# Evaluation of the influence of visual parameters on wave transmission velocity in sawn chestnut timber

**Abel Vega***[(1)], Manuel Guaita[(2)], Andrés Dieste[(3)], Juan Majada[(4)], Isabel Fernández[(5)], Vanessa Baño[(6)]

**Abstract** Non-destructive, visual evaluation and mechanical testing techniques were used to assess the structural properties of 374 samples of chestnut (*Castanea sativa*). The principal components method was applied to establish and interpret correlations between variables obtained of modulus of elasticity, bending strength and density. The static modulus of elasticity presented higher correlation values than those obtained using non-destructive methods. Bending strength presented low correlations with the non-destructive parameters, but there was some relation to the different knot ratios defined. The relationship was stronger with the most widely used ratio, CKDR. No significant correlations were observed between any of the variables and density.

**Keywords** chestnut, NDT, structural timber

## 1. INTRODUCTION

The predictive capability of non-destructive techniques to evaluate the mechanical properties of timber, such as methods based on the relationship between wave velocity and Young's modulus (Bucur 1995), has been widely studied. Many works, mostly related to conifer species, demonstrate the adequacy of these techniques to estimate the modulus of elasticity (Acuña et al. 2006, Casado et al. 2007, Divos and Tanaka 1997, Divos 2002, Divos and Sismandy 2010, Íñiguez 2007, Esteban 2003). However, their predictive capability in relation to bending strength, which is influenced by peculiarities of the wood (knots, grain deviation), is not so established. The relationships and interdependencies of factors, both physical and visual, must be evaluated together, identifying

[1] Abel Vega, Timber Construction Area, CETEMAS-Forest and Wood Technololgy Centre, Spain, avega@cetemas.es
[2] Manuel Guaita, Departamento Enxeñeria Agroforestal, University of Santiago de Compostela, Spain, m.guaita@usc.es
[3] Andrés Dieste, Wood Technology Area, CETEMAS-Forest and Wood Technololgy Centre, Spain, adieste@cetemas.es
[4] Juan Majada, Sustainable Forest Management Area, CETEMAS-Forest and Wood Technololgy Centre, Spain, jmajada@cetemas.es
[5] Isabel Fernández, Timber Construction Area, CETEMAS-Forest and Wood Technololgy Centre, Spain, iparrado@cetemas.es
[6] Vanessa Baño, Timber Construction Area, CETEMAS-Forest and Wood Technololgy Centre, Asturias, Spain, vbanho@cetemas.es

variables that explain variability in physical and mechanical properties. This approach can be carried out using a multivariate analysis of principal components. The transformation of the original variables into a smaller number of components allows the analysis of the correlations between groups of variables and the exclusion of those with no significant effect on the overall variance. The objective of this paper is the analysis of the mechanical properties of chestnut timber in relation to non-destructive variables and visual parameters, applying the statistical method of principal component analysis.

## 2. MATERIAL AND METHODS

### 2.1. Physical and mechanical variables

The database used in this paper is composed of the results of several tests performed on 374 samples of Spanish chestnut structural timber, with three different sections (40x100 mm, 40x150 mm and 70x150 mm). All the pieces were considered without previous visual classification to account for variability of the mechanical properties and singularities. The samples were conditioned at 60% relative humidity and 20 º C temperature.

The physical and mechanical properties of wood and acoustic variables obtained in non-destructive testing were obtained for every specimen (Table 1).

**Table 1** - Physical and mechanical variables considered in the analysis

| Symbol | Definition |
|---|---|
| $\rho$ | Density (kg/m$^3$) |
| ***MOEglo*** | Global modulus of elasticity (kN/mm$^2$) |
| ***MOEloc*** | Local modulus of elasticity (kN/mm$^2$) |
| ***MOR*** | Bending strength (N/mm$^2$) |
| ***Vu*** | Ultrasonic velocity (m/s) |
| ***Vi*** | Impact wave velocity (m/s) |
| ***Vv*** | Longitudinal vibrational velocity (m/s) |
| ***MOEu*** | Dynamic modulus of elasticity (ultrasounds) (kN/mm$^2$) |
| ***MOEi*** | Dynamic modulus of elasticity (impact wave) (kN/mm$^2$) |
| ***MOEv*** | Dynamic modulus of elasticity (vibrational analysis) (kN/mm$^2$) |

Density ($\rho$) was calculated from the weight and volume of each sample. The values of the static modulus of elasticity (*MOEloc* and *MOEglo*) and bending strength (*MOR*) were obtained from a four-point bending test in accord with the UNE EN 408:2010. Before the mechanical tests, the acoustic wave transmission velocity was measured by applying three different non-destructive techniques: ultrasound (CBT Sylvatest Trio-CBS), impact waves (Microsecond Timer, Fakopp) and vibrational analysis (Portable Lumber Grade, Fakopp). From these velocity values, the corresponding dynamic modulus of elasticity was calculated (Equation 1).

$$MOEdyn = \rho \cdot v^2 \quad (1)$$

where $\rho$ = density (kg/m$^3$), $v$ = wave transmission velocity (mm/µs)

The values of static modulus of elasticity and density were adjusted to a reference moisture content of 12%, in accord with the EN 384. Wave velocities were also adjusted to a moisture content of 12%, reducing its value by 0.8% for each 1% moisture increase (Sandoz 1989).

### 2.2. Visual variables

Some visual variables were established to define the influence of the singularities of the wood on its mechanical properties. Visual parameters of the Spanish visual classification UNE 56546 were considered besides different specific knot ratios were defined for this work in function of their diameter (*d*) and position. These visual parameters are presented in Table 2.

The variables were obtained from the Spanish visual grading standard UNE 56546 or they were specifically defined, such as for *kp*, as a function of the characteristics of the knots which have an influence on mechanical properties (size, area, location on the sample, etc)

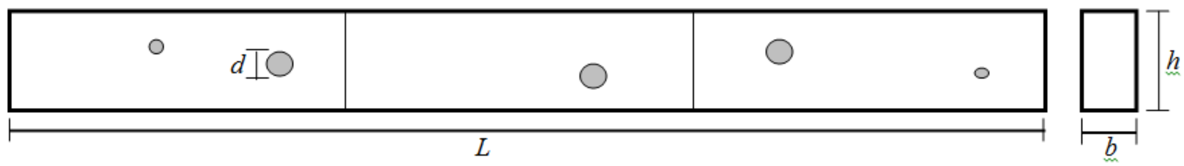


**Figure 1** – Dimensional parameters of the samples and knot diameter measurement

**Table 2** - Visual variables and knot ratios considered in the analysis

| Symbol | Definition | Font |
|---|---|---|
| ***CKDR*** | Concentrated knot diameter ratio [equation 2] | Bibliography/PLG |
| ***Nu*** | Number of knots per meter | Specifically defined |
| ***K*** | Mean diameter of all knots in relation to height (h) | Specifically defined |
| ***Kh*** | Maximum knot diameter in relation to height (h) | UNE 56546 |
| ***Kb*** | Maximum knot diameter in relation to width (b) | UNE 56546 |
| ***Kc*** | Maximum ratio of knot diameter / height (h) within the central third | Specifically defined |
| ***Kp*** | Maximum relative diameter in the central third in relation to its distance from the tension side [equation 3] | Specifically defined |
| ***Kt*** | Presence of a cut knot in the tension side within the central third (Yes / No) | Specifically defined |
| ***Kcm*** | Presence of knot in the compression side within the central third (Yes / No) | Specifically defined |
| ***P*** | Presence of pith (Yes/No) | UNE 56546 |
| ***Gd*** | General grain deviation (%) | UNE 56546 |

*CKDR* is the Concentrated Knot Diameter Ratio. The knot diameter is the distance between the two tangential lines parallel to the grain (longitudinal direction) of a lumber surface in which the knot exists. The knot diameter ratio (*KDR*) is the diameter of the knot expressed as a percentage of the width of the timber it is located within. The concentrated *KDR* (*CKDR*) is the sum of the *KDR* relating to all the knots existing in any 15 cm length of a piece of the lumber (Divos and Sismandy 2010).

$$CKDR = \frac{\sum d_i}{2 \cdot (b+h)} \tag{2}$$

where $d_i$ = diameter of the knot (mm), b and h = height and width, respectively (mm)

Kp ratio, specifically defined, refers to the relative size of the knot with respect to the height of the sample (within the central third) and the knot´s proximity to the inferior side (zone of maximum tension).

$$Kp = \left(\frac{d}{h}\right) / \, dist \tag{3}$$

where $d$ = knot diameter (mm), $h$ = height of the sample (mm), $dist$ = distance between the center of the knot and the inferior side of the sample (mm)

### 2.3. Statistical analysis

A principal component analysis was carried out to determine which variables had a significant effect on the overall variance and to determine groups or components associated with the most influential variables. The principal components method was applied because it analyzes variables without establishing hierarchies between them and without satisfying the condition of multivariate normality. The analysis was performed using the statistical software *R*, through the libraries *psych* and *pls*.

A first analysis was conducted to eliminate variables with little influence on the overall variance. Once the final variables were defined, a second analysis was performed considering mechanical, visual and acoustic variables, and groups of variables (components) were established to simplify the analysis of correlations without significant loss of information.

## 3. RESULTS

### 3.1. Direct correlations

Analysis of the correlation matrix with *MOEglo*, *MOEloc*, *MOR* and $\rho$, confirmed known relationships (*MOEloc* vs *MOEglo*, *MOEglo* vs any dynamic *MOE*) and demonstrated the inverse relationship between MOR and all defined knot ratios, especially with *k* and *kp*.

**Table 3 –** Correlation matrix

| | ***Den*** | ***MOEloc*** | ***MOEglo*** | ***MOR*** |
|---|---|---|---|---|
| $\boldsymbol{\rho}$ | 1.00 | 0.24 | 0.27 | 0.11 |
| ***MOEloc*** | 0.24 | 1.00 | 0.89 | 0.43 |
| ***MOEglo*** | 0.27 | 0.89 | 1.00 | 0.51 |
| ***MOR*** | 0.11 | 0.43 | 0.51 | 1.00 |
| ***Vu*** | -0.23 | 0.66 | 0.70 | 0.30 |
| ***Vi*** | -0.21 | 0.63 | 0.70 | 0.25 |
| ***Vv*** | -0.25 | 0.66 | 0.71 | 0.30 |
| ***MOEu*** | 0.39 | 0.77 | 0.83 | 0.35 |
| ***MOEi*** | 0.37 | 0.73 | 0.81 | 0.29 |
| ***MOEv*** | 0.29 | 0.79 | 0.85 | 0.36 |
| ***CKDR*** | 0.10 | -0.14 | -0.19 | -0.23 |
| ***Nu*** | 0.11 | -0.19 | -0.22 | -0.28 |
| ***k*** | 0.07 | -0.16 | -0.22 | -0.37 |
| ***kh*** | 0.07 | -0.10 | -0.18 | -0.23 |
| ***kb*** | 0.11 | -0.18 | -0.24 | -0.27 |
| ***kc*** | 0.03 | -0.17 | -0.19 | -0.27 |
| ***kp*** | 0.08 | -0.15 | -0.17 | -0.38 |
| ***Sk*** | 0.15 | -0.25 | -0.29 | -0.32 |
| ***Gd*** | 0.01 | -0.01 | -0.04 | 0.00 |
| ***P*** | -0.03 | -0.03 | -0.02 | -0.17 |
| ***kt*** | 0.11 | -0.09 | -0.10 | -0.34 |
| ***kcm*** | 0.06 | -0.10 | -0.09 | -0.06 |

### 3.2. Principal components analysis

The first analysis resulted in the original 21 variables being reduced to 6 components, which explained 75% of the variance. From the correlation matrix and the loadings of each variable within the components, it was decided to delete the variables *kcm* and *kt* (knot ratios), *Gd* (grain deviation) and *P* (presence of pith) with no significant effect on overall variability. A new analysis was carried out with the remaining 17 variables, resulting in a reduction to 4 components that explained 76% of overall variance (Table 4).

**Table 4** - Eigenvalues and proportion of variance explained by each component

| | **Comp.1** | **Comp.2** | **Comp.3** | **Comp.4** |
|---|---|---|---|---|
| **Standard deviation** | 2.72 | 1.87 | 1.25 | 1.09 |
| **Variance proportion** | 0.41 | 0.20 | 0.09 | 0.07 |
| **Cumulative proportion** | 0.41 | 0.61 | 0.69 | 0.76 |

The first component (explaining 41% of the overall variance) appears to be strongly associated with the variables of wave velocities and the modulus of elasticity (static and dynamic). The second component (explaining 19% of the variance) is more related to knot variables, especially with *k*, *kh*, and *Sk* (all indicative of the knot size). The *CKDR* ratio showed no obvious correlation with any mechanical variable or with density and had a lower importance (0.66) than *k*, *kh* and *Sk* (0.84, 0.86 and 0.86 respectively) on Component 2. The knot ratios appear inversely related (very weakly) with mechanical properties and non-destructive variables, with *MOR* being the most relevant relationship. The third component can be seen to be related to density *ρ* (0.95), while the fourth is associated with two knot ratios, *kc* and *kp* (indicative of the knot´s position in the sample). The variable *MOR* is more important in this component (0.49) than in the others and is inversely correlated with *kc* y *kp* ,(Table 5).

**Table 5** - Principal component analysis

| | Variable | Comp.1 | Comp.2 | Comp.3 | Comp.4 |
|---|---|---|---|---|---|
| Physical and mechanical variables | ***ρ*** | 0.15 | 0.11 | 0.95 | 0.03 |
| | ***MOEloc*** | 0.84 | -0.08 | 0.20 | -0.15 |
| | ***MOEglo*** | 0.88 | -0.15 | 0.22 | -0.16 |
| | ***MOR*** | 0.34 | -0.25 | 0.24 | -0.49 |
| NDt variables | ***Vud*** | 0.87 | -0.14 | -0.34 | -0.03 |
| | ***Vid*** | 0.88 | -0.13 | -0.36 | -0.04 |
| | ***Vv*** | 0.85 | -0.16 | -0.38 | -0.15 |
| | ***MOEu*** | 0.92 | -0.06 | 0.24 | -0.01 |
| | ***MOEi*** | 0.92 | -0.06 | 0.20 | -0.03 |
| | ***MOEv*** | 0.92 | -0.10 | 0.13 | -0.14 |
| Knot ratios | ***CKDR*** | -0.12 | 0.66 | 0.08 | 0.06 |
| | ***Nu*** | -0.12 | 0.61 | 0.12 | 0.42 |
| | ***k*** | -0.05 | 0.84 | -0.09 | 0.09 |
| | ***kh*** | -0.04 | 0.86 | -0.04 | 0.08 |
| | ***Sk*** | -0.17 | 0.86 | 0.09 | 0.24 |
| | ***kb*** | -0.13 | 0.52 | 0.14 | 0.39 |
| | ***kc*** | -0.05 | 0.32 | -0.02 | 0.72 |
| | ***kp*** | -0.07 | 0.10 | 0.09 | 0.88 |

Wave velocities presented no strong correlations with any knot ratio. The variable *Sk* appeared with the highest correlation coefficients (0.30 – 0.35), and the other ratios showed correlations between 0.15 and 0.24 (Figure 2).

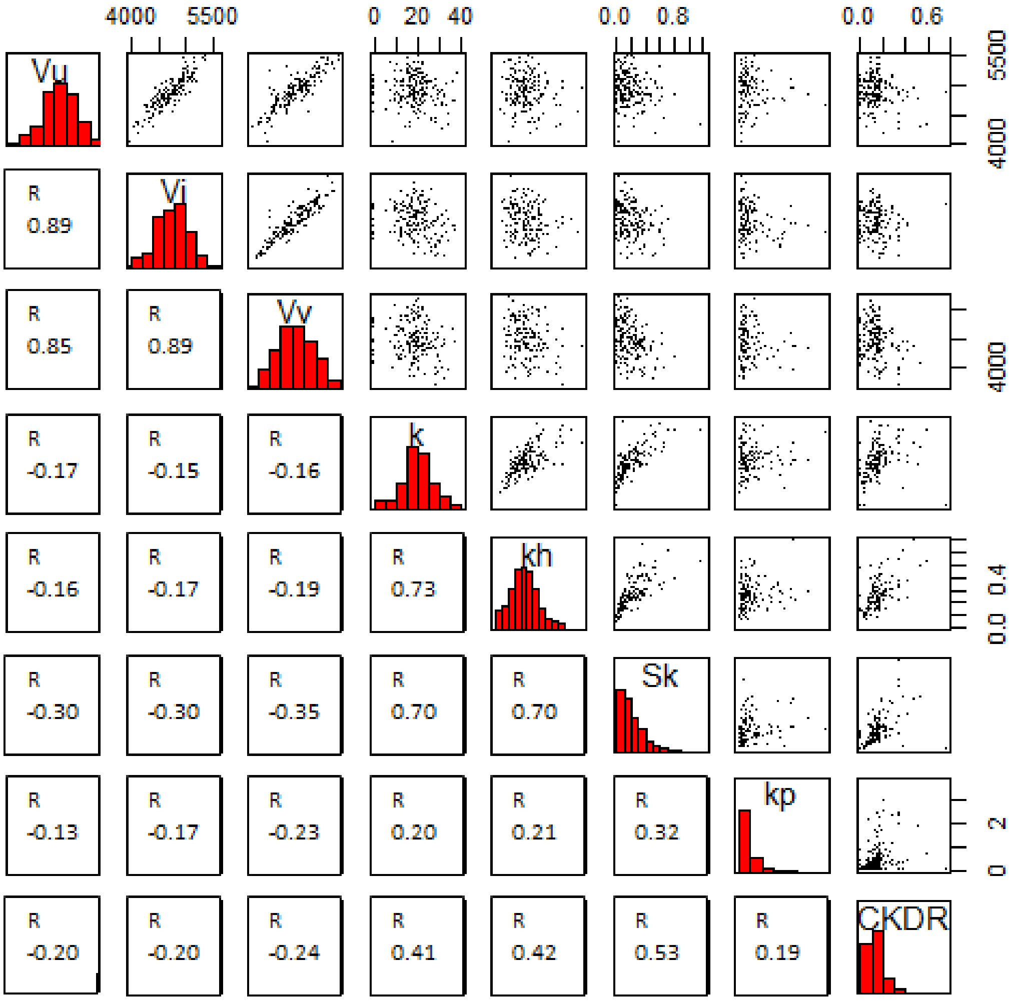


**Figure 2** – Correlation graphics and coefficients between wave velocities (*Vu*, *Vi* and *Vv*) and knot ratios (*k*, *kh*, *Sk*, *kp* and *CKDR*).

## 4. CONCLUSIONS

Principal component analysis allowed the interpretation of the relationships between different variables. The parameters obtained by non-destructive techniques (wave velocity and dynamic modulus of elasticity) are suitable for estimating the static modulus of elasticity in chestnut wood, due to the high degree of correlation observed between these variables. However, the non-destructive variables evaluated did not seem adequate by themselves to estimate bending strength.

Density had no significant correlation with any other variable, while some effect of knot ratios on bending strength was observed. Some of the knot ratios defined, the same as other visual variables such as grain deviation or the presence of pith, showed no significant effect on mechanical properties or non-destructive parameters. However, in the analysis of the variables related to the size of knot (*k*, *kh*, *SK*) and the position of the knot in the piece (*Kp*), a higher correlation with bending strength in chestnut timber was observed than that obtained with the *CKDR*. The importance of this result relates to the fact that *CKDR* is usually included in linear models for prediction of *MOE* and *MOR*, and in the estimation of the modulus of elasticity in some commercial equipment such as PLG. In view of the results presented here, it would seem more logical, in these circumstances, to use other knot ratios that have a higher correlation with the modulus of elasticity and bending strength.

There were no high correlations observed between wave velocities by non-destructive techniques and the different knot ratios defined.

## ACKNOWLEDGMENTS

Ministerio de Ciencia e Innovación. Proyecto Singular Estratégico VALOCAS, financed by the Consejería de Educación y Ciencia del Principado de Asturias.

## REFERENCES

Acuña, L., Díaz, M.R., and Casado, M. (2006). "Los ultrasonidos y la calidad de la madera estructural. Aplicación a *Pinus pinaster*". *Boletín del CIDEU 2: 7-26. ISSN 1885-5237*

Bucur, V. (1995). "Acoustics of wood". *CRC Press. Springer Series in Wood Science.*

Casado, M., Acuña, L., Vecilla, D., Basterra, A., Pando, V., and Relea, E. (2007). "Determinación de la capacidad resistente de madera estructural de Pinus sylvestris mediante PLG". *11º Congreso Español de END. Gijón.*

Divos, F., and Tanaka, T. (1997) "Lumber Strength Estimation by Multiple Regression". *Holzforschung 51 467-471*

Divos, F. (2002) "Portable Lumber Grader". *13th International Symposium on Non-destructive Testing of Wood. Berkeley, California, USA.*

Divos, F., and Sismandy, F. (2010). "Strength Grading of Structural Lumber by Portable Lumber Grading - effect of knots". *Final Conference of COST Action E53. Edinburgh*

Esteban, M. (2003). "Determinación de la capacidad resistente de la madera estructural de gran escuadría y su aplicación en estructuras existentes de madera de conífera". *Tesis Doctoral. Universidad Politécnica de Madrid. 365 p.*

Íñiguez, G. (2007). "Clasificación mediante técnicas no destructivas y evaluación de las propiedades mecánicas de la madera aserrada de coníferas de gran escuadría para uso estructural". *Tesis Doctoral. Universidad Politécnica de Madrid. 236 p.*

Sandoz, J. (1989). "Grading of construction timber by ultrasound". *Wood Science and Technology 23, pp. 95-108.*

EN 384 (2004). "Structural timber. Determination of characteristic values of mechanical properties and density".

EN 408 (2003) "Timber structures. Sawn timber and glued laminated timber for structural use. Determination of some physical and mechanical properties".