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The influence of size in predicting the elastic modulus of Populus x euramericana timber using vibration techniques

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ABSTRACT: Non-destructive techniques based on the frequency of the longitudinal vibration are useful for predicting mechanical properties of sawn timber. The combination of wave velocity, calculated from frequency, and density give dynamic modulus of elasticity (MOE_{din}), which is used for grading timber. However, beam size has an influence over measurements of the resonance frequency. Therefore, the influence of different sizes on frequency must be studied for improving this technique.

322 beams of *Populus x euramericana* with typical standard sizes of structural sawn timber – 150 x 50; 150 x 80 and 200 x 100 mm-- were evaluated. First, frequency was acquired by a non-destructive test carried out with the Portable Lumber Grader (PLG) device manufactured by Fakopp Enterprise. Then, bending tests according UNE-EN-408:2004 were done in order to calculate static modulus of elasticity. Finally, destructive and non-destructive values were analyzed with linear regression for each size.

It was noted that larger beam sizes produced lower resonance frequencies. Therefore, the device should take into account the beam size. As a result, coefficients were estimated in order to get accurate predictions from MOE_{din}.

1 INTRODUCTION

The widespread cultivation of poplar is due to its fast growth and adaptability to different soil and climatic conditions, which is why poplar cultivation is increasing throughout Europe. The area occupied by plantations of poplars in Spain exceeds approximately 135,710 hectares, 50% are located in the Duero basin and 25% in the Ebro basin. The pieces tested for this work are from plantations of these two basins. In Castilla y Leon 87,600 are cultivated and it is the number one Spanish region in terms of poplar wood production. In 2006 345,408 m^3 of wood were cut representing 62% of national total (M.A.P.A. 2008). Currently poplar wood, although applicable to many different uses, is limited to non-structural applications due to the lack of a classification standard for its species. While the UNE 56544:1997 included the poplar along with conifers, as initially their elasto-mechanic values are significantly like them, in the following versions of the standard this tree species was excluded.

Poplar timber is no stranger to structural applications. Even today we find good evidence of its use for centuries, one clear example being its use in the Alhambra in Granada. However, it was in the countryside, close to meadows and riverbanks, where the wood was most used. Today, aside from its use in some structural elements for family housing, restoration work is also being carried out with this wood, especially in Italy ("Sala delle feste" - Castello del Valentino - Torino, XVIII, "Teatro Verdi -- Pisa, XIX, etc.) (Castro et al 2007) where the use of poplar was common from the seventeenth to nineteenth centuries because of its low material density, its good dimensional stability and, ultimately, its abundance near populated areas. In the last decade the behavior of poplar has been studied in new structural products such as LVL (Castro et al 2003, 2004 and 2008), the OSB (Zhou D. 1990) and, on a national level, there is a company that sells LSL made of poplar wood. The updated characterization of poplar wood can ensure the increased use of this species for structural purposes.

On the other hand, the development of wave measurements of wood dates back to the middle of last century. In the early eighties many scientific articles related to the topics discussed by Castro (2003, 2004), Sandoz (2000) and Earl (2007) appear. The application of induced vibrations for classification of wood began to be studied since the last century: Karsulovic and Leon (1994) analyzed the acoustic impedance of knotty wood, while other studies have focused on the study of the strength properties of wood and its variability using acoustic methods (Divos et al 2000, 2002, Pellerin et al 2002). There have been many articles published in the last decade on structural timber related: Brancheriau and Bailleres (2003), Arriaga (2005), Brancheriau (2006), Carballo (2008) and Married (2008) among many others.

Due to the transmission velocity and vibration frequency varies with the structure of the material, the method of inducing vibrations should be evaluated and developed for each species of wood before being implemented. Therefore one aim of this study is to analyze the applicability of prediction models for the mechanical quality of the *Populus x euramericana* I-214 structural timber based on the above-mentioned non-destructive technique.

2 MATERIAL AND METHODS

2.1 Test Specimens

The material being studied are 322 pieces from two batches of 18-year-old *Populus x euramericana* I-214 poplars which had been exposed to very few silvicultural treatments, namely, only two shape prunings. The characteristics of the batches are shown in Table 1. The batches analyzed are from poplar farms in the province of Palencia and were processed into lumber at a sawmill in Cervera de Pisuerga.

Table 1. Size and origin of the two batches analyzed.

Batches	Nº of pieces	Dimensions (mm)
1	130	150 x 50 x 3000
2	112	150 x 80 x 3000
3	80	200 x 100 x 4000

2.2 Clasification and visual inspection of the material

All pieces were inspected visually according to Spanish standard UNE 56544:1997, which included the poplar, and the French standard NF B52-001: 2007. Measurements were taken of the knots on the face and edges of each piece in order to determine the following variables:

- dc: Relative diameter of the largest knot on the face by % (widest diameter on the face divided by the width of the piece).
- dh: Relative diameter of the largest knot on the edge by % (widest diameter on the edge divided by the thickness of the piece).
- Aa: width of the rings according to the UNE 56544 standard.

2.3 Tests by vibration techniques

Tests carried out by vibration techniques with the Portable Lumber Grader (PLG of Fakopp) are based on measuring the resonance frequency of longitudinal vibration produced by the impact at one end of the piece, which crosses in its entirety. This vibration is affected by the content and position of knots, piece size, etc., within the specimen being studied. The way to produce vibration in the timber is to hit it at one end with a hammer while a microphone picks up the signal on the other. After passing through an amplifier, the signal is processed by computer indicating the main frequency of vibration, velocity, dynamic and strength classification according to the EN 338:1999 standard.

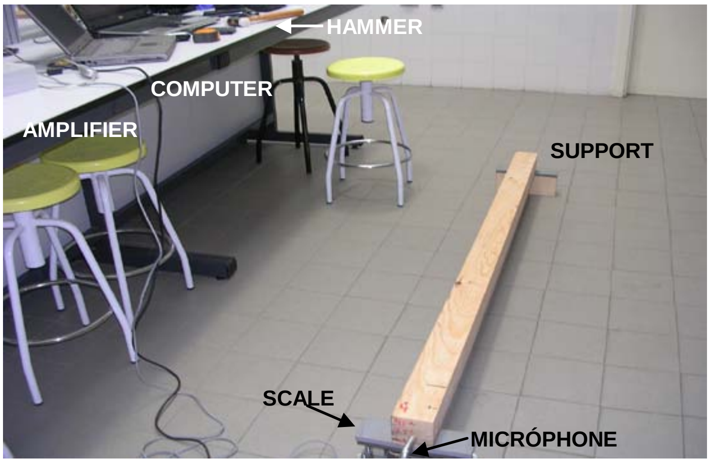


Figure 1.Outline of the PLG test.

The computer software determines the Dynamic modulus of elasticity through the following equation:

$$E_{dyn} = 0.92.\ \rho.\ (2.\ L.\ f_i)^2.\ (1 + \Delta H/50) \quad (1)$$

Where: 0,92 is an experimental coefficient defined by the computer software.

Therefore the objective of the analysis should be to test its effectiveness in different squared timber of Populus wood, ρ is the density, L is the length, fi is the frequency of longitudinal vibration and ΔH is the difference in moisture content compared to 12%. The software allows you to select some of the variables that influence the vibration wave, so much the environmental factors as the characteristics of the wood. After introducing all the variables and hitting the piece with a hammer, the classification appears on the screen followed by the detailed information obtained in the test such as: frequency, velocity, wave spectrum, elastic modulus, density, dimensions introduced and wood strength classification.

2.4 Mechanical tests according to the UNE- EN 408 standard

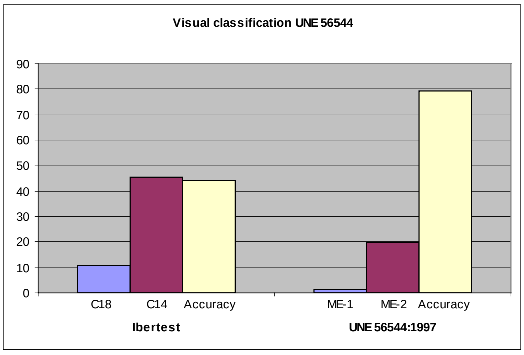
The bending tests were carried out according to the UNE-EN 408:2004 standard, with the universal testing machine IBERTEST, model ELIB-100W equipped with three load cells of 5, 50 and 100 kN. Under that standard, for determining the overall elastic modulus in edge bending (MOEGTO), the extensometer is placed on the edge of the piece to be tested. The rest of the machine's operating variables for the test were selected depending on the edge of the piece to be tested, using an appropriate velocity so that the test can be conducted in accordance to the standard set listed above. Once the load and edge deformation are recorded, the extensometer is removed from the edge and the MOE is calculated. Next, the rupture test is loaded and performed resulting in a modulus of rupture or MOR score. The results of bending tests were corrected to adjust them to a moisture content of 12% according to the UNE-EN 384 standard.

After carrying out all previous tests, it is necessary to remove a 10 cm long specimen from each piece of equal width and thickness as the piece, free of defects and near the rupture zone. With these specimens the density is determined according to the UNE-EN 408:2004 standard.

The statistical analysis was performed using the STATGRAPHICS Plus 5.1 program. In the different statistical analyses the variable normality hypothesis and the independence of the residuals were checked.

3. RESULTS AND DISCUSION

Applying the criteria of visual classification of the Spanish standard UNE 56544, the percentage of accuracy is 43%. This is because 46% of the timber is undervalued in order to define C14, as in most of the cases, and a few C18 as rejection pieces as shown in Figure 2.



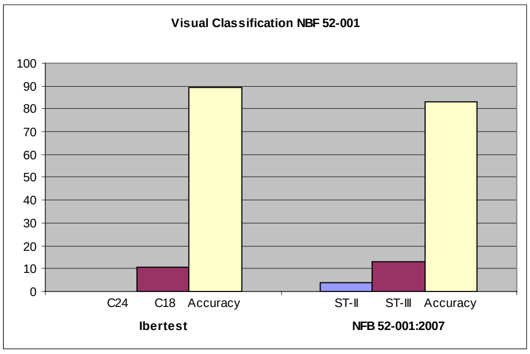


Figure 2 and 3. Comparative between the real classification of the timber and the UNE 56544 and NBF 52-100 standards.

However, the French visual classification standard achieves a high percentage of accuracy by 73% due to the fact that this standard classifies pieces below the C18 class as rejection pieces and 90% of the machine- tested pieces within the test batch yielded values lower than those defined in the C18 strength class as was shown in Graph 2.

Table 2 shows the correction coefficients "a" proposed for each of the sections of the pieces studied and the difference in frequency values obtained. Additionally, the difference between dynamic modulus of elasticity provided by the PLG (Edyn) and the result obtained using the correction factor "a" (MOEplg) are also noted. As shown in the table, according to the classification criteria of PLG two of the three batches have a greater dynamic modulus of elasticity than the results of given by the machine if using a coefficient of 0.92. However using an experimental coefficient of 0,76 for Batch 1 (squared timber 150 x 50 mm) and 0.85 for Batch 2 (squared timber 150 x 80 mm), the dynamic modulus will become almost equal to that obtained in bending tests which is consistent with previous research (Casado et al. 2009, Carballo et al 2008).

Table 2. Values of the coefficient of corrección “a” according to squared timber

Squared Timber	Frequency	E_{dyn}	Coef “a”	MOE_{plg}
150 x 50 x 3000	775.31	9528.84	0.76	7871.65
150 x 80 x 3000	765.57	8393.92	0.85	7755.25
100 x 200 x 4000	574.16	7699.41	0.92	7699.41

As shown in Table 3 the three batches are very similar in mechanical properties with average density and bending strength values similar to those obtained previously by other authors (Gutierrez 2001, Hernández 1998, Caves 2002, Casado et al 2009). The low values of elastic modulus significantly limit its application for structural use, as the three batches would be classified under strength class C14 as defined in the EN 338 standard. Similar results have been achieved with laminated wood joists made of I-214 (Castro 2007). Moreover, the resulting Elastic Modulus is similar to some structural products such as LSL (Lignum strand), by Tabsal, using poplar chips to make 50 mm-thick structural joists and LVL, made from 25 x 25 mm sections of Populus sp.

Table 3. Descriptive statistics of the PLG and bending test results according to the EN 408:2004 standard

Variables			Nº data	Mean	Coef. varia. (%)
PLG Variables	Density (k/m^3)	Batch 1	123	435.5	13.5
		Batch 2	111	403.3	11.9
		Batch 3	80	384.99	12.65
	Frequency (Hz)	Batch 1	123	775.3	5.5
		Batch 2	111	765.6	6.1
		Batch 3	80	574.16	5.18
	Velocity (m/s)	Batch 1	123	4805	5.1
		Batch 2	111	4761.2	6.1
		Batch 3	80	4697.43	4.76
	E_{dyn} (N/mm^2)	Batch 1	123	9528.84	17.58
		Batch 2	111	8393.92	10.81
		Batch 3	80	7699.41	15.04
	MOE_{PLG} (N/mm^2)	Batch 1	123	7755.25	10.8
		Batch 2	111	7871.6	17.6
		Batch 3	80	7699.41	15.04
EN 408	MOE (N/mm^2)	Batch 1	123	7052.8	18.2
		Batch 2	111	7431.8	14.1
		Batch 3	80	7658.64	29.22
	MOR_C (N/mm^2) (Characteristic value)*	Batch 1	123	39.9 (18.2)*	321.2
		Batch 2	111	37.0 (23.6)*	19.5
		Batch 3	80	34.59 (21.74)	21.74
Density standard EN 408	Densidad (k/m^3) (Characteristic value)*	Batch 1	123	355.2 (308.8)*	11.4
		Batch 2	111	334.3 (304.09)*	6.14
		Batch 3	80	373.67 (317.83)	12.59
Humidity Standard EN 13183	Humity (%)	Batch 1	123	9.73	7.1
		Batch 2	111	12.8	14.5
		Batch 3	80	12.43	37.01
Growth Rings width	Growth Rings width (mm)	Batch 1	123	11.38	25.74
		Batch 2	111	11.68	16.23
		Batch 3	80	11.3	17.31

Regression analysis techniques were applied with linear models to find the mathematical relationships between the variables identified through the tests. Three batches were studied separately since the statistical analysis indicated that there were significant differences according to the dynamic modulus of elasticity. As far as independent variables, those that were selected had a significant effect in predicting the elastic modulus obtained through the bending tests according to the EN 408 standard. The most significant models obtained for predicting the elastic modulus by bending are shown in Table 4. In all cases, the prediction is considered most accurate when considering the relative diameters of the largest knot on the face and edge and the width of the rings.

Table 4. Summary of the regressios recorded from each of the Populus x euramericana specimens from both batches

Batch of 150 x 50 x 3000 mm		
Dependent Variable	Independent Variables	R^2ajus (%)
MOE	E_{dyn}	47.17
	MOE_{plg}	47.60
	MOE_{plg} + DNc + DNh	52.45
	MOE_{plg} + DNc + DNh + Aa	52.54
Batch of 150 x 80 x 3000 cm		
Dependent Variable	Independent Variables	R^2ajus (%)
MOE	E_{dyn}	49.25
	MOE_{plg}	49.25
	MOE_{plg} + DNc + DNh	53.25
	MOE_{plg} + DNc + DNh + Aa	61.04
Batch of 200 x 100 x 4000 cm		
Dependent Variable	Independent Variables	R^2ajus (%)
MOE	E_{dyn}	76.97
	MOE_{plg}	76.97
	MOE_{plg} + DNc + DNh	76.78
	MOE_{plg} + DNc + DNh + Aa	76.87

E_{dyn}: Estimated dynamic modulus of elasticity from the PLG with a 0.92 coefficient.
MOE_{plg}: Dynamic modulus of elasticity from the PLG applying the section "a" coefficient.
DNc: Relative diameter of the largest knot on the face expressed by unit.
DNh: Relative diameter of the largest knot on the edge expressed by unit.
Aa: Average width of the first 5 growth rings (cm)

3 CONCLUSIONS

The detailed analysis of each piece shows a 43% rate of accuracy with the Spanish standard, while it overestimates 11% and underestimates 46% of the specimens. The French classification standard, given that it tends to assign higher strength values compared to the Spanish standard and due to the large number of rejections within the analyzed batches, raises the percentage of correct answers to 74%, while overestimating 16% and underestimating 10% of pieces.

The technique of acoustic transmission through the use of PLG, as a predictor technique for the elastic behavior of timber requires calibration for pieces of *Populus x euramericana* I-214 with dimensions smaller than 150 x 50 x 3000 mm and larger than 200 x 100 x 4000 mm. An overestimation of the poplar wood quality has been proven to occur for squared timber measuring between 150 x 50 and 150 x 80 mm, by which a rate lower than the software default of 0.92 should be applied. Exceptional linear regression models of the elastic modulus with correlation coefficients between 53% and 77% have been achieved as a result of dynamic modulus of elasticity , the relative diameter of knots on the face and edge and the thickness of growth rings.

The mechanical properties of tested batches indicate that the *Populus x euramericana* has an acceptable bending strength, but its elastic modulus is low. Therefore, its application as structural timber would be possible in strength classes below the EN 338: C14 and C16 standards.

4 ACKNOWLEDGEMENTS

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