Non-Destructive Methodologies for Assessment of the Mechanical Properties of New Utility Poles

Carlos E. J. Martins,[a] Alfredo M. P. G. Dias,[a] André F. S. Marques,[b,*] and André M. A. Dias [b]

The application of non-destructive technologies for the assessment of mechanical properties has been increasingly used due to its reliable assessment of the condition of timber elements. The application of such methods is well established for sawn timber and small-diameter roundwood. However, regarding the assessment of the mechanical properties for roundwood with larger diameters, which are usually used for new utility poles, a fewer number of studies are available. This research considered three different methodologies for application in Maritime Pine utility poles: i) longitudinal vibration, ii) transverse vibration, and iii) ultrasound. The methodology with better results was chosen for use in the second stage of testing. Furthermore, mechanical tests were performed to compare and validate the results from the non-destructive tests. The moisture contents and densities were also determined. Simple and multiple linear regression analyses were performed between the visual, dynamic, and mechanical properties. The longitudinal vibration method achieved the best correlation within the non-destructive methods, while the ultrasound method had no noticeable correlation. The vibration frequency (*f*) ($r = 0.51$) showed a better correlation with the bending strength (MOR) than the dynamic modulus of elasticity ($\mathrm{MOE_{dyn}}$) ($r = 0.45$). The static modulus of elasticity (MOE) was the best property used to predict MOR because it presented the highest correlation ($r = 0.79$).

Keywords: Utility poles; Non-destructive assessment; Longitudinal vibration; Transverse vibration; Ultrasounds; Mechanical properties; Maritime pine

Contact information: a: Institute for Sustainability and Innovation in Structural Engineering, Departamento de Engenharia Civil, Faculdade de Ciências e Tecnologia, Universidade de Coimbra, Rua Luís Reis Santos, Pólo II da FCTUC, 3030-788 Coimbra, Portugal; SerQ-Centro de Inovação e Competências da Floresta, Rua J, Nº9, Zona Industrial da Sertã, 6100-711 Sertã; b: SerQ- Centro de Inovação e Competências da Floresta, Rua J, Nº9, Zona Industrial da Sertã, 6100-711 Sertã, Portugal;
** Corresponding author: andre.markes.fs@gmail.com*

INTRODUCTION

Timber utility poles have been used for telecommunication and power lines globally since their first use more than a century ago. In 2008 there were roughly 135 million utility poles in service in the United States of America, with the majority of them made from timber (Wood *et al.* 2008). Timber utility poles have several advantages, namely their robustness and non-conductivity, as well as their ability to allow different ways of wire connections, and they are also a low-cost alternative compared with steel or concrete poles.

In Portugal, power lines are generally supported by utility poles made from steel or concrete, while timber utility poles are mostly used to support telecommunication lines.

Such lines can collapse, resulting in service interruption that can lead to costly emergency repairs (Mankowski *et al.* 2002). There might be several reasons for the failure of these lines, one of which might be the failure of the timber utility poles used.

To reduce this problem, the selection of timber utility poles for use in overhead lines is an important aspect. To minimize their failure resulting from a lack of mechanical strength, utility poles with adequate mechanical properties should be used.

There have been a number of studies on the assessment of the mechanical properties of timber utility poles, namely its modulus of elasticity (MOE) and bending strength (MOR), for different species from different regions. In the US, studies on poles of southern pine (*P. palustris, P. taeda, P. echinata,* and *P. elliotti*), Douglas fir (*Pseudotsuga menziesii*), and western redcedar (*Thuja plicata*) were performed to obtain the relevant mechanical properties (Phillips *et al*. 1985; Bodig *et al*. 1986; Bodig and Goodman 1986). Also in South America some studies can be found regarding the determination of the mechanical properties of poles from different species, namely radiata pine (*P. radiata*) from Chile (Cerda and Wolfe 2003), *Eucalyptus grandis* from Argentina (Torran *et al*. 2009) and also several species from Brazil (Carradine and Gonzalez 2006). In Portugal, the main species used for utility poles for overhead lines is Maritime pine (*Pinus pinaster* (Ait.)) with good results already obtained for the mechanical properties (Martins and Dias 2012).

In Europe, the EN 14229 (CEN 2010) standard provides guidelines for the production control of new timber utility poles and the guidelines for determining the mechanical properties through mechanical tests. However, during the determination of MOR, utility poles are destroyed; therefore, an alternative is to use non-destructive methodologies in the selection of timber utility poles.

The range of non-destructive methodologies available is wide, and they differ from each other in their principles and/or applications. In a simple way, the most current used methodologies can be divided into three groups: i) visual characterization, ii) ultrasound, and iii) vibration (transverse and longitudinal directions). In practice, visual characterization is the most common and most used.

Apart from the use of non-destructive techniques on grading sawn timber, they have also been used for the *in-situ* evaluation of the service conditions of utility poles (Baraneedaran *et al.* 2010; Tsang and Chan 2011; Dackermann *et al.* 2014) and after their removal from service (Anthony *et al.* 1998; Marques *et al.* 2016).

For the assessment of the mechanical properties of roundwood, the non-destructive methodologies commonly used are ultrasound (Sandoz 1991; Miná *et al*. 2004; Acuña *et al*. 2006; Prieto *et al.* 2007) and vibration, either longitudinal (Gard *et al.* 1998; Vries and Gard 1998; Morgado *et al.* 2010; Rodrigues and Vries 2010; Arriaga *et al*. 2014) or transverse (Chui *et al.* 1999; Wang *et al.* 2002; Green *et al.* 2004, 2005, 2006, 2008; Arriaga *et al*. 2014).

Despite the available studies regarding the determination of the mechanical properties of utility poles from different species, including one for Maritime pine, and also the availability of a wide literature on the application of non-destructive methodologies in the assessment of timber condition and mechanical properties, there is clearly a lack of information regarding the application of these techniques to Maritime pine utility poles. The present paper intends to assess the application of some non-destructive methods in Maritime pine species and compare the results with the ones obtained from the mechanical tests.

Therefore, the present paper describes the work performed to assess the mechanical properties of new timber utility poles from Maritime pine. Non-destructive methodologies were used, as well as mechanical tests, to compare the two types of methods, with the intention of being a first approach on the evaluation of the mechanical properties through the use of non-destructive methodologies. The objective was that such methods can be used as an effective way for the selection of Maritime pine new utility poles to be used in overhead lines. The experimental work was divided into two stages. The first stage focused on the evaluation of the best non-destructive methodology to estimate MOE. In this stage, several non-destructive methods were used and the MOE was determined following the indications from EN 14229 (CEN 2010). The second stage aimed to validate the use of the selected non-destructive method on the first stage and analyze its suitability to predict MOR. Several correlations between the anatomical, physical, and mechanical properties were established for a more accurate prediction of the mechanical properties of new timber utility poles.

EXPERIMENTAL

Materials

Sample characterization

The present study comprised a total sample of 72 new utility poles of Maritime pine (*Pinus pinaster* (Ait.)) grown in the coastal central area of Portugal. The utility poles had no preservative treatment and after harvested they were only debarked and cut with the desired length, after which they were spread in pole piles at the Pedrosa & Irmãos, Lda company facilities. The utility poles used in the present study were selected from these piles, ensuring that the moisture content was above the fiber saturation point (24%) for maritime pine (LNEC 1997). Also, the selection was performed considering the established procedures of the production unit for new utility poles without treatment and the requirements of EN 14229, namely i) the permissible deviations for utility pole size (8 m of nominal length), ii) the minimum nominal diameter (180 mm at ground line), and iii) straightness (CEN 2010).

Fig. 1. Debarked pole piles, at the company facilities, for the selection of the tested sample

To complement the sample characterization, visual features were also measured: i) nominal diameter (d_{nom}) (at ground-line (d_g) and load section point (d_q)), ii) ovality (at ground-line (o_g) and load section point (o_q)), iii) taper (between ground-line and load section point), iv) slope of grain, and v) growth rate. The measurement procedures used were the ones indicated in EN 14229 (CEN 2010) and described in detail in Martins and Dias (2012).

The total sample set of 72 new utility poles was divided in two samples matching the two stages of the work. The first stage involved 29 specimens, and its main purpose was the identification of the non-destructive method that presented the best MOE prediction. The second sample included 43 specimens that were tested with the goal of validating the non-destructive technique identified in the first stage for the prediction of MOE in new timber utility poles.

Methods

Different methodologies were used, firstly, non-destructive methodologies were considered for the determination of MOE_{dyn}, and the results were compared with MOE. Secondly, one of the non-destructive methodologies previously used, was considered and used for further testing and validation.

The selection of the non-destructive method used in the second stage of the work took into account not only the results and the correlations obtained with MOE, but also the applicability of the methodology at an industrial level.

After the tests, simple linear regression analyses (Microsoft Excel) were made in order to determine the correlation coefficients (r) and the coefficients of determination (r^2) between the measured features and the mechanical properties of the tested timber utility poles. Additionally, multiple linear regression analyses were also made to improve the coefficients from the simple linear regression analyses.

Non-destructive methodologies

The non-destructive methodologies considered in the first stage were: i) ultrasound, ii) transverse vibration and iii) longitudinal vibration. The objective was to determine the dynamic modulus of elasticity (MOE_{dyn}) and to further evaluate the correlations with the most relevant mechanical properties, namely with MOE, which is the key property to predict MOR.

For the ultrasound method was used the *Fakopp Microsecond Timer*, with a couple of transmitter and receiver probes, to measure the wave propagation time through the utility pole, in order to calculate the velocity, also considering the distance between the transmitter and receiver probes. The probes were applied in the specimens with an angle of 45º with the longitudinal axis, and the wave was generated by a hammer impact in the transmitter probe. Due to the length of the cables, it was not possible to test the entire specimen at once, so measurements in different positions were performed. Tests were performed with each utility pole simply supported in the two ends.

For the transverse vibration method, utility poles were placed as a simple supported element at both ends and a *National Instruments* piezoelectric accelerometer was used, connected in the mid-span of the pole to measure the signal which was started by a hammer impact also near the mid-span.

For the longitudinal vibration method, once more the utility poles were tested as simply supported elements in the two ends. The vibration of the elements was initiated by a longitudinal hammer impact and was measured in the same direction for the determination of the natural frequency.

Mechanical Tests

The non-destructive tests were performed to assess the methodology with higher correlations to the mechanical properties. Mechanical tests were performed: in the first stage only to determine MOE and in the second stage to determine MOE and MOR of the utility poles from the second sample.

The mechanical tests were performed following the indications of EN 14229 (CEN 2010) and using a cantilever test set up. The utility poles were tested in a position such that their underside in its "natural rest" was in tension. The first 1500 mm from the butt of the utility pole length was rigidly clamped through two wood clamps, each one with 500 mm (Fig. 2, left), and the load was applied at 150 mm from the tip by a cable fixed in a steel device incorporating a load cell (from Vetek) and a pair of wood clamps (Fig. 2, right).

In the second stage, after each failure test, the position and the type of failure were registered. Also, a 50-mm-thick disk was cut near the failure, avoiding areas with defects, to determine the moisture content (w) and density (ρ) in the laboratory. The density determined in the laboratory was adjusted to a moisture content of 12%, as suggested in EN 384 (CEN 2004) – when moisture content was higher than 12%, density was decreased 0.5% for every percentage point difference in moisture content.

Fig. 2. Set up for cantilever tests: (left) wood clamps used at the bottom and (right) application of load at the tip

RESULTS AND DISCUSSION

The values obtained from the visual characterization of both samples are presented in Table 1. The mean values and the coefficients of variation (CoV) are given.

The values obtained from both samples were compared with a previous study conducted on Maritime pine utility poles (Martins and Dias 2012). Out of all of the measured characteristics, taper presented a higher difference – 5.5% higher in the first sample and 15.9% higher in the second sample – when compared with the results of Martins and Dias (2012) (6.9 mm/m). The remaining measured characteristics were very similar in both studies, as was the case of the nominal diameter at ground-line – 0.8% higher in the first sample – and growth-rate – 2.3% higher in the first sample and 0.8% lower in the second sample – when compared with the values in Martins and Dias (2012), who obtained 196.1 mm for the nominal diameter at ground-line and 13.0 rings/25 mm for the growth-rate.

Table 2 presents results obtained in the first stage of the study for the first sample, relative to the tests of the non-destructive methods considered – UltraSound ($\text{MOE}_{\text{dyn,US}}$), Transverse Vibration ($\text{MOE}_{\text{dyn,TV}}$), and Longitudinal Vibration ($\text{MOE}_{\text{dyn,LV}}$) – as well as the results of MOE.

After analyzing the results, it became clear that the MOE_{dyn} values from the non-destructive tests were higher than the MOE values. It was also apparent that all of the methods presented similar MOE_{dyn} values when compared with each other.

Table 1. Anatomic and Geometric Characteristics Measured on the Utility Poles of the Present Study

		First Sample (29 Specimens)		**Second Sample** (43 Specimens)	
		Mean	**CoV (%)**	**Mean**	**CoV (%)**
Nominal Length (m)		8.0	0.57	8.0	0.38
d_{nom} (mm)	**Ground-line (d_g)**	197.7	5.4	196.1	5.3
	Loading Point (d_q)	150.6	10.9	145.4	11.4
Ovality (%)	**Ground-line (o_g)**	4.5	48.0	5.2	43.0
	Loading Point (o_q)	5.7	71.3	5.1	39.2
	Taper (mm/m)	7.3	25.8	8.2	30.1
	Slope of Grain (cm/m)	4.9	55.1	6.0	49.7
	Growth Rate (rings/25 mm)	13.3	29.7	12.9	32.2
	Density (green) (ρ_g) (kg/m^3) *	883.2	22.4	951.0	10.2
	Density (ρ) (kg/m^3) **	-	-	530.7	11.8
	Moisture Content (w) (%) ***	-	-	82.4	23.3

* - The density (green) – ρ_g – values presented were obtained based on the weight and volume of the entire utility pole in green condition; ** - Density values correspond to a moisture content of 12% and were determined in laboratory using the 50 mm thickness disk cut after the failure tests; *** - Moisture content values were determined in laboratory

Table 2. Results from Non-Destructive and Mechanical Tests Obtained from the First Sample

FIRST SAMPLE

	$MOE_{dyn,US}$ (GPa)	**$MOE_{dyn,TV}$ (GPa)**	**$MOE_{dyn,LV}$ (GPa)**	**MOE (GPa)**
Mean Value	13.8	13.7	13.9	10.3
Minimum Value	9.8	9.2	10.0	7.8
Maximum Value	18.8	18.4	17.1	13.5
CoV (%)	15.9	18.2	14.4	13.0
Number of Specimens	29			

To define which method fits better with the MOE, a linear regression analysis was made to calculate the correlation coefficients between the different MOE_{dyn} and MOE. **Table**Table 3 presents these correlation coefficients, together with the equations of the linear correlation. Also the coefficient of determination is presented together with the scatter charts of the respective relationships between MOE and MOE_{dyn} (Figs. 3 and 4 (left and right)).

Analyzing the correlation coefficient values, it was concluded that the ultrasound methodology presented a weak correlation with the MOE ($r = 0.14$) and that this correlation was not statistically significant (at a significance level of 0.05). The coefficient of determination obtained for the ultrasound method was much lower compared with other studies ($r^2 = 0.58$ in Miná *et al*. (2004)). According to Acuña *et al*. (2006), the ultrasound method can be influenced by the direction of measurement probes with the grain and also by the measurement distance. It is likely that the technical restraints of the test set up used in the present study influenced the results. Therefore, this method was excluded first for the non-destructive tests of the second stage.

Table 3. Values of Correlation Coefficients, and Corresponding Equations, between MOE_{dyn} from Non-Destructive Methods and MOE

Correlation Coefficient (*r*)		**Equations**
	MOE	
$\mathbf{MOE_{dyn,US}}$	0.14	**MOE** = 9156.39 + 0.08 $\mathbf{MOE_{dyn,US}}$
$\mathbf{MOE_{dyn,TV}}$	0.58	**MOE** = 6054.41 + 0.31 $\mathbf{MOE_{dyn,TV}}$
$\mathbf{MOE_{dyn,LV}}$	0.56	**MOE** = 5071.60 + 0.38 $\mathbf{MOE_{dyn,LV}}$

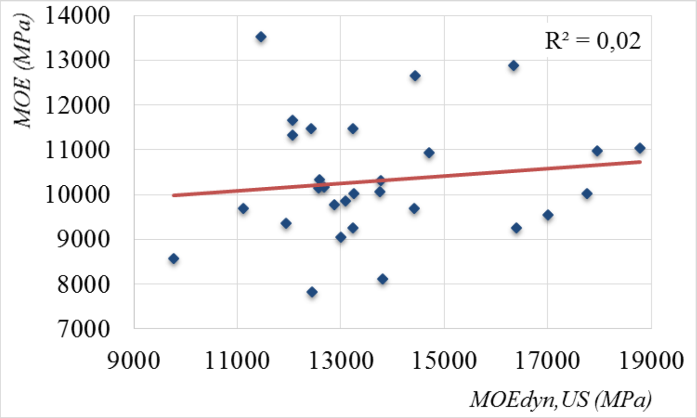

Fig. 3. Simple linear correlation between MOE and $MOE_{dyn,US}$, for the first sample

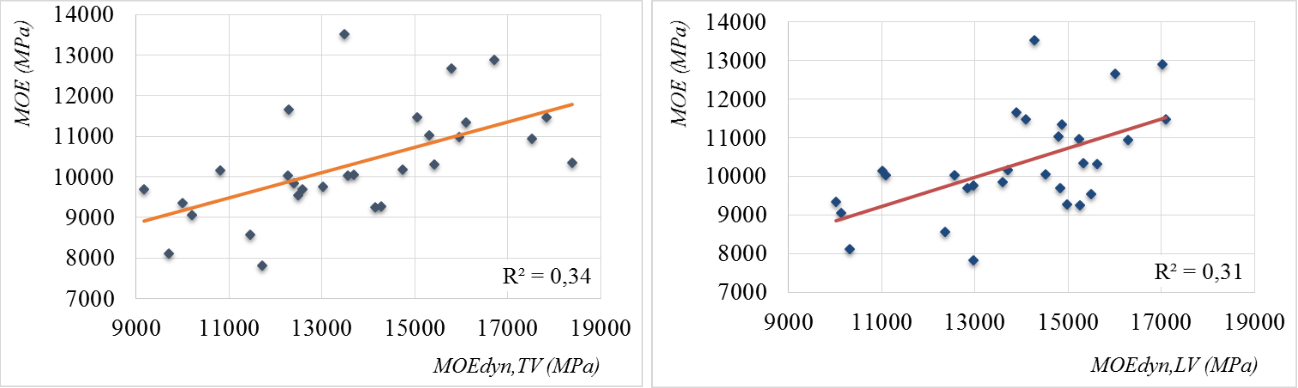

Fig. 4. Simple linear correlation between MOE and $MOE_{dyn,TV}$, for the first sample (left) and simple linear correlation between MOE and $MOE_{dyn,LV}$, for the first sample (right)

Regarding the remaining two methodologies, transverse vibration ($r = 0.58$) and longitudinal vibration ($r = 0.56$), the correlation coefficients were similar in both cases but were not found to be significantly different from each other (significance level of 0.05). Despite these values being considerably higher than the values from ultrasound methodology, the coefficients of determination were found to be lower than others found in the literature. For instance, Arriaga *et al*. (2014) obtained coefficients of correlation of $r^2 = 0.86$ and $r^2 = 0.87$, for the transverse and longitudinal vibration method, respectively.

Besides the prediction of MOE, the applicability of each methodology at an industrial environment was also evaluated. The ultrasound method again presented some technical disadvantages in relation to the vibration methods. During the vibration tests, the authors also noticed that the longitudinal vibration was easier to perform over the transverse vibration, specifically because of the ease of obtaining a clear signal. Several times, the acquired signal from the transverse vibration method was not clear and in some cases the test was repeated in order to achieve a clear signal.

Therefore, it was concluded that despite the correlation coefficient being slightly lower, the longitudinal vibration method was the easiest and fastest procedure to implement at an industrial level as a non-destructive methodology to assess the mechanical properties. Thus, the longitudinal vibration method was chosen for use in the second stage.

After the selection, in the previous stage, of the best non-destructive method to predict the MOE, the work performed in the second stage was intended to validate the longitudinal vibration method as a reliable method to predict the mechanical properties (MOE and MOR). Therefore, 43 specimens were tested using the longitudinal vibration method and their mechanical properties were also determined through the mechanical tests performed. The average distance of failure section to the ground-line was 615 mm (with a coefficient of variation of 92.4%), and the presence of knots in the failure area was observed in 86% of all utility poles from the second sample, which indicates that the presence of knots might had a great influence in the location of the failure.

TableTable 4 presents the results obtained from the second sample, namely the $MOE_{dyn,LV}$, MOE, and MOR.

As expected, the mean value of MOE from both samples was similar, and the difference in the values was not significant (significance level of 0.05). However, it was observed that the coefficient of variation in the second sample was higher. In fact, the second sample included a few utility poles with higher values of MOE, which lead to the higher variation observed.

A comparison was made between the results from this study and the previous study on Maritime pine utility poles performed by Martins and Dias (2012). Regarding the mechanical properties, the MOE mean value decreased 0.93% in comparison with Martins and Dias (2012) (10.9 GPa), and the MOR mean value from the present study was 4.6% higher than the value from the 2012 study (50.2 MPa). However, the density value from the present study – determined in the laboratory and adjusted to 12% moisture content – (Table 1) showed a 7.4% decrease when compared with the value obtained by Martins and Dias (2012) (573 kg/m^3).

Table 4. Results Obtained from the Second Sample Relative to Longitudinal Vibration Method and Mechanical Properties from the Second Sample

	SECOND SAMPLE		
	$MOE_{dyn,LV}$ (GPa)	**MOE (GPa)**	**MOR (MPa)**
Mean Value	12.8	10.8	52.5
Characteristic Value	-	-	33.5
Minimum Value	8.9	7.2	30.6
Maximum Value	20.9	17.4	78.1
CoV (%)	17.2	20.8	17.2
Number of Specimens	43		

A single linear regression analysis was performed between the anatomic, physical or mechanical properties with the MOE and/or the MOR to evaluate the possible relations between these properties. The determined correlation coefficients are shown in Table 5, also with the most relevant coefficients of determination (in parentheses).

Table 5. Correlation Coefficients and Coefficient of Determination (r^2) Obtained from Single Linear Regression Analysis

		Nominal Diameter		Ovality		Taper	ρ*	Growth Rate	MOE $_{dyn,US}$	MOE $_{dyn,TV}$	MOE $_{dyn,LV}$ **	MOE
		d_g	d_q	o_g	o_q							
First Sample	**MOE**	-0.05	0.37	0.41	0.04	-0.46	-0.34	0.04	0.14 (0.02)	0.58 (0.34)	0.56 (0.31)	-
Second Sample	**MOE**	-0.44	0.24	0.44	0.03	-0.42	0.71	0.27	-	-	0.68 (0.47)	-
	MOR	-0.37	0.50	0.41	-0.27	-0.61	0.70	0.31	-	-	0.45 (0.20)	0.79 (0.63)

* In the first sample, the density was obtained from the weight and the volume from the entire utility pole at green condition. In the second sample, the density was measured from the disks cut near the failure section, without defects, and adjusted to 12% of moisture content

** The values presented in this table for MOE$_{dyn,LV}$ were calculated considering the density values obtained from the weight and the volume from the entire utility pole at green condition

The correlation between density and MOE presented some differences when analyzing the values from both samples. These differences in the correlations were because, in the first sample, the density value obtained from the measurements from the entire pole in a green condition was considered (mass and approximate volume), once the utility poles were not tested until failure. In contrast, in the second sample, the density considered for the correlation was determined in the laboratory, using the 50-mm-thick disk, which was cut after the failure test, and adjusted to 12%, which gave more accurate results.

The analysis of the correlation coefficients showed that between MOR (only for the second sample), anatomical, and physical characteristics, the higher value was also obtained for density ($r = 0.70$), followed by taper ($r = -0.61$), and nominal diameter at load section point ($r = 0.50$), following the trend obtained by Martins and Dias (2012). The MOE presented the higher correlation coefficient ($r = 0.79$) with a corresponding coefficient of determination of $r^2 = 0.63$, strengthening the finding that it is the best property to predict MOR. Considering the mechanical properties from an element (MOE and MOR), the longitudinal vibration method presented a better correlation coefficient with MOE ($r = 0.68$ and $r^2 = 0.47$) than with MOR ($r = 0.45$ and $r^2 = 0.20$). Relatively to the first stage an increase of 21.9% was observed in the correlation coefficient between MO$_{\text{Edyn,LV}}$ and MOE, with a corresponding increase of 48.4% in the coefficient of determination. Despite this increase, the correlation coefficients are not significantly different (significance level of 0.05) and the coefficient of determination is lower than those usually found in literature ($r^2 = 0.87$ from Arriaga *et al.* (2014)).

As noted, the density showed different correlation coefficients with MOE; therefore, it was used to analyze its influence on the correlations involving $MOE_{dyn,LV}$. Regarding the density value used in the analysis, four different scenarios were considered: i) density measured from the whole utility pole in green condition, ii) density measured from the whole utility pole adjusted to 12% moisture content (measured by an electronic moisture meter), iii) density measured from a disk without defects collected near failure at green condition, and iv) density measured from a disk without defects collected near failure and adjusted to 12% moisture content (determined according to EN 13183 (CEN 2002)). Additionally, the correlation between natural frequency (*f*), MOE, and MOR was also considered. Table 6 presents the correlation coefficients for these scenarios and also the respective coefficients of determination (in parentheses).

The analysis of Table 6 clearly shows that the best results regarding the correlations between $MOE_{dyn,LV}$ and the mechanical properties were the ones where $MOE_{dyn,LV}$ was determined with the density measured from the disks collected near the failure section in green condition (r = 0.77 with r^2 = 0.60 and r = 0.62 with r^2 = 0.38). When considering this scenario, a 38% increase in the correlation coefficient between the $MOE_{dyn,LV}$ and MOR was observed.

Table 6. Correlation Coefficients and Coefficient of Determination between Longitudinal Vibration Method and Mechanical Properties

Conditions	$MOE_{dyn,LV}$ Correlation Coefficient and Coefficient of Determination Values, Using the Different Values of Density in Calculation				*f*
	Utility Pole		Disk Without Defects		
	Green	12%	Green	12%	
MOE	0.68 (0.47)	0.70 (0.48)	0.77 (0.60)	0.73 (0.53)	0.67 (0.45)
MOR	0.45 (0.20)	0.49 (0.24)	0.62 (0.38)	0.61 (0.38)	0.51 (0.26)

Despite these good results, the efficiency of collecting a disk from a section near the predicted failure zone is not admissible for a non-destructive methodology. For that purpose, further research should be developed to evaluate if the collection of a core is an adequate solution for determining density.

From the analysis of the correlation coefficient between $MOE_{dyn,LV}$, considering the different scenarios and density values, and the mechanical properties MOE and MOR, a wide variation was noticed in the values. Therefore, as an alternative to the prediction of the mechanical properties of utility poles, the natural vibration frequency was used to determine correlation coefficients with MOE (r = 0.67 with r^2 = 0.45) and MOR (r = 0.51 with r^2 = 0.26). A comparison of these values with the correlation coefficients among $MOE_{dyn,LV}$, MOE, and MOR is presented in Table 7. The values of $MOE_{dyn,LV}$ used to determine the correlation coefficients in Table 7 were calculated using the density value of the entire utility pole in green condition, which is the methodology usually used in practice.

Table 7. Comparison of Correlation Coefficients

	$MOE_{dyn,LV}$*	*f*	Variation
MOE	0.68	0.67	-2.2%
MOR	0.45	0.51	+13.5%

* - The values of $MOE_{dyn,LV}$ used to determine the correlation coefficients were calculated using density value of the entire utility pole in green condition.

As a simple, quick, and economical prediction of the mechanical properties, the frequency determination can be considered as an alternative because it observed a 13.5% increase in the correlation coefficient with MOR, when compared to the correlation coefficient between the $MOE_{dyn,LV}$ and MOR. However, further testing is required to clarify this issue.

Additionally, multiple linear regression analyses were undertaken to improve the correlations. These analyses considered the combination of geometric and anatomic characteristics, $MOE_{dyn,LV}$ from the non-destructive tests, and MOE with MOR. For that purpose, the value of density used was the one determined from the whole utility pole at green condition. The correlation coefficients obtained are presented in Table 8 together with the adjusted coefficients of determination (in parentheses).

The best correlation coefficient (r = 0.91 with r^2 = 0.78) was found for the situation where all of the characteristics and properties mentioned were considered. If MOE was not considered in the analysis, the correlation coefficient decreased to r = 0.82 (r^2 = 0.53) and to r = 0.78 (r^2 = 0.53), if only the anatomic and geometric characteristics were considered.

The same analysis was made but considering the density values, adjusted to 12% moisture content, obtained in the laboratory from the utility poles disks. Table 9 presents the results of the correlation coefficients for this situation. The correlation coefficient when all the features were considered did not change (r = 0.91), although an increase in the other correlation coefficients was observed (r = 0.84).

Table 1. Correlation Coefficients and Adjusted Coefficient of Determination from the Multiple Regression Analysis – Using Density from the Entire Utility Pole in Green Condition

***r* Values (adjusted r²)**		**MOE**	**$MOE_{dyn,LV}$**	**ρ***	**Nominal Diameter**		**Taper**	**Ovality**		**Growth Rate**	**Slope of Grain**
					d_g	**$\mathrm{d_q}$**		**o_g**	**o_q**		
MOR	0.91 (0.78)	X	X	X	X	X	X	X	X	X	X
	0.82 (0.58)	-	X	X	X	X	X	X	X	X	X
	0.78 (0.53)	-	-	X	X	X	X	X	X	X	X

* - For these correlations, density from the entire utility pole in green condition was used.

Table 2. Correlation Coefficients and Adjusted Coefficient of Determination from the Multiple Regression Analysis using Density Obtained in Laboratory from Utility Poles Disks Adjusted to 12% Moisture Content

***r* Values (adjusted r²)**		**MOE**	**$MOE_{dyn,LV}$**	**ρ***	**Nominal Diameter**		**Taper**	**Ovality**		**Growth Rate**	**Slope of Grain**
					d_g	**d_q**		**o_g**	**o_q**		
MOR	0.91 (0.78)	X	X	X	X	X	X	X	X	X	X
	0.84 (0.63)	-	X	X	X	X	X	X	X	X	X
	0.84 (0.64)	-	-	X	X	X	X	X	X	X	X

* - For these correlations, density obtained in laboratory and adjusted to 12% moisture content was used.

The consideration of these features resulted in an increase in the adjusted coefficient of determination of 290%, when compared with the scenario of just considering $MOE_{dyn,LV}$ (using density value determined in the field).

In summary, for the sample analyzed in this study containing 43 new utility poles, the longitudinal vibration method was simple to use, but the correlations established with the MOR were not so effective for sawn timber or even for roundwood with small diameters (Vries and Gard 1998; Morgado *et al.* 2010). Therefore, for the assessment of the mechanical properties of Maritime pine utility poles, the use of longitudinal vibration method requires further research and, given the results obtained in the present study, the consideration of extracting a core from the utility pole, for determination of density in green condition, should also be considered.

CONCLUSIONS

1. In the assessment of the mechanical properties of Maritime pine timber utility poles using non-destructive methodologies, the longitudinal vibration method was chosen over ultrasound and even transverse vibration method, because it was found to be easier and faster to perform at an industrial level.
2. Due to some technical disadvantages in the test set up of the ultrasound tests, the results from this method presented no relevant correlations with MOE, therefore it was discarded as a method to predict MOE.
3. The coefficients of determination between MOE_{dyn} and MOE, obtained from the longitudinal vibration tests and from the transverse vibration method, were lower than those found in literature.
4. When considering a multiple linear regression analysis, an increase in the correlation coefficients was obtained with MOR. If the measured visual characteristics were considered together with the $MOE_{dyn,LV}$ and MOE, the correlation coefficient increased to $r = 0.91$, corresponding to a $r^2 = 0.78$.
5. The different values of density had an influence on the correlation coefficients with MOE and MOR. If the density values obtained from a disk cut near the failure and adjusted to 12% moisture were considered, a 38% increase in the correlation coefficient between the $MOE_{dyn,LV}$ and MOR was observed. However, this procedure is not admissible in a non-destructive method; therefore, as an alternative, the collection of a small core from the utility pole for determining the density should be evaluated through further research.

ACKNOWLEDGMENTS

This work was partly financed by FEDER funds through the Competitiveness Factors Operational Program – COMPETE and by national funds through FCT – Foundation for Science and Technology within the scope of the project POCI-01-0145-FEDER-007633.

The authors also gratefully acknowledge the European Union Fund FEDER for financial support provided through the Research Project QREN 30224.

REFERENCES CITED

Acuña, L., Díez, M. R., and Casado, M. (2006). "Los ultrasonidos y la calidad de la madera estructural: Aplicación a *Pinus pinaster* Ait," Boletín del CIDEU, pp. 7-26.

Anthony, R. W., Renforth, L., and Nelson, R. F. (1998). "Nondestructive strength evaluation of *Pinus sylvestris* poles in the U.K.," in: *5th World Conference on Timber Engineering*, Montreaux, Switzerland, pp. 642-648.

Arriaga, F., Monton, J., Segues, E., and Iniguez-Gonzalez, G. (2014). "Determination of the mechanical properties of radiata pine timber by means of longitudinal and transverse vibration methods," *Holzforschung* 68(3), 299-305. DOI: 10.1515/hf-2013-0087.

Baraneedaran, S., Abdouka, K., Wilson, J. L., Gad, E. F., and Flatley, I. (2010). "Non destructive assessment of in service timber utility poles," in: *Incorporating Sustainable Practice in Mechanics and Structures of Materials*, S. Fragomeni and S. Venkatesan (eds.), CRC Press, Boca Raton, pp. 915-920. DOI: 10.1201/b10571-166

Bodig, J., and Goodman, J. R. (1986). “Western red cedar data and size effect,” *Wood Pole Properties,* Vol. 3, Research Institute of Colorado, Fort Collins, Colorado. (http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=EL-4109-V3)

Bodig, J., Goodman, J. R., Phillips, G. E. and Fagan, G. B. (1986). “Douglas fir data,” *Wood Pole Properties*, Vol. 2, Research Institute of Colorado, Fort Collins, Colorado. (http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=EL-4109-V2)

Carradine, D. M., and Gonzalez, J. R. (2006). “Evaluating Brazilian wood species for utility pole and cross arm use,” in: *World Conference on Timber Engineering,* Portland, Oregon, USA, pp. 466-473.

CEN EN 384 (2004). "Structural timber – Determination of characteristic values of mechanical properties and density," Comité Européen de Normalization, Brussels, Belgium.

CEN EN 13183-1 (2002). "Moisture content of a piece of sawn timber, Part 1: Determination by oven dry method,” Comité Européen de Normalization, Brussels, Belgium.

CEN EN 14229 (2010). "Structural Timber – Wood poles for overhead lines," Comité Européen de Normalization, Brussels, Belgium.

Cerda, G., and Wolfe, R. W. (2003). "Bending strength of Chilean radiata pine poles," *Forest Products Journal* 53(4), 61-65.

Chui, Y., Barclay, D., and Cooper, P. (1999). "Evaluation of wood poles using a free vibration technique," *Journal of Testing and Evaluation* 27(3), 191-195. DOI: 10.1520/JTE12061J

Dackermann, U., Skinner, B., and Li, J. (2014). "Guided wave-based condition assessment of *in situ* timber utility poles using machine learning algorithms," *Structural Health Monitoring-an International Journal* 13(4), 374-388. DOI: 10.1177/1475921714521269

Gard, W. F., Vries, P. D., and Lanvin, J. D. (1998). "Methods to determine mechanical properties in order to grade roundwood," in: *World Conference on Timber Engineering*, Lausanne, Switzerland, pp. 634-641.

Green, D. W., Gorrnan, T. M., Evans, J. W., and Murphy, J. F. (2004). "Improved grading system for structural logs for log homes," *Forest Products Journal* 54(9), 52-62.

Green, D. W., Evans, J. W., Murphy, J. F., and Hatfield, C. A. (2005). *Mechanical Grading of 6-Inch-Diameter Lodgepole Pine Logs for the Travelers’ Rest and*

Rattlesnake Creek Bridges (FPL-RN-0297), U.S. Department of Agriculture, Forest Products Laboratory, Madison, WI.

Green, D. W., Gorman, T. M., Evans, J. W., and Murphy, J. F. (2006). "Mechanical grading of round timber beams," *Journal of Materials in Civil Engineering* 18(1), 1-10. DOI: 10.1061/(Asce)0899-1561(2006)18:1(1)

Green, D. W., Gorman, T. M., Evans, J. W., Murphy, J. F., and Hatfield, C. A. (2008). "Grading and properties of small-diameter Douglas-fir and ponderosa pine tapered logs," *Forest Products Journal* 58(11), 33-41.

LNEC (1997). "Madeira para construção- Pinho Bravo para estruturas - Ficha M2," Laboratório Nacional de Engenharia Civil, Portugal.

Mankowski, M., Hansen, E., and Morrell, J. (2002). "Wood pole purchasing, inspection, and maintenance: A survey of utility practices," *Forest Products Journal* 52(11/12), 43.

Marques, A. F. S., Martins, C. E. J., Dias, A. M. P. G., Costa, R. J. T., and Morgado, T. F. M. (2016). "Assessment of reuse potential of maritime pine utility poles for structural applications after removal from service," *BioResources* 11(4), 9340-9349. DOI: 10.15376/biores.11.4.9340-9349

Martins, C., and Dias, A. (2012). "Bending strength and stiffness of Portuguese maritime pine utility poles," *Forest Products Journal* 62(2), 114-120.

Miná, A. J. S., De Oliveira, F. G. R., Calil, C., Jr., Dias, A. A., and Sales, A. (2004). "Nondestructive evaluation of logs using ultrasonic technique," *Scientia Forestalis/Forest Sciences*(65), 188-196 (*in Portuguese*).

Morgado, T. F. M., Machado, J. S., Dias, A. M. P. G., Cruz, H., and Rodrigues, J. N. A. (2010). "Grading and testing of maritime pine roundwood," in: *World Conference on Timber Engineering*, Trento, Italy.

Phillips, G. E., Bodig, J. and Goodman, J. R. (1985). “Background and southern pine data,” *Wood Pole Properties*, Vol. 1, Research Institute of Colorado, Fort Collins, Colorado. (http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=EL-4109-V1)

Prieto, E. H., Seco, J. I. F. -G., Barra, M. R. D., and Pérez, R. M. (2007). "Aplicación de los ultrasonidos a la evaluación de las propiedades mecánicas de la madera en rollo de pequeño diámetro," *Informes de la Construcción* 59(506), 87-95. DOI: 10.3989/ic.2007.v59.i506.511

Rodrigues, J., and Vries, P. D. (2010). "Visual and strength grading of dutch larch and portuguese maritime pine small diameter roundwood timber," in: *COST Action E55-Modelling of the Performance of Timber Structures*, Portugal.

Sandoz, J. L. (1991). "Form and treatment effects on conical roundwood tested in bending," *Wood Science and Technology* 25(3), 203-214. DOI: 10.1007/bf00223471

Torran, E. A., Sosa, Z. M. A., Cotrina, A. D., and Piter, J. C. (2009). "Bending strength and stiffness of poles of Argentinean *Eucalyptus grandis*," *Maderas-Ciencia Y Tecnologia*, 11(1), 71-84. DOI: 10.4067/s0718-221x2009000100006

Tsang, K. M., and Chan, W. L. (2011). "Non-destructive stiffness detection of utility wooden poles using wireless MEMS sensor," *Measurement* 44(6), 1201-1207. DOI: 10.1016/j.measurement.2011.03.025

Vries, P. D., and Gard, W. F. (1998). "The development of a strength grading system for small diameter roundwood," *HERON* 43(4).

Wang, X., Ross, R. J., Mattson, J. A., Erickson, J. R., Forsman, J. W., Geske, E. A., and Wehr, M. A. (2002). "Nondestructive evaluation techniques for assessing modulus of elasticity and stifness of small-diameter logs," *Forest Products Journal* 52(2), 79.

Wood, A., Reddy, D., and Koganti, R. (2008). “The environmental impact of utility poles – Final paper,” ENGS 171, (https://engineering.dartmouth.edu/~d30345d/courses/engs171/UtilityPoles.pdf)

Article submitted: Oct. 25, 2016; Peer review completed: Dec. 12, 2016; Revised version received and accepted: Jan. 18, 2017; Published: February 2, 2017.
DOI: 10.15376/biores.12.2.2269-2283