Analytical study of the curve of static bending test for wood specimens

Estudo analítico do ensaio de flexão estática para corpos de prova de madeira

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Abstract

The NBR 7190:1997 “Design of Timber Structures” provides the procedure for several mechanical tests, and among them, the Static bending test for Modulus of Elasticity ($E_m$) and Conventional Value of Strength ($f_m$) determinations. It is common to characterize wood batches with a small number of specimens, what makes it difficult to perform an estimative test for rupture determination, and afterwards, to carry out the loading cycle for $E_m$ estimation. In these cases, instead of Force parameters, Deflection parameters are used for the loading cycle. This paper aims to identify a pattern between Force and Deflection parameters by investigating the Force vs. Deflection curve of the static bending test of wood specimens. According to results, there is a well pronounced pattern between Force and Deflection parameters in the linear part of the Force vs. Deflection curve, and based on this, we proposed a linear regression model between logarithm values of the force percentage (in relation to the rupture) and the denominator of the span value (as a Deflection parameter), resulting $R^2$ equal to 97.41%. This result makes the conduction of the static bending test easier in specialized laboratories for testing of wood.

Keywords: Deflection. Force. Regression model. Static bending test. Testing of wood.

Keywords: Deflexão. Ensaio de flexão estática. Força. Modelo de regressão. Ensaio em madeira.

Palavras-chave: Deflexão. Ensaio de flexão estática. Força. Modelo de regressão. Ensaio em madeira.

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Introduction

Wood may be used for structural purposes (Freitas; Gonçalez; Del Manezzi, 2016; Trianoski et al., 2014) and the physical and mechanical characterization activities are important within this background (Dahlen et al., 2017; Pereira et al., 2018; Guntekin; Ozkan; Yilmaz, 2014). NBR 7190 (ABNT, 1997) “Design of Timber Structures” is the normative Brazilian code which prescribes both structural calculation and properties determination procedures. The annex B of the Brazilian standard code denominated “Determination of Wood Properties for Structural Design” provides the procedure for the static bending test in item B.14. This test provides the Modulus of Elasticity in Static Bending test (Em) and the Conventional Value of the Strength in Static Bending test (fm). These data are important for the wood beam design (Yoshihara et al., 1998; Segundinho et al., 2015; Cavalcheiro et al., 2018) as well as engineered wood composites characterization such as Glulam (Segundinho et al., 2013) and wood-based panels (Park et al., 2016).

In specialized laboratories for testing of materials, despite the fact that force parameters are advocated for static bending tests, during the loading cycle activity for the Em determination the use of deflection parameters is common, according to the Brazilian standard code. The values of 1/1000, 1/200 and 1/100 of the span are the most used in these cases, which makes the Em determination (performing the loading cycle) without a rupture value (provided by an estimative test) easier, in cases when there are not so many specimens for the mechanical characterization (custom made glulam beams on demand, for example – provides a small number of specimens). Another important value related to the Force vs. Deflection curve is the Elastic Limit being about 70% of the rupture (Almeida et al., 2018), and above this value, the curve presents a non-linear shape.

NBR 7190 (ABNT, 2013) (version under review - PN02: 126.10-001-1) prescribes eight strength classes of wood for structural uses. These strength classes are divided into three groups for softwood (C20, C25 and C30), and five groups for hardwood (D20, D30, D40, D50 and D60). These groups are determined based on the characteristic value of the strength in compression parallel to the grain (Ferro et al., 2015), covering characteristic strength values between 20 and 60 MPa. The strength classes parameters may be used for basing the sampling activity in wood properties researches, leading these studies to more generalized conclusions (Almeida et al., 2016).

This paper aims to identify a pattern between force and deflection parameters by investigating the Force vs. Deflection curve of the static bending test of wood specimens, covering the eight strength classes of the under review Brazilian standard code, with these results being important for performing the loading cycle for wood batches with a small number of specimens.

Materials and methods

In order to investigate the behavior of wood specimens under static bending tests with the objective of determining a pattern between the Force and Deflection variables, we considered five tropical Brazilian wood species as hardwoods, and Pinus sp. grown in Brazil as softwoods, covering the eight strength classes of the Brazilian standard code (version under review). According to Almeida et al. (2016) the sampling based on the strength classes of wood leads to more general results. Table 1 presents the eight wood samples considered for this study.

In order to investigate the pattern between force and deflection variables of wood specimens under static bending tests we performed eighteen mechanical tests for each wood species considered (Pinus sp. samples were divided into three strength classes based on the characteristic value of the strength in compression parallel to grain, as shown in Table 1). Therefore, we performed the total of 144 static bending tests. Figure 1 shows a static bending test carried out using the Universal Testing Machine EMIC 30kN capacity.

The specimens for static bending tests presented dimensions equal to 320 x 20 x 20 mm, with the highest dimension being parallel to the grain (reduced dimensions were considered for preparation of free-defect specimens). The span (L) considered for the mechanical tests was equal to 280 mm (Span-height ratio equal to 14 – this parameter does not affect the conventional value of strength in static bending), and the test velocity was 5 mm deflection per minute.

In order to investigate the pattern between force and deflection variables during the static bending test of wood specimens, the forces applied for 0.28, 1.4 and 2.8 mm (L/1000, L/200 and L/100, respectively), were measured based on the experimental Force vs. Deflection curve, using the software Origin (OriginLab,
Northampton, MA). These deflection parameters were considered since they are the most usually used in specialized laboratories. Figure 2 illustrates the Force vs. Deflection curve for wood samples. As it can be seen, using the Force vs. Deflection curve, we were able to determine the necessary force for the specimen by presenting the three deflection parameters considered, as well as the Elastic limit for each wood specimen considered. The total of 576 determinations were performed and evaluated.

Forces for \(L/1000\), \(L/200\) and \(L/100\) deflections were measured using the experimental Force vs. Deflection curves. We made a table summarizing the force results considered, and also we tested the normality of these results using the Anderson-Darling test at 5% significance level. Base on the normal distributed data, we calculated the confidence intervals of forces for each deflection parameter considered, as well as the Elastic limit (\(LE\)) force. At last, we tested a linear regression model fitted by the ordinary least square method between deflection and force parameters in the static bending test, using Analysis of Variance (ANOVA) at the same significance level. For the statistical analysis we used the software R version 3.5.1.

Table 1 - Wood species considered

| Strength Class | Wood Species       |
|----------------|--------------------|
| C20            | Pinus sp.          |
| C25            | Pinus sp.          |
| C30            | Pinus sp.          |
| D20            | Simarouba amara    |
| D30            | Anacardium giganteum |
| D40            | Erisma uncinatum   |
| D50            | Bagassa guianensis |
| D60            | Peltogyne sp.      |

Figure 1 - Static bending test

Figure 2 - Force vs. Deflection curve

\[
\begin{align*}
L/1000 &= 0.28\text{mm} \\
L/200 &= 1.40\text{mm} \\
L/100 &= 2.80\text{mm}
\end{align*}
\]
Results and discussions

Measuring the force values \( F \) for \( L/1000 \), \( L/200 \) and \( L/100 \) deflections and the \( LE \) parameter based on the experimental Force vs. Deflection curves we have determined the results that are summarized in the Table 2. This table presents force values as a percentage related to the rupture.

Table 2 shows that the average values of force for \( L/1000 \), \( L/200 \) and \( L/100 \) values (\( F(L/1000) \), \( F(L/200) \), \( F(L/100) \), respectively) are 4.03, 22.63 and 43.62%, respectively. The \( F(LE) \) average value was 68.82% that represents Elastic limit (or proportional limit). The highest coefficient of variation value was 18.59% for \( L/1000 \) deflection parameter and the lowest value of coefficient of variation was 12.58% for \( LE \) values.

Anderson-Darling (AD) normality tests were performed for the parameters studied here. Figures 3 to 6 show the quantile plots and histograms for \( F(L/1000) \), \( F(L/200) \), \( F(L/100) \) and \( F(LE) \) values, respectively.

Table 2 - Summary of results

|        | \( F(L/1000) \) (%) | \( F(L/200) \) (%) | \( F(L/100) \) (%) | \( F(LE) \) (%) |
|--------|---------------------|-------------------|-------------------|----------------|
| Average value | 4.03               | 22.63             | 43.86             | 68.82          |
| CV (%) | 18.59               | 15.56             | 14.08             | 12.58          |
| Minimum | 2.09               | 15.29             | 20.92             | 52.61          |
| Maximum | 6.53               | 39.57             | 62.38             | 97.66          |
| Count   | 144                 | 144               | 144               | 144            |

Figure 3 - Quantile plot and histogram of \( L/1000 \) values

AD test - \( p = 0.081 \)

Figure 4 - Quantile plot and histogram of \( L/200 \) values

AD test - \( p = 0.061 \)
Analytical study of the curve of static bending test for wood specimens

Figure 5 - Quantile plot and histogram of $L/100$ values

AD test - $p = 0.287$

forces for L

deflection

Theoretical Quantiles

Sample Quantiles

20 30 40 50 60

-2 -1 0 1 2

Density

0.00 0.02 0.04 0.06

20 30 40 50 60

Figure 6 - Quantile plot and histogram of $LE$ values

AD test - $p = 0.080$

forces for El

Theoretical Quantiles

Sample Quantiles

55 60 65 70 75 80

-2 -1 0 1 2

Density

0.00 0.02 0.04

50 60 70 80

Figure 3 shows the normality test for $F(L/1000)$ data, that resulted $p$-value equal to 0.081. Figure 4 shows the normality test for $F(L/200)$ data, that resulted $p$-value equal to 0.062. Figure 5 shows the normality test for $F(L/100)$ data, that resulted $p$-value equal to 0.287. And Figure 6 shows the normality test for $F(LE)$ data resulting $p$-value equal to 0.08. The null hypothesis of the Anderson Darling normality test is to accept that the data comes from normal distributed populations.

Based on the proven normal distribution of the $F(L/1000)$, $F(L/200)$, $F(L/100)$ and $LE$ data, we have calculated the confidence interval at 95% confidence level for each group. Table 3 shows the confidence intervals determined for the $F(L/1000)$, $F(L/200)$, $F(L/100)$ and $LE$ groups.

Table 3 shows the confidence interval for each force parameter determined in the static bending tests performed. As we can see, the average value of $F(L/1000)$ was 4.03% varying between 3.91 and 4.15% with 95% confidence. The $F(L/200)$ was 22.63% varying between 22.05 and 23.21% with 95% confidence. $F(L/100)$ was 43.86% varying between 42.84 and 44.88% with 95% confidence. And at last, $F(LE)$ was 68.82% varying between 67.39 and 70.24% with 95% confidence.

To make this information more useful we have determined a regression model between force percentage and the denominator of the span value (for deflection value determination). The logarithm of force percentage as a function of the logarithm of the denominator using a linear regression model was fitted using the ordinary least square method and tested by ANOVA at 5% significance level. Figure 7 presents the linear model fitted for the results, the linear equation that better fits the experimental data, the Adjusted Coefficient of Determination $R^2$ and the $p$-value of the ANOVA test.
Table 3 - Confidence intervals

| 95% Confidence level | Lower limit | Average value | Upper limit |
|-----------------------|-------------|---------------|-------------|
| F(L/1000) (%)         | 3.91        | 4.03          | 4.15        |
| F(L/200) (%)          | 22.05       | 22.63         | 23.21       |
| F(L/100) (%)          | 42.84       | 43.86         | 44.88       |
| F(LE) (%)             | 67.39       | 68.82         | 70.24       |

Figure 7 - Regression model for the force percentage and the denominator value

Regression model
\[ y = 3.741 - 1.046 \times x \] -- R²adj

Figure 6 shows the model between denominator value (span/denominator providing the deflection parameter) and force percentage value (force applied divided by the rupture). The model determined resulted \[ y = 3.741 - 1.046 \times x \], being significative and showing R² equal to 97.41%, which is a good result. Using this model, it is possible to determine the force percentual for the rupture based on the deflection value, bringing more background for structural uses of wood samples under static bending position, as well as making the mechanical characterization of small batches of wood specimens easier.

Conclusion

According to results, there is a well pronounced pattern between force percentage to the rupture and the deflection value (represented by the denominator value) of structural wood under static bending tests. Results show that \( F(L/1000), F(L/200), F(L/100) \) and \( F(LE) \) are about 4.03, 22.63, 43.86 and 68.82% to the rupture force, presenting a calculated confidence interval at 95% confidence level. The model \( y = 3.741 - 1.046 \times x \), being “y” the logarithm of force percentage to the rupture and “x” the logarithm of the denominator of the span value as a deflection parameter, can explain the pattern between these variables, presenting R² 97.41%. Consequently, information provides background for wood static bending tests as well as wood beams design consequently.

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