In-Situ Assessment of Structural Timber Density Using Non-Destructive and Semi-Destructive Testing

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Both non-destructive and semi-destructive tests can potentially be very efficient methods for the assessment of structural timber density. This paper describes an investigation into the suitability of three techniques: core drilling, probing, and screw withdrawal. It presents the results after testing 150 pieces of large cross-section (80 mm x 120 mm) structural timber of radiata pine (*Pinus radiata* D. Don.) from a Spanish source. A strong correlation was found between specimen density and core drilling. Meanwhile, there was also a meaningful correlation with the screw withdrawal, and an acceptable correlation with probing. Even though differences were observed in their predictive capacity, none of these procedures should be rejected as a way of estimating density, as each has its own respective advantages and limitations.

Keywords: Core drilling; Density; In-situ assessment; Probing; Screw withdrawal; Timber

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INTRODUCTION

During the assessment of existing timber structures, diagnostic examination of the structural members and connections is generally necessary. The evaluation of the mechanical properties of the structural members often requires appropriate non-destructive testing (NDT), as well as semi-destructive testing (SDT) techniques. Several NDT and SDT techniques were shown to potentially be very efficient methods decades ago (Ross and Pellerin 1994).

Although it is relatively easy to conduct a non-destructive test, it is important to note that several non-destructive parameters are still not well known. Accordingly, there is still a gap between laboratory tests and the *in situ* results of timber inspection. Furthermore, many parameters influence the testing results, and timber inspectors may feel doubts and uncertainty when deciding which parameters to use. Experience and simple tools continue to be the main aids in the decision process. The relationships between penetration resistance, or screw withdrawal force, and density or other properties have been analyzed with satisfactory results (Rammer and Zelinka 2004; Walter *et al.* 2005; Kruglowa 2012; Ponneth *et al.* 2014).

Another uncertain topic in most ancient timber structures is related to the material itself. Members were not graded following modern criteria, and they vary greatly in size and regularity. *In situ* results, therefore, usually differ significantly from the "scientific" results.

In practice, the visual grading of existing timber pieces is difficult, because typically there is no visual access to all surfaces of the piece, or the piece may be dirty or stained. It is evident that complementary, non-destructive techniques should be applied in grading procedures.

In Spain, because of its vast and rich timber construction heritage, increased research efforts have been made in recent years to calibrate equipment and techniques, as well as to develop grading procedures for species in existing structures. Some doctoral theses have been presented as a result of these studies (Esteban 2003; Íñiguez 2007), and research work has also been conducted as well (Arriaga *et al.* 2005; Íñiguez *et al.* 2008; Arriaga *et al.* 2009; 2012; 2014).

Density is a very good quality indicator of structural properties, and when used in combination with non-destructive parameters, such as stress wave velocity, it increases the predictive value considerably.

The primary goal of this research is to contribute to the assessment of the mechanical properties of structural coniferous timber members by means of density estimation, as well as to analyze predictive values and examine some commercial portable equipment.

EXPERIMENTAL

Materials

The test material was composed of 150 structural size specimens of sawn radiata pine (*Pinus radiata* D. Don.) timber, 80 mm x 120 mm in cross section and 2,500 mm in length, from Catalonia, Spain. Two contiguous slices (50 mm and 150 mm in length) of the whole cross-section were extracted from these 150 structural specimens. One was used for moisture content (MC) determination (oven dry method) and the other for semi-destructive measurements for density estimation (core drilling, probing, and screw withdrawal).

Methods

Moisture content

The moisture content (MC) was measured in the samples using electrical resistance equipment, following the procedure defined in European Standard EN 13183-2 (2002). The mean MC of the specimens was 11.1%, with a coefficient of variation of 12.5%.

Additionally, MC was also measured in the whole cross-sectional slices, in accordance with procedure CEN EN 13183-1 (2002) standard (oven dry method), as specified in the CEN EN 408 (2010) standard. The mean MC of the specimens (whole cross-section slice) was 10.5%, with a coefficient of variation of 6.5%.

Density

The density of the whole pieces was measured by dividing the mass by the volume (global density). The slice density was obtained by dividing the mass by the volume of the 50 mm length slice (local density), according to the CEN EN 408 (2010) standard. The global and local densities were adjusted to a 12% reference MC, according to the EN 384 (2010) standard, with a 0.5% decrease in density for each 1% decrease in MC.

Core drilling

Four cylindrical cores, with two different diameters, were extracted from each slice of the whole cross-section by means of an electric drill with a hollow bit.

Two cores, with an inner nominal diameter of 16 mm and an outer diameter of 22 mm, were extracted. One core was tangential and the other radial; these were taken together with two more cylindrical cores, with an inner nominal diameter of 10 mm and an outer diameter of 14 mm, also tangential and radial. For each specimen, the tangential and radial directions were selected according to the cut pattern of the cross-section (drilling on the face or in the edge of the piece; Fig. 1). The average length of the cylindrical cores was 36 mm.

The extraction of cores leave holes of 22 or 14 mm, which are comparable to small knots in timber members, but are not negligible. In practical applications, extraction should occur in areas of the piece that are not subjected to high stresses. Voids left by drilling should be plugged to prevent insect penetration, to recover some of the lost compressive strength, and to preserve the appearance of the member.

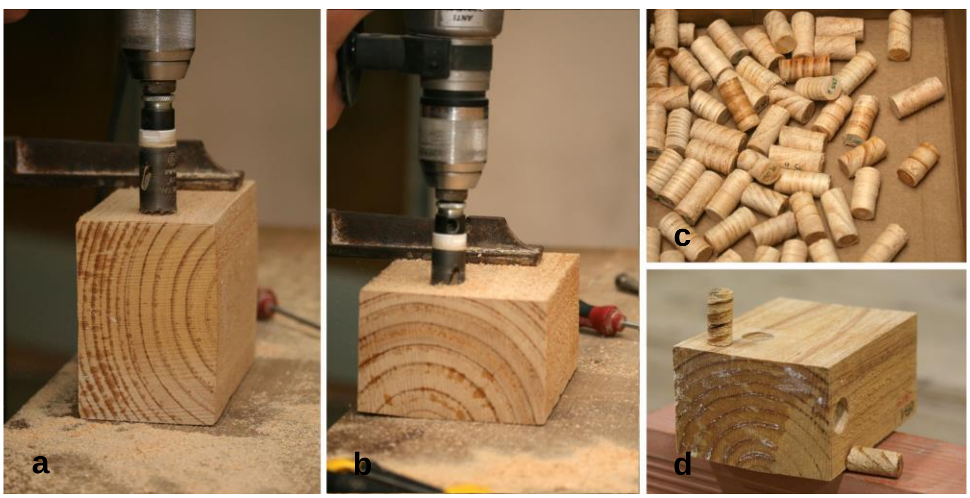

Fig. 1. Drilling for tangential (a) and radial (b) cores. Resulting cores are shown in (c) and (d).

The cores were conditioned at 20 ± 2 ºC temperature and 65 ± 5% relative humidity, until constant mass was achieved. The density was obtained by dividing the conditioned mass of the cores by their volume. Finally, the MC was obtained using the oven dry method, yielding an average MC of 9.62%, with a coefficient of variation of 8% for the 16 mm diameter cores, and 8.99% MC and 6% CoV for the 10-mm-diameter cylinders.

Probing

In this research, the Pilodyn 6J Forest device (Proceq, Switzerland) was used, as shown in Fig. 2. The device measures the penetration depth of a 2.5-mm-diameter steel needle, which is shot into the wood with a constant energy (6 J). The penetration depth is used to evaluate the level of damage to the timber, which depends on its surface hardness and density (Hoffmeyer 1978; Bobadilla *et al.* 2007). Other research studies have examined the relationship between penetration depth and wood density. The correlation coefficient typically varied from 0.74 to 0.92, and depended on the number of measurements and species (Görlacher 1987; Kasal and Anthony 2004; Kasal and Tannert 2011).

Fig. 2. Pilodyn 6J Forest device (Proceq, Switzerland)

The Pilodyn 6J Forest device was designed to estimate the density and hardness of sawn timber and standing trees. It is considered a non-destructive method because it only makes a small hole, 2.5 mm in diameter, with a variable depth of 0 to 40 mm, depending on the penetration resistance of the timber. This hole causes no significant damage to timber or living plants.

In the same manner as the core drilling tests, two readings were recorded for each test specimen, one radial and one tangential.

Screw withdrawal

The screw withdrawal non-destructive value is measured using a test device designed specifically to record the maximum load required to extract a screw previously inserted into the timber. One assumes that the higher the withdrawal force needed to extract the screw, the higher the density of the timber.

Fig. 3. Screw withdrawal force meter (Fakopp, Hungary)

The screw withdrawal test was performed using the portable Screw Withdrawal Resistance Meter (SWRM), designed by Fakopp (Hungary). The meter consists of the following components (Fig. 3): the crank handle, loading cell to record the maximum value of withdrawal force, and screw support.

The type of screw used in the SWRM was a Heco-Fix plus with a Spax (PZD) type head, which was yellow zinc plated. A 4-mm-diameter, 70-mm-long screw, with a penetration depth of 20 mm, was selected for the purpose of this study. The average withdrawal force of this screw is approximately half the maximum load of the equipment, which is optimum for measuring.

The effect of pre-drilling was also evaluated prior to testing. The researchers came to the conclusion that the effect was negligible. There was no significant statistical difference between the withdrawal force needed for screws with or without pre-drilling, at a 95% level of confidence. The statistical analysis used to discriminate between means (one-way analysis of variance (ANOVA)) was the Fisher's Least Significant Difference (LSD) test, performed using STATGRAPHICS Centurion XVI. v.16.1.18 software. Thus, the screws were used without pre-drilling.

For each test specimen, in accordance with the core drilling and probing tests, two readings were recorded, one radial and the other tangential.

RESULTS AND DISCUSSION

The results for global and local density are shown in Table 1.

Table 1. Global and Local Density Results

	Measurement	N	Mean	Standard deviation	CoV (%)
Density ($kg \cdot m^{-3}$)	Global	150	515	57.4	11.1
	Local	150	501	58.2	11.6

As can be seen in the table, the local density was slightly lower than global density. The density difference was probably because the slice for local density determination was obtained from a defect-free part of the piece. Knots, which are a common defect, have higher density.

Both variables exhibited normal distributions, with slight differences between then, as shown in Fig. 4.

In practical applications, such as assessing the mechanical properties of structural timber, global density is preferred because it is easier to obtain under practical industrial conditions. Hence, global density was used in this work for further analysis.

As explained above, two non-destructive and semi-destructive readings were taken for each method and specimen, one radial and the other tangential. The probability distributions of all values were normal in shape, and statistical analyses did not show any evidence of the influence of reading direction for any method. For example, Fig. 5 shows the probability distributions of 16-mm-diameter radial and tangential cylindrical core drilled specimen density.

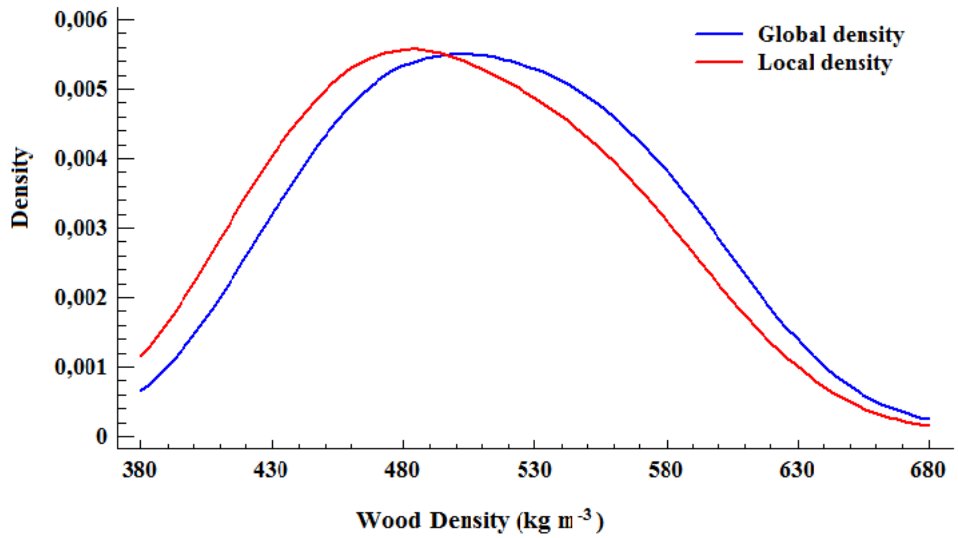

Fig. 4. Probability distributions of global and local densities (kg·m^{-3})

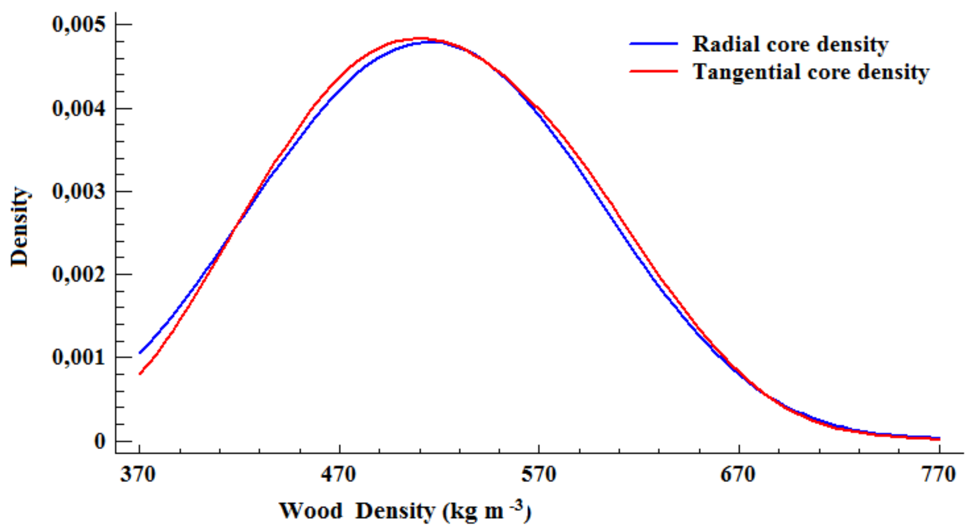

Fig. 5. Probability distributions of density for 16-mm-diameter radial and tangential cylindrical core drilled specimens (kg·m^{-3})

Thus, the arithmetical mean for the radial and tangential readings from each method will, therefore, be used in further analyses as the reference values. The results of the non-destructive and semi-destructive measurements are summarized in Table 2.

The 16-mm-diameter cylindrical core drilled specimens showed a density value very close to that of the global density, and had the same coefficient of variation as well. The 10-mm cylindrical specimens showed a density 8% greater than the 16-mm-diameter cylinders, which is probably due to the greater effect of heating and hardening of the specimen surface during drilling (which has a greater effect as smaller is the specimen`s volume). The CoV is lower in core drilling (about 12%) than it is in probing and screw withdrawal (16.2% and 19.6%, respectively).

Table 2. Summary of Non- and Semi-Destructive Measurements

Measurement			N	Mean	Standard deviation	CoV (%)
Core drilling (kg·m^{-3})	16 mm	Radial	150	515	67.0	13.0
		Tangential	150	519	63.0	12.1
		Mean	150	517	62.1	12.0
	10 mm	Radial	150	556	68.8	12.4
		Tangential	150	560	70.2	12.5
		Mean	150	558	65.7	11.8
Probing (mm)		Radial	150	12.2	1.93	15.8
		Tangential	150	12.8	2.67	20.8
		Mean	150	12.5	2.02	16.2
Screw withdrawal (kN)		Radial	150	2.10	0.44	20.9
		Tangential	150	2.06	0.48	23.4
		Mean	150	2.08	0.41	19.6

Analysis of the density values determined by the cores (at a 95% confidence level) showed statistically significant differences for the global density of the 10-mm core. Figure 6 shows the means plot of ANOVA for the global density and the 16 and 10 core densities as well, showing statistically significant differences for the 10-mm cores.

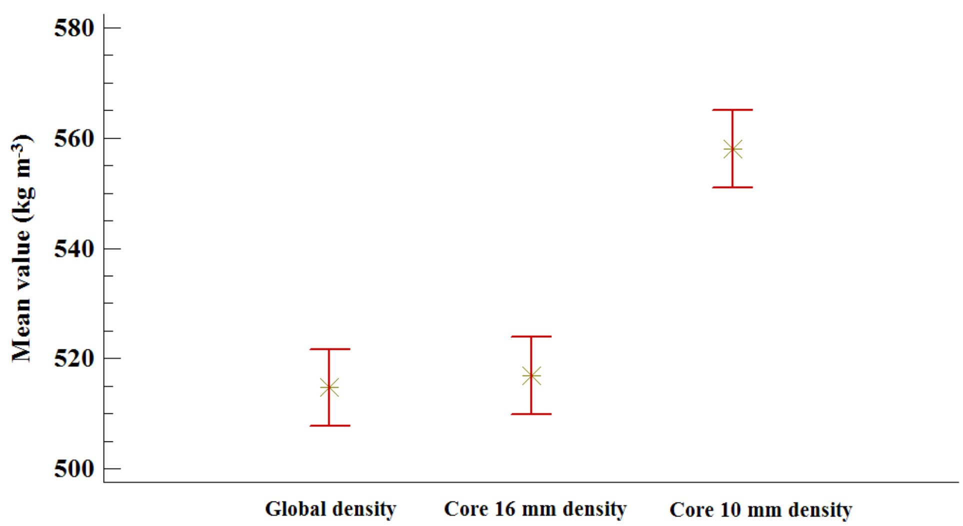

Fig. 6. Means plot of core density values (kg·m^{-3})

Linear regression models, comparing global densities for non-destructive and semi-destructive variables, are summarized in Table 3. The validity of assumptions regarding normality distribution, linearity, homoscedasticity, and independence of the models was analyzed.

As expected, the best prediction models were obtained with cylindrical cores (r^2 = 0.80), and there were no differences in the predictions whether 10- or 16-mm-diameter cores were used. The poorest correlation was obtained during depth penetration (r^2 = 0.30), but this procedure is simple and easy to use. Finally, the screw withdrawal procedure gave intermediate results (r^2 = 0.57).

For example, Fig. 7 shows the linear regression model between the global density and the density of 16-mm-diameter cylindrical specimens.

Table 3. Linear Regression Models Comparing Global and Core Density, Penetration Depth (Probing), and Screw Withdrawal Force (Screw Withdrawal).

Method		r^2	Global density = A·x+B	
			A	B
Core drilled (kg·m^{-3})	16 mm	0.80	0.827	87
	10 mm	0.80	0.779	80
Probing (mm)		0.30	-15.52	709
Screw withdrawal (kN)		0.57	106.174	294

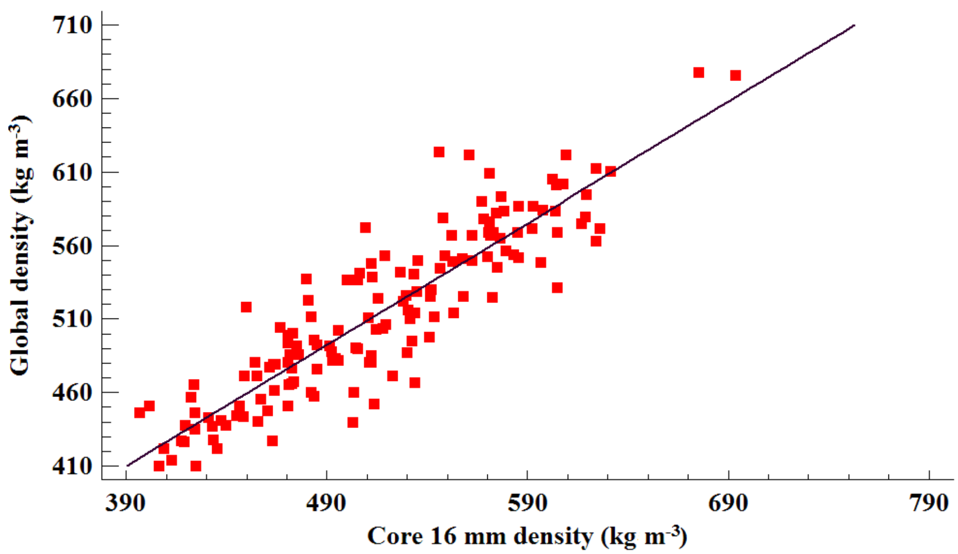

Fig. 7. Linear regression model: global density (kg·m^{-3}) *vs*. density of 16-mm-diameter cylindrical cores (kg·m^{-3})

CONCLUSIONS

1. There were only slight differences between the global and local densities of specimens, as their mean values were very similar. Therefore, depending on the procedure or method used, either density could be used as a reference value.
2. Statistical analysis showed no sign of the influence of reading direction (radial or tangential) in any of the non-destructive or semi-destructive methods. Therefore, the average value of both readings was used. Accordingly, it is proposed that practical applications do not need to take into account test reading direction.
3. The relationship between specimen density and the non-destructive and semi-destructive methods can be accurately established by means of linear regression analysis. The strongest relationship was obtained during core drilling (r^2 = 0.80). No statistical differences in the prediction were found between 10- and 16-mm drilled cores. Therefore, for practical applications, the authors propose using 10 mm diameter cores, as they cause less damage to pieces.

4. Overall, screw withdrawal has less predictive capacity, but it is still quite remarkable (r^2 = 0.57). Although probing gave poor results in terms of the determination coefficient (r^2 = 0.30), this technique should not be undervalued. This is because it is simple and quick to apply, and is very useful as a first approach to the question of in-situ assessment.

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