predictions estimated by means of the plateau model.

RESULTS

Tab. 1 shows averages of the apparent elastic modulus in bending E_a for each S/h ratio regarding the wood species in question in view of the load application direction.

Tab. 1: Averages of apparent elastic modulus in bending for each S/h ratio regarding the three wood species under investigation in view of the load application direction (Tang. = Tangential and Perp. = Perpendicular).

S/h	**Apparent longitudinal elastic modulus E_a(MPa)**					
	Peroba Rosa		**Eucalyptus**		**Jatobá**	
	Tang.	**Perp.**	**Tang.**	**Perp.**	**Tang.**	**Perp.**
4	2661.17	3176.08	3975.17	4278.50	4370.00	4676.83
6	4943.67	5415.17	5569.33	6033.50	6869.00	7342.83
8	6553.42	7120.25	6880.17	7508.83	9392.33	9976.67
10	7826.17	8265.75	8163.00	8907.50	11107.00	11728.67
12	8928.75	9099.33	8793.50	9591.33	12657.17	13349.67
14	9723.00	9758.17	9512.67	10173.67	13201.83	14071.17
16	10150.17	10464.92	10086.33	10898.17	13926.50	14824.00
18	10446.17	10932.83	10400.33	11331.83	14339.33	15296.50
20	10819.58	11619.83	10650.83	11539.33	15215.00	16264.67
22	11109.00	11748.00	10718.50	11619.33	15431.67	16539.67
24	11018.33	11728.67	10693.50	11644.00	15305.83	16421.00
26	11170.33	12130.00	10704.00	11628.50	15453.17	16539.17

Tabs. 2 to 4 shows F-test results for lack of adjustment for the three models under investigation adjusted to Peroba Rosa, Eucalyptus, Jatobá woods and loads applied tangentially and perpendicular to the grain.

Tab. 2: Analysis of variance and F-test for specimens with no adjustment of models to Peroba Rosa and loads tangential and perpendicular to the grain.

Peroba Rosa - load tangential					
Models	**Source of variation**	**G. L.**	**Q. M.**	**F**	**P-value**
QPM	Reg. Mod. (not corrected)	3	4033490644	0.118^{ns}	0.9991
	No Adjustment	9	546428.56		
	Residue (Pure Error)	132	4633577		
NLEM1	Reg. Mod. (not corrected)	3	4028600000	0.468^{ns}	0.8925
	No Adjustment	9	2166428.56		
	Residue (Pure Error)	132	4633577		
NLEM2	Reg. Mod. (not corrected)	3	4028800000	0.468^{ns}	0.8925
	No Adjustment	9	2166574.56		
	Residue (Pure Error)	132	4633577		
Peroba Rosa - load perpendicular					
Models	**Source of variation**	**G. L.**	**Q. M.**	**F**	**P-value**
QPM	Reg. Mod. (not corrected)	3	4489769560	0.247^{ns}	0.9860
	No Adjustment	9	1049120.89		
	Residue (Pure Error)	132	4253014		
NLEM1	Reg. Mod. (not corrected)	3	4483300000	0.751^{ns}	0.6625
	No Adjustment	9	3193565.33		
	Residue (Pure Error)	132	4253014		
NLEM2	Reg. Mod. (not corrected)	3	4483300000	0.751^{ns}	0.6625
	No Adjustment	9	3193565.33		
	Residue (Pure Error)	132	4253014		

^{ns} = not significant, means followed by the same letter, in each section, do not differ one to another ($P \geq 0.05$).

Tab. 3: Analysis of variance and F-test for specimens with no adjustment of models to Eucalyptus and loads tangential and perpendicular to the grain.

Eucalyptus - load tangential					
Models	**Source of variation**	**G. L.**	**Q. M.**	**F**	**P-value**
QPM	Reg. Mod. (not corrected)	3	3869231890	0.025^{ns}	0.9999
	No Adjustment	9	55877.97		
	Residue (Pure Error)	60	2259285		
NLEM1	Reg. Mod. (not corrected)	3	1990500000	0.151^{ns}	0.9978
	No Adjustment	9	341433.52		
	Residue (Pure Error)	60	2259285		
NLEM2	Reg. Mod. (not corrected)	3	1990500000	0.151^{ns}	0.9978
	No Adjustment	9	341433.52		
	Residue (Pure Error)	60	2259285		
Eucalyptus - load perpendicular					
Models	**Source of variation**	**G. L.**	**Q. M.**	**F**	**P-value**
QPM	Reg. Mod. (not corrected)	3	4553888856	0.049^{ns}	0.9999
	No Adjustment	9	122878.91		
	Residue (Pure Error)	60	2510901.5		

NLEM1	Reg. Mod. (not corrected)	3	2342600000	0.212ns	0.9920
	No Adjustment	9	532878.91		
	Residue (Pure Error)	60	2510901.5		
NLEM2	Reg. Mod. (not corrected)	3	2342600000	0.212ns	0.9920
	No Adjustment	9	532878.91		
	Residue (Pure Error)	60	2510901.5		

ns = not significant, means followed by the same letter, in each section, do not differ one to another ($P \geq 0.05$).

Tab. 4: Analysis of variance and F-test for specimens with no adjustment of models to Jatobá and loads tangential and perpendicular to the grain (continuation).

Jatobá - load tangential					
Models	**Source of variation**	**G. L.**	**Q. M.**	**F**	**P-value**
QPM	Reg. Mod. (not corrected)	3	7521762763	0.054ns	0.9999
	No Adjustment	9	720773.67		
	Residue (Pure Error)	60	13386384		
NLEM1	Reg. Mod. (not corrected)	3	3902700000	0.164ns	0.9971
	No Adjustment	9	2192995.89		
	Residue (Pure Error)	60	13386384		
NLEM2	Reg. Mod. (not corrected)	3	3902700000	0.164ns	0.9971
	No Adjustment	9	2192995.89		
	Residue (Pure Error)	60	13386384		
Jatobá - load perpendicular					
Models	**Source of variation**	**G. L.**	**Q. M.**	**F**	**P-value**
QPM	Reg. Mod. (not corrected)	3	8555829284	0.046ns	0.9999
	No Adjustment	9	728299.11		
	Residue (Pure Error)	60	15694588		
NLEM1	Reg. Mod. (not corrected)	3	4440800000	0.158ns	0.9971
	No Adjustment	9	2478299.11		
	Residue (Pure Error)	60	15694588		
NLEM2	Reg. Mod. (not corrected)	3	4440800000	0.158ns	0.9971
	No Adjustment	9	2478299.11		
	Residue (Pure Error)	60	15694588		

ns = not significant, means followed by the same letter, in each section, do not differ one to another ($P \geq 0.05$).

Tabs. 5 to 7 shows equations for different regression models adjusted to Peroba Rosa, Eucalyptus, Jatobá and loads applied tangentially and perpendicular to the grain and determination coefficients *(R^2)*, maximum ratios (x_0), and plateaus (*p*).

Tab. 5: Equations for different models, coefficients of determination, S/h maximum ratios and plateaus adjusted to Peroba Rosa and loads tangential and perpendicular to the grain.

Peroba Rosa - load tangential				
Models	Adjusted equations	R^2 (%)	$x_0\,(S/h)$	p (MPa)
QPM	$\hat{y} = -1471.0 + 1220.0x - 29.9602x^2$	99.5	20.36	10948.97
NLEM1	$\hat{y} = 10808.0exp\left[-0.00645\left(x - 17.3979\right)^2\right]$	98.1	17.40	10807.98
NLEM2	$\hat{y} = 1532.3exp\left(0.2246x - 0.00645x^2\right)$	98.1	17.40	10807.94
Peroba Rosa - load perpendicular				
Models	Adjusted equations	R^2 (%)	$x_0\,(S/h)$	p (MPa)
QPM	$\hat{y} = -179.5 + 1041.2x - 22.6216x^2$	99.1	23.01	11800.13
NLEM1	$\hat{y} = 11670.1exp\left[-0.00389\left(x - 20.2776\right)^2\right]$	97.3	20.28	11670.05
NLEM2	$\hat{y} = 2355.1exp\left(0.1579x - 0.00389x^2\right)$	97.3	20.28	11670.05

Tab. 6: Equations for different models, coefficients of determination, S/h maximum ratios and plateaus adjusted to Eucalyptus and loads tangential and perpendicular to the grain.

Eucalyptus - load tangential				
Models	Adjusted equations	R^2 (%)	$x_0\,(S/h)$	p (MPa)
QPM	$\hat{y} = 540.6 + 975.3x - 23.4762x^2$	99.9	20.77	10669.94
NLEM1	$\hat{y} = 10595.0exp\left[-0.00423\left(x - 18.4877\right)^2\right]$	99.1	18.49	10595.02
NLEM2	$\hat{y} = 2496.9exp\left(0.1564x - 0.00423x^2\right)$	99.1	18.49	10595.00
Eucalyptus - load perpendicular				
Models	Adjusted Equations	R^2 (%)	$x_0\,(S/h)$	p (MPa)
QPM	$\hat{y} = 605.6 + 1053.6x - 25.2829x^2$	99.7	20.84	11582.57
NLEM1	$\hat{y} = 11503.7exp\left[-0.00414\left(x - 18.6098\right)^2\right]$	98.8	18.61	11503.72
NLEM2	$\hat{y} = 2742.0exp\left(0.1541x - 0.00414x^2\right)$	98.8	18.61	11503.70

Tab. 7: Equations for different models, coefficients of determination, S/h maximum ratios and plateaus adjusted to Jatobá and loads tangential and perpendicular to the grain.

Jatobá - load tangential				
Models	Adjusted equations	R^2 (%)	$x_0\,(S/h)$	p (MPa)
QPM	$\hat{y} = -945.8 + 1542.0x - 36.7505x^2$	99.3	20.98	15229.98
NLEM1	$\hat{y} = 15002.2exp\left[-0.00559\left(x - 17.8207\right)^2\right]$	97.8	17.82	15002.17
NLEM2	$\hat{y} = 2540.9exp\left(0.1993x - 0.00559x^2\right)$	97.8	17.82	15002.17
Jatobá - load perpendicular				
Models	Adjusted equations	R^2 (%)	$x_0\,(S/h)$	p (MPa)
QPM	$\hat{y} = -780.2 + 1590.0x - 36.9095x^2$	99.4	21.54	16342.85
NLEM1	$\hat{y} = 16110.0exp\left[-0.00506\left(x - 18.4631\right)^2\right]$	97.8	18.46	16110.00
NLEM2	$\hat{y} = 2875.7exp\left(0.1867x - 0.00505x^2\right)$	97.8	18.46	16110.11

Figs. 1 to 3. shows and compares graphically the curve obtained from values observed experimentally to those obtained from the three models with apparent elastic modulus E_a as a function of *S/h* ratio adjusted to Peroba Rosa, Eucalyptus, Jatobá and loads applied tangentially and perpendicularly to the grain.

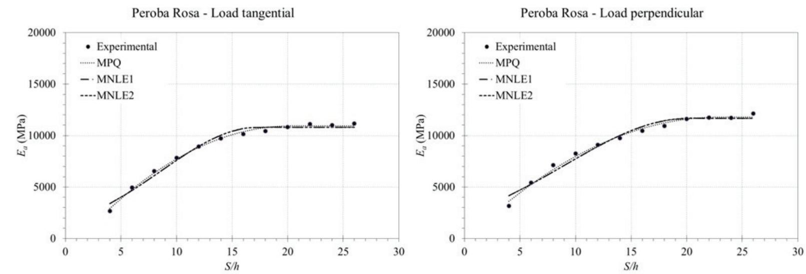

Fig. 1: Curves for apparent elastic modulus E_a as a function of S/h ratio for Peroba Rosa and loads tangential and perpendicular to the grain.

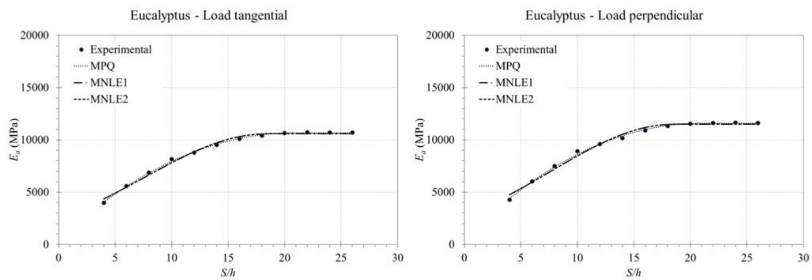

Fig. 2: Curves for apparent elastic modulus E_a as a function of S/h ratio for Eucalyptus and loads tangential and perpendicular to the grain.

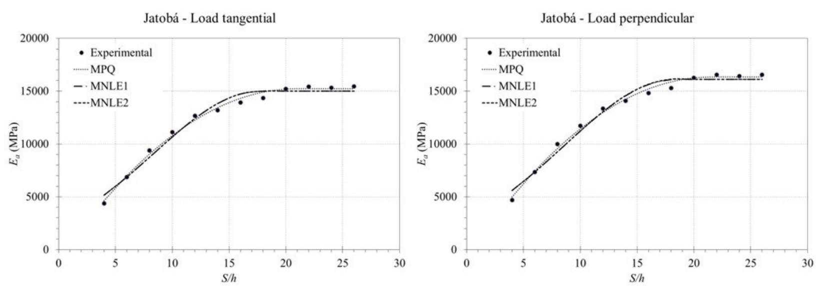

Fig. 3: Curves for apparent elastic modulus E_a as a function of S/h ratio for Jatobá and loads tangential and perpendicular to the grain.

DISCUSSION

Tab. 1 indicates that the apparent longitudinal elastic modulus E_a differs significantly with respect to load application directions (tangential and perpendicular) for each wood species (Peroba Rosa, Eucalyptus and Jatobá) at 1 % level of probability by means Student's t-test. Therefore, changing the load application direction had a significant effect on the apparent longitudinal elastic modulus E_a. This difference corresponds to 6.1, 8.5, and 6.8 % for Peroba Rosa, Eucalyptus, and Jatobá, in that order.

The results in the Tabs. 2 to 4 show that F-test results for specimens with the three models not adjusted to the wood species under investigation are not always significant, thereby indicating the ability of these models to describe the data analyzed, i.e., the hypothesis that the models are adequate is not rejected. In addition, it may be noted that the models show high determination coefficient values (R^2), close to 100 %. They also present very similar curves, especially in the case of Eucalyptus, to the extent that their overlapping hinders individual identification of graphic dispersion among the experimental model and the adjusted models. It is possible to observe that the exponential models 1 and 2 with plateau response (NLEM1 and NLEM2) are very similar in that they show virtually the same values for (x_0) and (P). The quadratic polynomial model with plateau response (QPM) shows larger values for *S/h* ratio and E_a as compared to those of NLEM1 and NLEM2.

As to the practical interpretation of these parameters in the Tabs. 5 to 7, it is possible to see that the *S/h* ratio that takes into account the average for the wood species in question under loads applied tangentially and perpendicularly to the growth rings is 20.70 and 21.80, respectively, in the quadratic polynomial model with plateau response.

The results in the Tabs. 5 to 7 show that the *S/h* ratio that takes into account the average for the wood species under investigation under loads applied tangentially and perpendicularly to the grain is 17.90 and 19.12, respectively, in both exponential models with plateau response (NLEM1 and NLEM2). Hence, the *S/h* values found for the quadratic and exponential models are in accordance with NBR 7190 (1997), which stipulates *S/h* equal to 21 for bending to occur without shearing deformations and are at odds with the *S/h* equal to 14 ratio recommended by ASTM D 143 (2009), thus generating values of apparent elastic modulus with significant shearing deformations, i.e., smaller than actual ones. The ratio *S/h* equal to 21 has also been validated by Christoforo et al. (2013) in structural static bending tests at three points, in spite of acknowledging that shear strength is not null at the load application point.

As to the best model obtained in the Tabs. 5 to 7, it is preferable to opt for the exponential model 1 with plateau response (NLEM1) because it is more practical as regards interpreting (x_0) and (p), which correspond to the parameters b and a, *S/h* and E_a, respectively. The quadratic polynomial model with plateau response (QPM) presents larger E_a values as compared to those obtained from the exponential models with plateau response. Taking into consideration all wood species and models under investigation, the plateau that physically represents E_a is larger when the load is applied perpendicular to the growth rings.

In Figs. 1 to 3, the curves presented are very similar and close to the experimental, especially in Eucalyptus wood species, in which there is an overlap between the experimental and fitted models. However, from the Figs. 1 to 3 it can be mentioned that all the models are adapted.

CONCLUSIONS

The results obtained in this study indicate that the design of wooden structures whose elements are subjected to static bending can be enhanced. Overall, the results presented facilitate and improve the estimation and execution of wooden structures. The *S/h* equal to 21 ratio found in our study safely meets that recommended by NBR 7190 (1997), i.e., the Brazilian standard for wooden structure design. In addition, our study indicates that this value can be reduced to *S/h* equal to 19 without compromising safety for loads applied tangentially. The apparent longitudinal elastic modulus E_a in static bending obtained experimentally in the *S/h* equal to 14 ratio recommended by ASTM D 143 (2009) for bending to occur with shearing deformations. Moreover, all models evaluated were shown to beequally appropriate to study the *S/h* ratio and E_a; therefore, it is impossible to indicate the best one to this end. Not with standing, we recommend the exponential model 1 with plateau response (NLEM1) is because it is more practical to use, since it promptly provides the maximum *S/h* ratio and plateau response, which physically represents the maximum apparent longitudinal elastic modulus E_a.

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