NONDESTRUCTIVE TESTING USED ON TIMBER IN SPAIN: A LITERATURE REVIEW

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ABSTRACT

Nondestructive testing (NDT) includes several highly efficient techniques for the estimation of the physical and mechanical properties of structural timber. Apart from visual grading, scientific research using Nondestructive testing on timber has been used in Spain since the 1990s. Nondestructive testing can be used for two different purposes: timber grading and the assessment of existing timber structures. The most common devices used in Spain are portable ones based on ultrasound, stress waves, vibration and probing techniques. Many statistical linear models for estimating the mechanical properties of new sawn timber and timber from existing structures have been proposed. Furthermore, several factors that affect Nondestructive testing measurements have been studied (moisture content, temperature, specimen dimensions, sensors position-grain angle, among others) and adjustment factors have also been proposed. Species have been characterized for visual grading standards from the 1980s to date. The large number of research works using different species, devices and procedures shows the need of homogenization and standardization of Nondestructive testing use. This paper presents a review of research works using Nondestructive testing on timber in Spain, in order to add to knowledge, elucidate the concepts to unify Nondestructive testing used and promote research group collaboration in the near future.

Keywords: Acoustic techniques, nondestructive testing, stress waves, structural timber, ultrasound waves, vibration techniques.

INTRODUCTION

Scientific research into the determination of timber mechanical properties began in Spain in the 1960s, in the INIA Structural Timber Laboratory (Figure 1a). Arriaga et al. (1992) published the first scientific research work using Nondestructive Testing (NDT) on timber in Spain. The Steinkamp BP-V (BPV), a portable ultrasound device with exponential tip 50 kHz sensors, was used on 34 pieces from existing structures to estimate their mechanical properties with determination coefficients ($R^2$) between the modulus of elasticity (MOE) and the dynamic modulus of elasticity (Edyn) of 37 % (Figure 1b). Martinez (1992) used the same NDT device on structural maritime pine timber (40 mm x 100 mm and 50 mm x 150 mm) in his PhD thesis. Bucur et al. (1993) presented the first SCI JCR publication in Spain of NDT on timber using the BPV and X-ray for fungal decay detection in pine and European beech. Several other works were presented with a focus on detecting decay and defects using ultrasound waves (Palaia et al. 1993, Galvañ et al. 1994, Martín 1994, Troya and Navarrete 1994). Rodríguez-Liñán and Rubio (1995) and Rubio (1997) estimated MOE and bending strength (MOR)
of new Scots pine timber, timber from existing structures and small clear specimens using the BPV with a $R^2$ from 36\% to 44\% for MOE and MOR, respectively. Pedras et al. (1997) estimated MOE from velocity, with a $R^2$ of 81\% in small clear sweet chestnut specimens. Palaia et al. (2000) proposed models for density ($p$) estimation from needle penetration resistance (NPR) depth using the Pilodyn with a $R^2$ of 80\% using small clear specimens of Scots, maritime and Caribbean pitch pine. Riesco (2001) used BPV velocity to estimate the MOE of small clear specimens of European oak with a 40\% $R^2$. At the end of the 1990s an automatic bending classification machine, the Cook Bolinders (SG-AF Tecmach Ltd., St. Albans, UK), arrived in the INIA Structural Timber Laboratory (Figure 1c). Hermoso (2001) reported the settings used to classify Spanish Scots pine with this machine, and Conde (2003) presented the settings for Salzmann pine. Furthermore, both doctoral theses also estimated structural timber MOE and MOR from ultrasound wave velocity using the Sylvatest (Syl) portable device combined with visual grading parameters.

**Acoustic techniques (ultrasound and stress waves)**

Esteban (2003) used BPV and Sylvatest Duo (SylDuo) measurements combined with visual parameters to estimate the mechanical properties of Scots and maritime pine from existing structures. Hermoso et al. (2003) compared grading results using the Syl and Cook Bolinders, obtaining a lower rejection percentage with the latter for Scots and Salzmann pine. Arriaga et al. (2006) reported a $R^2$ of 73\% when estimating MOE from SylDuo velocity in missanda. Capuz et al. (2007) estimated a C18 strength class based on in-situ SylDuo measurements in the timber structured historic building “Lonja de Mercaderes” in Valencia. Hermoso et al. (2007) studied Salzmann pine round small-diameter timber, estimating MOE from Edyn with a 68\% $R^2$. Íñiguez-González (2007) used ultrasound on large cross-section radiata, Scots and Salzmann pine timber (150 mm x 200 mm, 200 mm x 250 mm) to estimate their properties. Palaia et al. (2008) presented a procedure for the assessment of timber structures using several NDT techniques, testing them on Scots pine from existing structures. Basterra et al. (2009) evaluated historic buildings in “Chinchón Plaza Mayor” using ultrasound and probing techniques. Carballo et al. (2009a), Carballo et al. (2009b) presented a review of 30 years of NDT, together with an estimation of maritime pine MOE using the SylDuo and MicroSecond Timer (MST) velocity with a $R^2$ of 55\% and 70\% with the Edyn. In the case of MOR, a $R^2$ of 39\% was found when a knottiness parameter was included. Esteban et al. (2009) estimated MOE and MOR by stress waves and probing methods using the Íñiguez-González (2007) models, and assigned a strength class in the assessment of the Valsain sawmill historic building (Figure 1d). Atienza-Conejo (2012) used pulse-echo ultrasound to detect xylophage insect attack in timber ships. Casado et al. (2012) estimated the MOE of black poplar timber by combining SylDuo velocity and visual parameters with a $R^2$ of 68\%. Montón (2012) tested Catalonian radiata pine, estimating its properties with ultrasound and stress waves. Vega et al. (2012) estimated the mechanical properties of sweet chestnut using the Sylvatest Trio (SylTrio) and MST, obtaining a $R^2$ of 70\% using Edyn or velocity and density. However, MOR was estimated with a $R^2$ of 27\% even when a knottiness parameter was included. Merlo et al. (2014) used the IML Micro Hammer (IML MH) device (IML, Wiesloch, Germany) on standing maritime pine trees estimating the MOE of sawn boards from these trees with a $R^2$ of 55\%. Vázquez et al. (2015) used 13 polyhedral small clear specimens of sweet chestnut to determine Young’s moduli, shear moduli and Poisson’s ratios by ultrasound with 1 MHz sensors, finding a good correlation with MOE of structural timber. Vilches et al. (2015) assigned strength classes C14 and C18 to Scots pine beams from an existing structure by stress waves using the Íñiguez-González (2007) models. Abián and Segura (2016) estimated the residual capacity of fire-damaged Scots pine timber from existing structures using the ultrasound wave method. Llana (2016) used the USLab device with 45 kHz sensors to estimate MOE from Edyn with a $R^2$ of 90\%. Crespo et al. (2017) tested small clear specimens of southern blue gum with 1 MHz ultrasound sensors to obtain their elastic values. Morales-Conde and Machado (2017) used PUNDITplus (Proceq, Schwerzenbach, Switzerland) with 54 kHz sensors and MST on 30 clear wood pieces of maritime pine to estimate MOE from Edyn. Higher $R^2$ (91\%) combining MST measurements at different depths than using PUNDIT (71\%) was found. Hillig et al. (2018) used SylDuo, USLab and MST devices to study wood-polymer-composites in the Universidad Politécnica de Madrid Timber Laboratory. Osuna-Sequera et al. (2019a) studied several criteria to determine the cross-section in existing timber structures to estimate MOE from Edyn. Vega et al. (2019a) estimated MOE of 216 dry sweet chestnut small-diameter logs using MST velocity and Edyn with $R^2$ of 64\% and 67\%, respectively and a grading system was designed based on MST velocity.
Nondestructive testing used: Llana et al.

Figure 1: Spanish scientific timber research facts: a) INIA Structural Timber Laboratory in the 1960s and 1970s. b) Arriaga et al. (1992) ultrasound measurements. c) Cook Bolinders, INIA Structural Timber Laboratory. d) Valsaín sawmill historic building.

Vibration techniques

Arriaga et al. (2005a) published the first scientific research work done in Spain with vibration technique to grade 75 radiata pine specimens using the Portable Lumber Grader (PLG). Broto et al. (2007) tested 211 specimens of Scots pine using the Mechanical Timber Grader (MTG), finding that 73% of the specimens were undergraded and 7% were overgraded. Iñiguez-González (2007) applied the PLG to large cross-timber of radiata, Scots and Salzmann pine, obtaining similar R² for MOE estimation from vibration and ultrasound velocity. Santaclara et al. (2009) tested 200 sawn timber pieces of Douglas fir containing a large amount of juvenile wood using PLG, and they found a better R² in MOE estimation which combined velocity and knottiness parameters rather than velocity and density. Villanueva (2009) tested Spanish juniper round wood by longitudinal vibration, obtaining a R² of 43% when estimating MOE by combining Edyn and conicity parameters. Rojas et al. (2011) used a microphone to record the natural frequencies of veneer samples for species identification. Santaclara and Merlo (2011) used the Hitman Director HM200 (HM200) on 162 logs of maritime pine before testing sawn timber from them. A R² of 73% was reported when estimating sawn timber MOE from logs using the Edyn. Arriaga et al. (2012) published the preliminary grading settings for European standard EN 14081-2 (2010) of PLG for Spanish radiata, Scots and Salzmann pine, but were not implemented in the Spanish industry. Montero (2013) tested Scots pine sawn timber with several NDT devices, concluding that PLG results are the best mechanical property estimators. Vega (2013) compared sweet chestnut results from two different vibration devices, the PLG with a microphone and the HM200 with a contact accelerometer, finding better mechanical properties estimation with the PLG measurements. Arriaga et al. (2014) estimated radiata pine mechanical properties based on longitudinal and transversal vibration with similar accuracy. Llana (2016) used the PLG with a microphone and the MTG with a contact accelerometer to estimate MOE with a 91% R² and MOR at 70% using the Edyn, and found no significant differences between the results of both devices. Osuna-Sequera (2017) tested 11 m long large cross-section Salzmann pine beams from an 18th century timber structure using the PLG and estimating MOE using the Edyn with an 80% R². Not only restraint-free isolated specimens were analyzed using the vibration technique, as multiple contact accelerometers were also used to evaluate timber structures. Baño et al. (2011) studied resonance risk in Scots pine timber footbridges, while Castro-Triguero et al. (2017) evaluated a 125 m length timber footbridge and Arce-Blanco (2017) tested Salzmann pine plank timber arches. Currently, the first research experience on vibration testing of light frame timber floors in Spain is carried out by the Timber Structures and Wood Technology Research Group of the University of Valladolid, after developing their own accelerometers (Villacorta-Calvo et al. 2019). Furthermore, scientists from the previous research group patented a transversal vibration system using several microphone receptors for the evaluation of existing timber structures (Gutiérrez-Sánchez et al. 2019).
Probing techniques

Probing methods (needle and drill penetration resistance, screw and nail withdrawal resistance) are mainly used to estimate density in existing timber structures. Palaia et al. (2000) used the Pilodyn to estimate the density of small clear specimens of Scots, maritime and Caribbean pitch pine. Casado et al. (2005) predicted density using the Screw Withdrawal Resistance Meter (SWRM) on 39 Scots pine joists from an existing structure. Bobadilla et al. (2007) estimated density using the Pilodyn and SWRM on 395 large cross-section specimens of radiata, Scots and Salzmann pine with a R² of 35% and 49%, respectively. Íñiguez-González et al. (2010) proposed estimation density models for large cross-section radiata, Scots, Salzmann and maritime pine, finding a better R² with probing techniques than was the case with ultrasound waves. Montón (2012) introduced core drilling technique for density estimation in Spain, obtaining a higher R² than was the case with the Pilodyn or SWRM in radiata pine. Bobadilla et al. (2013) presented the definitive prototype of the RML Wood Extractor (GICM-UPM, Madrid, Spain) in a NDT wood conference in Madison, WI, USA. The device was designed to be coupled to a commercial drill to collect all of the chips produced during drilling inside a paper bag filter. Density is determined from the mass of chips and the volume of the hole. The UNE 41809 (2014) was published for use of the penetrometer in wood elements to diagnose existing buildings. Íñiguez-González et al. (2015a) compared density estimation by using the Pilodyn, SWRM and core drilling, obtaining the highest R² with the latter. Bobadilla et al. (2018) estimated density by core drilling technique on small clear specimens of 10 species with a R² of 98%. Llana et al. (2018a) presented a comparison between the Pilodyn, Wood Pecker, SWRM, core drill and RML WoodEx for density estimation of Norway spruce from an existing timber structure, obtaining a better R² with the core drill and RML WoodEx. The drilling resistance technique using Resistograph and IML Resi devices was used to evaluate timber structures (Capuz et al. 2007, Basterra et al. 2009, Touza 2009, Montoya-Morgui 2010, González-Sanz 2012, Lozano et al. 2013, Abián and Segura 2016) and also for density estimation (Mariño et al. 2002, Casado et al. 2005, Vilches and Correal 2009, Soto-Martínez 2010, Acuña et al. 2011, Morales-Conde et al. 2014, Camacho-Valero 2017).

Other NDT techniques

Neuronal networks using data from NDT were studied for timber grading (Mier 2001, García-Esteban et al. 2009, García-de-Ceca et al. 2013, García-Iruela et al. 2016, Villasante et al. 2019). Mariño et al. (2010) studied the influence of pith distance on velocity using acoustic tomography. Rodríguez-Abad et al. (2011) used ground-penetrating radar (GPR) on 22 maritime pine joists to estimate MC and Martínez-Sala et al. (2013) studied the differences between longitudinal and transversal GPR measurements. Morales-Conde et al. (2013) used infrared thermography (IRT) to detect MC differences. Oliver and Abián (2013) developed a sensor to monitor timber structures for termites using light emission and fungi risk by moisture content estimation. Sánchez-Beitia et al. (2015) presented the application of Hole-Drilling technique on small clear specimens of radiata pine for stress quantification, and Crespo-de-Antonio et al. (2016) used it to assess two existing timber structures. López et al. (2018) estimated wood density from the variation of surface temperature when specimens are cooled using IRT. Ruano et al. (2019) determined the ratio of juvenile wood to mature wood using near infrared-hyperspectral imaging.

Adjustment factors

The results of NDT are affected by several factors: moisture content (MC), temperature (T), specimen dimensions, sensor positioning and grain angle and timber-sensor coupling, to mention just a few. Íñiguez-González et al. (2015b) published a compilation of NDT adjustment factors from the national and international literature. Rodríguez-Liñán and Rubio (1995), Rodríguez-Liñán and Rubio (2000) and Palaia et al. (2000) published some of the first Spanish studies of MC influence on NDT measurements using the BPV. Regarding T, Llana et al. (2014) reported the influence of T on NDT, showing a clear linear tendency below 0°C and no significant tendency above 0°C for dry Scots pine small clear specimens. The length effect was found several times in ultrasound velocity using the SylDuo (Arriaga 2017a) found differences between the velocity obtained in end-to-end measurements and surface or crossed measurements equal to or less than 4,4 % on average.
Nondestructive testing used... Llana et al.

Pinus halepensis - Pinus nigra

Juniperus thurifera

Pinus sylvestris

Pinus radiata

Eucalyptus globulus

Populus x steinkamp BP-V (Ultratest, Achim, Germany) ultrasound device (600 V output power) equipped with 50 kHz exponential tip sensors (Figure 2a).

(2) The Sylvatest Duo (220-250 V output power) and the Trio (CBS-CBT, Lausanne, Switzerland) instrument equipped with conical 22 kHz sensors (Figure 2b, Figure 2c).

(3) The USLab (Agricef, Campinas, Brazil) ultrasound device (700 V output power and 0.1 μs resolution) which can be used with different sensors from 20 to 90 kHz (Figure 2e).

(4) The MicroSecond Timer (Fakopp, Sopron, Hungary) an impact stress wave device (Figure 2d). Velocity is calculated by dividing length over ToF.
Figure 2: NDT devices: a) Steinkamp BP-V. b) Sylvatest Duo. c) Sylvatest Trio. d) MicroSecond Timer. e) USLab. f) PLG. g) Hitman HM 200 (courtesy of Dr. Abel Vega). h) MTG.

Vibration devices

Natural frequency data is recorded after inducing vibration by hammer impact. The most common devices found in the literature are: (1) The Portable Lumber Grader PLG (Fakopp, Sopron, Hungary) equipped with a microphone that is placed in front of one end (Figure 2f), (2) The Hitman Director HM 200 (Fibre-gen, Christchurch, New Zealand) equipped with a contact accelerometer (Figure 2g), (3) The Mechanical Timber Grader MTG 960 (Brookhuis, Enschede, Netherlands) equipped with a contact accelerometer (Figure 2h). Velocity from the first mode of natural frequency is calculated as the product of two times length and frequency.

Probing devices

The most common probing devices used in Spain for density estimation and structural inspections found in the literature review are: (1) The Pilodyn 6 J Forest (Proceq, Schwerzenbach, Switzerland) (Figure 3a). This consists of a calibrated spring that releases a 2.5 mm diameter steel needle with a constant energy of 6 J. NPR depth of this needle into the timber is measured in mm. (2) The Wood Pecker (DRC, Ancona, Italy) (Figure 3b). This modified sclerometer inserts a 2.5 mm diameter steel needle by striking several times with constant energy. NPR depth is measured in mm after each strike. (3) The Screw Withdrawal Resistance Meter SWRM (Fakopp, Sopron, Hungary) (Figure 3c). SWR force is measured in kN when a standard screw is pulled out. (4) Commercial core bits with different external diameters, usually from 10 to 22 mm (Figure 3d). The mass and volume of the cylindrical extracted core are measured. (5) The RML Wood Extractor (RML WoodEx) (GICM-UPM, Madrid, Spain) coupled to a commercial drill (Figure 3e). This Spanish design was patented in 2013 (Martinez and Bobadilla 2013) using drilling chips extraction technique. A bit is drilled to a standard depth in wood specimens (so the hollow volume is known) vacuum collecting all of the chips produced during drilling in a paper filter bag. Density is estimated from the mass of chips and volume of the hollow. (6) The Resistograph (RinnTech, Heidelberg, Germany) is a drilling resistance tool where relative resistance is measured against the introduction of a small diameter drill at a constant speed (Figure 3f). (7) The IML Resi (IML, Wiesloch, Germany) uses drilling resistance technique in a similar way to the Resistograph. There are several models, and Figure 3g shows the F400-S. Probing measurements should be taken while avoiding areas close to the pith and other singularities such as knots and resin pockets, etc.
RESULTS AND DISCUSSION

Acoustic techniques (ultrasound and stress waves) for property estimation

Velocity is calculated from ToF by dividing length over ToF. The dynamic modulus of elasticity (Edyn) is calculated as the product of density and square velocity. Several authors have presented mechanical properties estimation models using velocity and Edyn (Table 1).

Table 1: Mechanical properties estimation models by acoustic techniques.

| Property       | Method and acoustic model (MHz) | MOEloc (MPa) | MOEEN384=MOE*1.3-2690 (MPa) |
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| MOR (MPa)      |                                 |              |                             |
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Measurements in longitudinal direction: \( V \) (m \( \text{s}^{-1} \)), velocity. \( \text{Edyn} = \rho \cdot V^2 \) (MPa).

\( \rho \) (kg m\(^{-3}\)) density. \( \text{MOR} \) (MPa). \( \text{MOEloc} \) (MPa). \( \text{MOEEN384} = \text{MOE} \cdot 1.3 - 2690 \) (MPa).

Zrad, Zsco, Zsal and Zmar are constants for radiata, Scots, Salzmann and maritime pine, which are only equal to 1 for this species, for other species are 0; \( Zp \) is a constant for boards, which is equal to 1 for particleboards and 0 for MDF; \( L \) (mm) length; \( dc \) and \( dh \)=knottiness parameters; \( Rw \)=ring parameter; \( \text{BAL}, \text{G}, \text{H}_0 \) and \( \text{DBH} \)=forest inventory parameters.

(1) Small clear specimens, (2) Three-point bending test, (3) Timber from existing structures, (4) Round timber, (5) 45 kHz sensors, (6) 22 kHz sensors, (7) Martínez 1992, (8) Rodríguez-Liñán and Rubio 1995, (9) Pedras et al. 1997, (10) Rubio 1997, (11) Hermoso 2001, (12) Hermoso et al. 2002, (13) Conde 2003, (14) Esteban 2003, (15) Hermoso et al. 2003, (16) Arriaga et al. 2006, (17) Conde et al. 2007, (18) Hermoso et al. 2007, (19) Íñiguez-González 2007, (20) Carballo et al. 2009b, (21) Casado et al. 2012, (22) Montón 2012, (23) Pérez-García 2012, (24) Casado et al. 2013, (25) Montero 2013, (26) Sevilla et al. 2013, (27) Vega 2013, (28) Merlo et al. 2014, (29) Cáceres-Hidalgo 2016, (30) Llana 2016, (31) Arriaga et al. 2017a, (32) Morales-Conde & Machado 2017, (33) Osuna-Sequera 2017, (34) Aire et al. 2019, (35) Arriaga et al. 2019.
Vibration techniques used to estimate properties

Longitudinal velocity from first mode natural frequency is calculated as the product of two times length and frequency. The dynamic modulus of elasticity (Edyn) was calculated as product of density and square velocity. Several authors have presented estimation models using vibration techniques (Table 2).

Several authors improved the prediction models of MOR by combining acoustic or vibration results with visual parameters. Hermoso (2001) found an absolute $R^2$ increase of 11%, while the corresponding figure for Íñiguez-González (2007) was 15% and for Arriaga et al. (2014) it stood at 4%, including knottiness parameters.

Table 2: Mechanical properties estimation models by vibration techniques.

| Device       | MOE and MOR models (MPa) | $R^2$ (%) | Species          | Reference          |
|--------------|--------------------------|-----------|------------------|--------------------|
| PLG          | MOE=395±1.119%×925×Edyn  | 77        | Radiata p.       | (1)                |
|              | MOR=230.2×8095%×62×(2×CDR) | 68        | Scots p.         | (9)                |
| MTG          | MOE=43.7%×925×Edyn       | 50        | Scots p.         | (9)                |
| PLG          | MOE=0.693%×925×(6.2×KDR) | 46        | Scots p.         | (9)                |
|              | MOR=4.31×0.047%×925×57   | 44        | Scots p.         | (9)                |
| PLG          | MOE=353×1.9%×925×(6.2×KDR) | 65        | Maritime p.      | (12)               |
|              | MOR=353×1.9%×925×57       | 47        | Black poplar     | (10)               |
| PLG          | MOE=132.4×12.70%×1.69%   | 54        | Douglas fir      | (10)               |
|              | MOR=2.4×0.0372×925×57    | 38        | Radiata p.       | (11)               |
| PLG          | MOE=1662±0.025%×925×(6.2×KDR) | 72        | Radiata, Scots,  | (11)               |
|              | MOR=353×1.9%×925×(6.2×KDR) | 61        | Scots, Salzman p.| (11)               |
| PLG          | MOE=1402×1.9%×925×(6.2×KDR) | 70        | Black poplar     | (11)               |
| PLG          | MOE=0.8×7.4%×925×57       | 45        | Radiata p.       | (11)               |
| PLG          | MOE=0.3×3.9%×925×57       | 47        | Paulevina        | (11)               |
| PLG          | MOE=508±0.0314±22.05%×(0.0009×L) | 33        | Scots p.         | (11)               |
| PLG          | MOE=353×1.9%×925×57       | 57        | Sweat chestnut   | (11)               |
| PLG          | MOE=362.7×0.554%×925×57  | 45        | Scots p.         | (11)               |
| PLG          | MOE=18.3×0.029%×925×57   | 26        | Sweat chestnut   | (11)               |
| PLG          | MOE=43.7×0.039%×925×57   | 78        | Scots p.         | (11)               |
| PLG          | MOE=300×0.039%×925×57    | 20        | Scots p.         | (11)               |
| IIM200       | MOE=2.4×0.0372×925×57    | 70        | Scots p.         | (11)               |
| PLG          | MOE=12.4×0.029%×925×57   | 15        | Scots p.         | (11)               |
| PLG          | MOE=322×0.076%×925×57    | 87        | Scots p.         | (11)               |
| PLG          | MOE=5.26×0.0315%×925×57  | 66        | Scots p.         | (11)               |
| PLG          | MOE=92×0.0125%×925×57    | 86        | Scots p.         | (11)               |
| PLG          | MOE=1.25×0.0489%×925×57  | 50        | Scots p.         | (11)               |
| PLG          | MOE=387×0.320%×925×57    | 42        | Scots p.         | (11)               |
| PLG          | MOE=2416×0.035%×925×57   | 41        | Scots p.         | (11)               |
| PLG          | MOE=387×0.320%×925×57    | 42        | Scots p.         | (11)               |
| PLG          | MOE=220×0.0314±22.05%×(0.0009×L) | 33        | Scots p.         | (11)               |
| PLG          | MOE=392×0.0315%×925×57   | 50        | Scots p.         | (11)               |
| PLG          | MOE=1402×1.9%×925×(6.2×KDR) | 70        | Scots p.         | (11)               |
| PLG          | MOE=353×1.9%×925×(6.2×KDR) | 61        | Scots p.         | (11)               |
| PLG          | MOE=0.8×7.4%×925×57       | 45        | Scots p.         | (11)               |

Measurements in longitudinal or transversal (1) direction: V (m·s⁻¹) velocity, Edyn=ρ×V² (MPa); ρ (kg·m⁻³) density, f (Hz) frequency, MOR (MPa), MOE (MPa), MOEloc (MPa), MOEEN³²⁴=MOE×1.3-2690 (MPa). Zrad, Zsco, Zsal and Zmar are constants for radiata, Scots, Salzman and maritime pine, which are only equal to 1 for this species, for other species are 0; L (mm) length; CKDR, kh, dc and dh=knottiness parameters; C=taper parameter; Rw=ring parameter. (2)Transversal measurements, (3)Transversal measurements on cantilever beam, (4)Round timber, (5)TIMBER from existing structures, (6)Arriaga et al. 2005, (7)Broto et al. 2007, (8)Casado et al. 2007, (9)Íñiguez-González 2007, (10)Casado et al. 2008, (11)Casado et al. 2009, (12)Santacrella et al. 2009, (13)Villanueva 2009, (14)Arriaga et al. 2012, (15)Casado et al. 2012, (16)Montón 2012, (17)Vega et al. 2012, (18)Montero 2013, (19)Vega 2013, (20)Arriaga et al. 2014, (21)Cáceres-Hidalgo 2016, (22)Llana 2016, (23)Osuna-Sequera 2017, (24)Vega et al. 2019b.
Probing techniques for density estimation

According to several authors (Bobadilla et al. 2007, Íñiguez-González 2007, Calderón 2012, Martínez 2016) no significant differences were found between radial and tangential measurements (with respect to an annual rings). Furthermore, in the assessment of timber structures (the most common use for probing techniques) it is not usually possible to select the probing direction. Density estimation models using acoustic and probing techniques have been presented by several Spanish authors (Table 3).

| Device | Variable | Density model (lg m⁻³) | RF (%) | Species/ product | Reference |
|--------|----------|------------------------|--------|------------------|-----------|
| HPV    | Full saga | e⁻²⁸⁵,44[LG-4.76]      | 11     | Scots p.         | Llana 2016 |
| HPV    | End saga | e⁻²⁸⁵,44[LG-4.76]      | 11     | Scots p.         | Llana 2016 |
| Llana  | Zsco     | e⁻²⁸⁵,44[LG-4.76]      | 11     | Scots p.         | Llana 2016 |
| Zsco   | Zsal     | e⁻²⁸⁵,44[LG-4.76]      | 11     | Scots p.         | Llana 2016 |
| Zmar   | Zsal     | e⁻²⁸⁵,44[LG-4.76]      | 11     | Scots p.         | Llana 2016 |

**Table 3:** Density estimation models from Spanish research works.

Zrad, Zsco, Zsal and Zmar are the constants for radiata, Scots, Salzmann and maritime pine, which are only equal to 1 for this species, for other species are 0; Zp is a constant for boards, which is equal to 1 for particleboards and 0 for MDF, (1)Small clear specimens, (2)Timber from existing structures, (3)Internal bit diameter (mm), (4)3 strikes, (5)5 strikes, (6)Martínez 1992, (7)Rubio 1997, (8)Palaià et al. 2000, (9)Maríño et al. 2002, (10)Casado et al. 2005, (11)Bobadilla et al. 2007, (12)Íñiguez-González 2007, (13)Vilches & Correal 2009, (14)Íñiguez-González et al. 2010, (15)Soto-Martínez 2010, (16)Acuña et al. 2011, (17)Casado et al. 2012, (18)Montón 2012, (19)Pérez-Garcia 2012, (20)Cañas-Gutiérrez 2013, (21)Montero 2013, (22)Sevilla et al. 2013, (23)Moraes-Conde et al. 2014, (24)Íñiguez-González et al. 2015, (25)Llana 2016, (26)Martínez 2016, (27)Camacho-Valero 2016, (28)Moraes-Conde & Machado 2017, (29)Salamanca 2017, (30)Bobadilla et al. 2018, (31)Llana et al. 2018a, (32)López et al. 2018, (33)Martínez et al. 2018, (34)Osuna-Sequeria et al. 2019b.

**MC adjustment factors**

Adjustment factors are important to achieve comparable results. Most research studies focus on MC influence. Palaià et al. (2000) showed that MC influence on ultrasound velocity measured on small clear specimens of Scots, maritime and Caribbean pitch pine varied with a power function. The higher the MC, the lower its influence. Rodríguez-Liñán and Rubio (1995), Llana et al. (2018b) and Llana et al. (2018c) reported
two different tendencies in which slopes were steeper below fiber saturation point (FSP) than above it, where MC influence is considered insignificant. Table 4 therefore presents adjustment factors to a reference MC value of 12 %, below FSP, as proposed for Spanish-grown species by Equation 1, Equation 2 and Equation 3:

\[ Vel_{12\%MC} = \frac{Vel_{MC}}{1 - k_{MC} \times (MC - 12)} \]  
\[ Depth_{12\%MC} = \frac{Depth_{MC}}{1 + k_{MC} \times (MC - 12)} \]  
\[ Force_{12\%MC} = \frac{Force_{MC}}{1 - k_{MC} \times (MC - 12)} \]

Where: \( Vel_{12\%MC} \) (m·s\(^{-1}\)) obtained from ToF or longitudinal frequency at 12 % of MC, \( Vel_{MC} \) (m·s\(^{-1}\)) at a given MC, \( Depth_{12\%MC} \) (mm) obtained by the Pilodyn 6J Forest NPR instrument, \( Depth_{MC} \) (mm) at a given MC, \( Force_{12\%MC} \) (kN) obtained by the SWRM instrument, \( Force_{MC} \) (kN) at a given MC, \( k_{MC} \) (as per unit) adjustment factors, which are listed in Table 4.

Table 4: MC adjustment factors (\( k_{MC} \)) in % for Spanish-grown species (below FSP).

| Device      | Variable corrected | \( k_{MC} \)% | Species       | Reference   |
|-------------|--------------------|---------------|---------------|-------------|
| BPV         | Velocity           | 0.70 (1)      | Scots p.      | (2)         |
| Pilodyn     | Depth              | 1.16          | Radiata p.    | (3)         |
| SWRM        | Force              | 3.20          |               |             |
| Hitman HM200| Velocity           | 1.20          | Sweet chestnut| (4)         |
| Sylduo      | Velocity           | 0.70 (1)      | Scots p.      | (5)         |
| BPV         |                   | 0.59 (1)      |               |             |
| Grindsosonic MK5 | Edyn            | 1.06 (1)      |               |             |
| Sytrio      | Velocity           | 0.48          |               |             |
| MST         | Velocity           | 0.50          | Scots p.      | (6)         |
| PLG         |                   | 0.65          |               |             |
| Sylduo      | Velocity           | 0.62          | Radiata p.    | (7)         |
| USLab       |                    | 0.61          | Scots p.      |             |
| MST         |                    | 0.62          | Salzmann p.   |             |
| PLG         | Velocity           | 0.63          | Scots p.      |             |
| MTG         |                    | 0.73          | Salzmann p.   |             |
|             |                    | 0.76          | Maritime p.   |             |
| Pilodyn     | Depth              | 2.20          | Radiata p.    | (8)         |
|             |                    | 1.60          | Scots p.      |             |
|             |                    | 1.70          | Salzmann p.   |             |
|             |                    | 2.00          | Maritime p.   |             |
| SWRM        | Force              | 2.20          | Radiata p.    |             |
|             |                    | 2.80          | Scots p.      |             |
|             |                    | 2.50          | Salzmann p.   |             |
|             |                    | 2.10          | Maritime p.   |             |

(1) Small clear specimens, (2) Rodriguez-Liñán and Rubio 1995, (3) Calderón 2012, (4) Vega 2013, (5) Llana et al. 2014, (6) Montero et al. 2015, (7) Llana et al. 2018b, (8) Llana et al. 2018c.
Visual grading

In order to add a new species to the visual grading standard it has to be characterized. Several research works in Spain during the past 30 years focused on this characterization. Fernández-Golfín et al. (1998) summarized the works done in the INIA Structural Timber Laboratory during several years for the characterization of radiata, Scots and maritime pine that led to the production of the first version of the UNE 56544 (1997) standard with two visual grades (ME-1, ME-2). Fernández-Golfín et al. (2001) published the works involved in adding Salzmann pine in the same standard. The results from Íñiguez-González et al. (2007b) made it possible to introduce the new visual grade MEG in the UNE 56544 (2007) for large cross-section timber (thickness > 70 mm). Fernández-Golfín et al. (2007) characterized southern blue gum for the first version of the hardwoods visual standard UNE 56546 (2007). Correal et al. (2013) and Vega et al. (2013) proposed visual grading criteria for structural sweet chestnut that were included in UNE 56546 (2013). Preliminary characterization works were also performed for other species that were not included in standards, such as Spanish juniper (Diez et al. 2006). Furthermore, five Spanish species appear in the EN 1912 (2012), and another one has been approved (Table 5). The latest allocations in EN 1912 (2012) were approved according to the works of Vega et al. (2013) and Hermoso et al. (2016). A new revision of the Spanish visual grading standards would be recommendable following the works of Montón et al. (2015), Llana et al. (2019) and the new version of European standard EN 14081:1 (2016). Several research studies were published comparing visual grading according to the Spanish standard UNE 56544 and the German standard DIN 4074-1, (Diez et al. 2000, Conde 2003, Arriaga et al. 2005b, Adell et al. 2008, Llana et al. 2019). In general, more pieces are rejected using the Spanish standard based on knot evaluation. A research work into the load carrying capacity of timber pieces from existing structures (Arriaga et al. 2005b) proposed a visual grading procedure limited to the main parameters (knots and slope of grain) in an attempt to simplify and adapt the procedure used in new timber to in-situ grading particularities. Other works studied the practically zero influence of some defects, such as fissures and wanes, on mechanical properties (Arriaga et al. 2007, Esteban et al. 2010). Touza et al. (2013) proposed a new visual grading criterion for large cross-section American pitch pine specimens from existing structures, based on knots, grain slope and boring insect attacks. Arriaga et al. (2017b) showed that visual grading standards (designed for new sawn timber) lead to a high percentage of rejection in existing timber structures, and it is usually not possible to access all 4 faces. Furthermore, beam cross-section is not homogeneous (Osuna-Sequera et al. 2017). Vega et al. (2019a) found ineffective visual strength grading of 216 dry sweet chestnut small-diameter logs using EN 1927-1 (2008), EN 1927-2 (2008) and DIN 4074-2 (1958) standards.

Table 5: Correspondence between Spanish visual grades and strength classes according to the European standard EN 1912 (2012) and later approvals.

| Species                  | (2) Strength class | (3) Spanish visual grade | (4) |
|--------------------------|--------------------|--------------------------|-----|
| Salzmann pine            |                    | ME1: C30, C18, C22      |     |
| Scots pine               |                    | ME2: C27, C18, C22      |     |
| Radiata pine             |                    | MEG: C24, C18, C20 (1)  |     |
| Maritime pine            |                    |                          |     |
| Southern blue gum        |                    | D40                      |     |
| Sweet chestnut           |                    | D27 (2)                  | D24 (3) |

(1) Approved by CEN/TC124/WG2-TG1 in October 2014 and not yet included in (2)EN 1912 (2012), (3)UNE 56544 (2011),(4) UNE 56546 (2013).
ME1 and ME2: Madera Estructural de 1ª y 2ª (structural timber 1st and 2nd quality)
MEG: Madera Estructural Gruesa escuadría (large cross-section structural timber)
MEF: Madera Estructural de Frondosas (hardwood structural timber)
MEF-G: Madera Estructural de Frondosas de Gruesa escuadría (hardwood large cross-section structural timber).

Final discussion

To summarise, 68 mechanical property estimation models from 29 research works were collected in Table
1 (acoustic techniques), 43 estimation models from 19 research works were included in Table 2 (vibration techniques) and 60 density estimation models from 29 research works were compiled in Table 3 (acoustic and probing techniques). These estimation models were developed from 1992 to 2019 in Spain. Most of these estimation models are valid for the same species, e.g. 24 different models to estimate MOE of the Scots pine (Spanish reference wood species) from ultrasound, stress waves and vibration devices are presented. If these different models are used to calculate MOE from common Spanish-grown Scots pine measurement values (acoustic velocity 5400 m s\(^{-1}\), vibration velocity 4750 m s\(^{-1}\) and density 510 kg m\(^{-3}\), values from Llana (2016)), the mean MOE value obtained is 11734 MPa with a coefficient of variation of 12.6% and standard deviation of 1474 MPa. No significant differences between MOE results of acoustic and vibration techniques were found. From the point of view of the authors, the results should be further studied to elucidate whether the recommended mechanical property estimation models for different NDT devices and species should be included in a new standard or at least in a protocol. However, if end-users develop their own models, these can be used instead of the standardized models. Furthermore, several MC adjustment factors for Spanish-grown species are presented in Table 4 that would be also included in a new standard or protocol. NDT measurement procedures should be unified, e.g. Osuna-Sequera et al. (2019b) concluded that in order to increase the accuracy of density estimation using probing techniques, from three to five measurements in at least two different cross-section areas including the middle point are needed. This should be included in UNE 41809 (2014) as a measurement recommendation.

Better knowledge of the research undertaken should help to prevent overlapping between research groups’ works and promote cooperation between them. Some research works presented here are almost unknown: e.g. several interesting and useful results were only published as final degree projects. In 2016 a net of Spanish-timber research groups was created under the name LIGNOMAD to find common objectives and promote collaboration. Research groups should identify potential research objectives, find other research groups with similar objectives and apply together for funding. Furthermore, useful information from previous research works compiled in this review paper can be helpful. E.g. a potential new topic is the reuse and recycling of recovered timber. In this review it was reported that at least one research group in Spain is working on this topic, and several estimation models for timber from existing structures were developed and visual grading criteria for timber from existing structures were proposed. Finally, apart from visual grading, NDT techniques are not used by the Spanish industry for grading purposes, while they are commonly used in most European countries. Therefore, closer collaboration between research groups and industry is needed to implement NDT for grading.

**Future milestones**

The main milestones that are expected to be achieved in the near future, given that some Spanish research groups are currently working on them, are: (1) a NDT grading standard for new structural sawn timber, (2) further implementation of NDT in Spanish timber industry, (3) assessment protocol for existing timber structures, including special guidelines for visual grading and for NDT use, (4) models for estimating properties in existing timber structures.

**CONCLUSIONS**

Most Spanish research works focus on NDT portable devices which can be used both in new sawn and round timber grading and to assess existing structures. These techniques are not used in practice in the Spanish industry for grading. However, they are frequently used to assess timber structures. Several statistical linear models for the estimation of mechanical properties using different NDT devices (68 models based on acoustic techniques, 43 based on vibration and 60 for density estimation) were developed in Spain from 1992 to 2019, most of them for new sawn timber.

The results obtained are very variable because the methods used are not exactly the same (size of the pieces, wood free of defects vs. structural size timber and the arrangement of measuring equipment, etc.). It is therefore difficult to extrapolate the use of a model for general application. It is very important that in the future different research groups use unified procedures (MC adjustment factors, number of measurements and the way to carry out them) to enhance the capacity of these techniques.

Although many research works have been published in Spanish and in Spanish conferences and work-
shops, fortunately in recent years more research has been published in English and in scientific journals, allowing international dissemination. Some useful research works presented here are almost unknown. Information from previous research works compiled in this review paper should help research groups to identify potential research objectives, find other research groups with similar objectives and avoid overlapping works.

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