WOOD RESEARCH
57 (3): 2012
359-366

# NONDESTRUCTIVE EVALUATION OF STATIC BENDING PROPERTIES OF SCOTS PINE WOOD USING STRESS WAVE TECHNIQUE

Petr Horáček, Jan Tippner
Mendel University in Brno, Faculty of Forestry and Wood Technology
Department of Wood Science
Brno, Czech Republic

Khaled T. Hassan
Mendel University in Brno
Faculty of Forestry and Wood Technology
Department of Wood Science
Brno, Czech Republic

Alexandria University
Faculty of Agriculture
Department of Forestry and Wood Technology
Alexandria, Egypt

(Received April 2011)

## ABSTRACT

The aim of this study was to evaluate the dynamic modulus of elasticity of scots pine (*Pinus sylvestris* L.) wood nondestructively through longitudinal stress wave propagation and to determine the strength of the relationship between dynamic modulus of elasticity ($MOE_D$) predicted from stress wave technique and static bending properties [static modulus of elasticity ($MOE_S$) and modulus of rupture (MOR)]. A comparison between longitudinal stress wave velocity of the standing trees and the boards was conducted. The results showed that the $MOE_D$ was higher than the static modulus of elasticity ($MOE_S$) but both were highly correlated. The stress wave velocity squared had significant correlation with the $MOE_S$ (r = 0.72) and MOR (r = 0.60). There was significant correlation between the dynamic modulus of elasticity ($MOE_D$) and static bending properties ($MOE_S$ and MOR). The correlation coefficient was (r = 0.96 and r = 0.74) for $MOE_S$ and MOR respectively.

KEYWORDS: Nondestructive evaluation, dynamic modulus of elasticity, stress wave velocity.

## INTRODUCTION

The nondestructive evaluation is the approach of identifying the physical and mechanical properties of materials without altering its end-use capabilities (Ross and Pellerin 1994). Nondestructive testing is now used widely for evaluation standing trees, logs, lumber strength grading, and detecting defects. These methods not only apply to solid wood but also so wood composites such as particleboards (Han et al. 2006). Nondestructive evaluation is an important tool for the characterization of wood and can be used in industry to improve quality control process through reducing the property variation of the raw material and its by-products (Oliveira and Sales 2006).

Conventional bending tests for modulus of elasticity (MOE) are costly, destructive, and difficult to carry out rapidly when applied to standing trees. This reduces the opportunity to correctly target trees for a specific wood products such as structural timber (Ilic 2003).

There are three different techniques for velocity determination in wood: Stress wave, ultrasonics and the longitudinal vibration method (Divos et al. 2007). Ultrasound techniques, used in more common structural materials in modern construction such as concrete and steel, have been applied quite successfully to predict the residual strength of timber structures (García et al. 2007).

The principal wave types used for measuring wood properties are the bulk waves (longitudinal or transverse-shear) and surface waves (Rayleigh, Lamb, and Love waves). The waves are characterized by the direction of propagation and by the particle motion, i.e., for longitudinal waves the particle trajectory is in the direction of propagation, for transverse waves the particle motion is perpendicular to the direction of propagation; for Rayleigh waves the particle trajectory is elliptical in the plane that is perpendicular to the tested surface and parallel to the direction of propagation (Bucur 2006).

Ross et al. (2005) indicated that stress wave testing of peeler cores was found to be a good predictor of static and dynamic modulus of elasticity (MOE) of lumber sawn from the cores. However, correlations between stress wave MOE of the peeler cores and bending and tensile strength of derived standard-size lumber were low.

Stress-wave propagation is also a dynamic method, but normally uses mechanical longitudinal excitation at frequencies substantially higher than for transverse vibration. Using a simplified approach for an isotropic, homogeneous specimen with small lateral dimensions compared with the propagating wave length (Beall 2008).

Nondestructive stress wave technique can be used to track property changes in trees and help determine how forests could be managed to meet desired wood and fiber qualities (Wang et al. 2000). Two fundamental material properties are measured with longitudinal stress wave techniques: energy storage and energy dissipation. Energy storage is manifested as the speed at which a wave travels in a material. In contrast, the rate at which a wave attenuates is an indication of energy dissipation (Wang et al. 2001).

Dzbeński and Wiktorski (2007) indicated that velocity of ultrasonic wave propagation in coniferous standing tree trunks (pine, spruce) is a good indicator of mechanical properties of the resulted sawn timber and reported that satisfactory correlations were achieved between longitudinal wave velocity ($r = 0.867$) and transverse wave velocity ($r = 0.711$) in standing trees trunks, and modulus of elasticity of sawn timber obtained; parallel correlation coefficients relating to bending strength ($r = 0.663$; $r = 0.796$). Ross et al. (1997) conducted a study on eastern spruce and balsam fir logs and reported that a relationship exists between the MOE of individual lumber specimens obtained from the log and the MOE of the log.

Matheson et al. (2002) concluded that there was a significant positive relationship between acoustic wave velocity and the timber stiffness in *Pinus radiata*, which suggests an opportunity to segregate timber while the trees are still standing and to select logs that will yield predominantly high stiffness lumber.

The objectives of this study are to evaluate the dynamic modulus of elasticity for scots pine (*Pinus sylvestris* L.) wood nondestructively through longitudinal stress wave propagation and examine the strength of the relationship between the dynamic modulus of elasticity ($MOE_D$) predicted from stress wave velocity and static bending properties ($MOE_S$ and MOR).

## MATERIAL AND METHODS

Five trees were selected of scots pine (*Pinus sylvestris* L.) from the forest located in (Habrůvka, Brno, Czech Republic) at altitude of 440 m above sea level. The diameter of the stand at breast height ranged from 40 to 45 cm, the height ranged from 31-32 m, and the age of the trees was 118-125 years. Stress wave velocity of each tree was assessed by measuring acoustic velocity using a Fakopp 2D time of flight instrument. Fakopp 2D equipped with two transducers (transmitting and receiving probes), the starter probe was inserted in the tree stem 50 cm above the ground, the receiving probe was placed at 100 and 200 cm from the starter probe. The stress wave is generated by a hammer impact and the measurements replicated on opposite sides of the stem.

Three trees were felled at approximately 7 cm above ground level, rectangular 18 boards with dimension of 450 x 50 x 1000 mm were selected randomly. The longitudinal stress-wave transmission time was measured along the boards length. The average of moisture content of the boards was reached to (approximately 12 %) in ambient conditions in the laboratory. The moisture content was monitored and checked by dielectric capacitance type moisture meter (Wagner L601-3).

### Determination of dynamic modulus of elasticity ($MOE_D$)

The dynamic modulus of wood elasticity ($MOE_D$) was measured using a one-dimensional wave equation (Wang et al. 2001) as follows:

$$MOE_D = SWS^2 \times \rho \qquad (1)$$

where: $MOE_D$ - the dynamic modulus of elasticity (Pa),
SWS - stress wave speed through the material ($m.s^{-1}$),
$\rho$ - the density of wood ($kg.m^{-3}$).

The stress wave speed (SWS) calculated by the following equation:

$$SWS = L \cdot t^{-1} \qquad (2)$$

where: SWS - stress wave speed ($m.s^{-1}$),
L - the test span (the distance between the two accelerometers) (m),
t - the transmission time (s).

### Determination of static modulus of elasticity ($MOE_S$)

The boards stiffness and bending strength were determined using the average values of small clear specimens for each board, 162 small clear specimens with dimensions of 20 x 20 x 300 mm were used. The static bending test was carried out to determine the static modulus of elasticity

($MOE_S$) and modulus of rupture (MOR) using a Universal Testing Machine (Zwick testing machine, model no. Z050), according to Czech standard (ČSN 49 0115, 1979) for MOR and (ČSN 49 0116, 1982) for $MOE_S$. The air dry density was calculated from the mass and volume of the specimens. The mechanical properties were adjusted to equivalent values for 12 % moisture content.

## RESULTS AND DISCUSSION

The results showed that the average values of the stress wave velocity applied longitudinally through the tree trunk were 3771.5 $m.s^{-1}$ and for the boards were 4362.83 $m.s^{-1}$ (Tab. 1). The results from t-test indicated that mean sample values were significantly different from each other at 95 % confidence level. The main reason for the difference is the difference in moisture content where the moisture content of the boards was below the fiber saturation point (FSP) and in the living trees was above the FSP. The values of velocities in the dry conditions are highest compared with those in saturated conditions (Bucur 2006). Oliveira et al. (2005) in a study to evaluate ultrasonic technique sensitivity to the moisture content in wood, the results obtained showed that velocity of ultrasonic waves is sensitive to changes in moisture content of lumber during drying. The velocity under dry conditions was always higher than the velocity under more humid conditions. Kabir et al. (1998) indicated that ultrasonic properties were affected considerably by the moisture content and grain direction. The dried wood showed higher ultrasonic velocity and elastic stiffness constant as compared to green wood. It was stated by several researchers that there was a significant correlation between standing trees and lumbers. In this study the strength of the relationship between the dynamic modulus of elasticity ($MOE_D$) of the standing trees and the static modulus of elasticity ($MOE_S$) not determined because the boards were selected randomly from the whole three trees. Furthermore, several literature stated that there is a high correlation between the $MOE_D$ and $MOE_S$. Grabianowski et al. (2006) reported that the correlation using Fakopp between the log values of radiata pine and those for the average of the outerwood boards from each log was 0.94. Edlund et al. (2006) found that there is agreement between the modulus of elasticity of Norway spruce saw logs and the structural grade of sawn lumber.

*Tab. 1: Mean values of stress wave velocity for the standing trees and boards.*

| Parameter | N | Min. | Max. | Mean* | T-value | DF | P-Value |
|---|---|---|---|---|---|---|---|
| Trees | 5 | 3713.1 | 3804.1 | 3771.5(1.07)** | -5.57 | 21 | 0.000 |
| Boards | 18 | 3985 | 4362.8 | 4398 (5.33)** | | | |

* Mean values in ($m.s^{-1}$) ** Values in parentheses are coefficient of variation

The $MOE_S$ values ranged from 5913 – 10707 $N.mm^{-2}$ and for $MOE_D$ 7141 - 13000 $N.mm^{-2}$. The values of $MOE_D$ were higher than those obtained from $MOE_S$. The results obtained by (Oliveira et al. 2002) showed that the dynamic tests were 17 % higher than those of the static tests. Divos et al. (2007) reported that MOE determined by density and velocity is always higher than static MOE. The main reason for the difference is creep (Divos and Tanaka 2000). Halabe et al. (1997) explained the reason for the difference between dynamic modulus of elasticity and the static modulus by considering wood as a highly damping and viscoelastic material. For a vibrating lumber specimen, the elastic restoring force is proportional to the displacement and the dissipative force (damping) is proportional to the velocity. Therefore, when a force is applied for a very short time, the material behaves like an elastic solid, while for longer duration, the behavior is like that of a viscous liquid. This behavior is more prominent for long duration static bending tests as compared to stress wave tests.

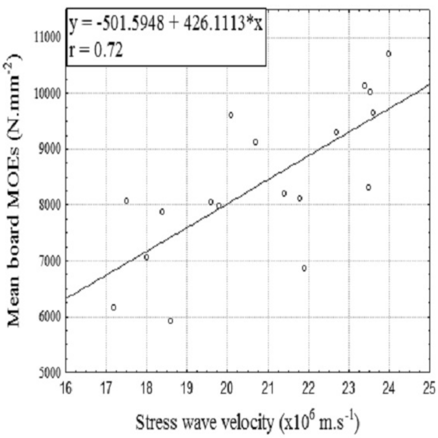


*Fig. 1: Relationship between stress wave velocity squared and mean board $MOE_S$.*

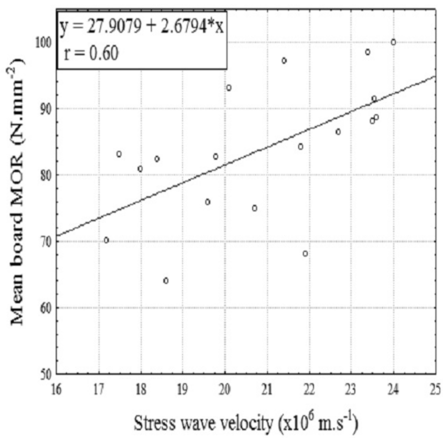


*Fig. 2: Relationship between stress wave velocity squared and mean board MOR.*

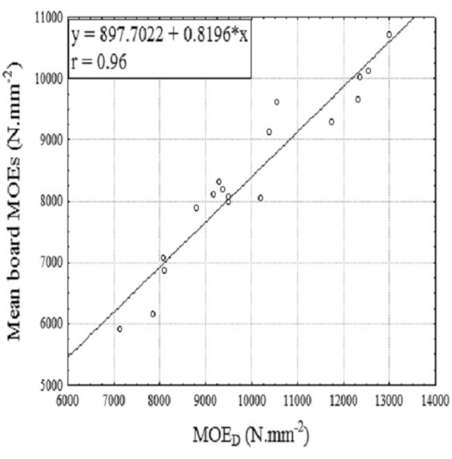


*Fig. 3: Relationship between $MOE_D$ and mean board $MOE_S$.*

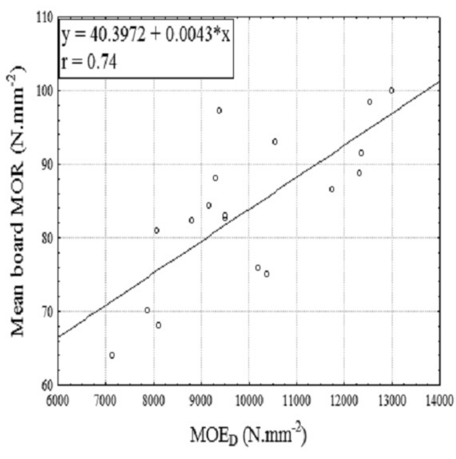


*Fig. 4: Relationship between $MOE_D$ and mean board MOR.*

There was a good correlation between stress wave velocity squared and $MOE_S$. The correlation coefficient was (r = 0.72), also there was a good correlation between stress wave velocity squared and MOR (r = 0.60) but lower than the coefficient from $MOE_S$ and stress wave. The correlation coefficient for both $MOE_S$ and MOR and stress wave velocity squared was significant at the 95 % confidence level (Fig. 1 and Fig. 2). Halabe et al. (1997) reported that coefficient of determination ($R^2$) value between static bending MOE and stress wave velocity was 0.61 and 0.45 for the green and dry southern pine wood. The relationship between $MOE_D$ and ($MOE_S$ and MOR) was well correlated. The correlation coefficient was (r = 0.96 and r = 0.74) for $MOE_S$ and MOR respectively (Fig. 3 and Fig. 4). The correlation coefficient for both $MOE_S$ and MOR and $MOE_D$ was significant at the 95 % confidence level.

The results obtained from this study showed that the density ranged from 370–543 $kg.m^{-3}$. The results indicated that the density correlated well with the static bending properties ($MOE_S$ and MOR). The Correlation coefficient was r = 0.73 and r = 0.50 for $MOE_S$ and MOR respectively. Ilic (2001) reported that the density is highly related to the wood stiffness and strength as indicated by the relatively coefficients of correlation with MOE and MOR.

## CONCLUSIONS

The results obtained from this study showed that there was a significant correlation between stress wave velocity squared and $MOE_S$ (r = 0.72) and MOR (r = 0.60). The $MOE_D$ predicted from stress wave technique was higher than $MOE_S$ obtained from static bending test but both were highly correlated, the correlation coefficient between $MOE_D$ and $MOE_S$ was (r = 0.96) and MOR (r = 0.74). The stiffness ($MOE_S$) and the strength (MOR) of scots pine wood well correlated with $MOE_D$. Stress wave technique provided a good estimate and predictor of wood stiffness and strength.

## ACKNOWLEDGMENTS

This work supported by the Ministry of Education, Youth and Sports of the Czech Republic, Project No. 6215648902.

## REFERENCES

1. Beall, F.C., 2008: Wood products: Nondestructive evaluation. Encyclopedia of Materials: Science and Technology. Pp 9702-9707.
2. Bucur, V., 2006: Acoustics of wood. Springer-Verlag, Berlin, 393 pp.
3. ČSN 49 0115, 1979: Wood. Evaluation of strength in static bending. (Dřevo. Zjišťování meze pevnosti v statickém ohybu) (in Czech).
4. ČSN 49 0116, 1982 : Wood. Determination of the modulus of elasticity in static bending. (Drevo. Metóda zisťovania modulu pružnosti pri statickom ohybe) (in Slovak).
5. Divos, F., Divos, P., Divos, G., 2007: Acoustic techniques: From seedling to wood structures. Proceedings of the 15th International Symposium on Nondestructive Testing of Wood. Duluth, MN. Pp 3-12.
6. Divos, F., Tanaka, T., 2000: Effect of creep on modulus of elasticity determination of wood. J. of Vibration and Acoustics- Transactions of the ASME 122(1): 89-92.
7. Dzbeński, W., Wiktorski, T., 2007: Ultrasonic evaluation of mechanical properties of wood in standing trees. COST E 53 Conference - Quality Control for Wood and Wood Products, 15 - 17th October 2007, Warsaw. Pp 21-26.

8. Edlund, J., Lindström, H., Nilsson, F., Reale, M., 2006: Modulus of elasticity of Norway spruce saw logs vs. structural lumber grade. Holz als Roh- und Werkstoff 64(4): 273-279.
9. Garcia, M.C., Seco, J.I.F., Prieto, E.H., 2007: Improving the prediction of strength and rigidity of structural timber by combining ultrasound techniques with visual grading parameters. (Mejora de la predicción de la resistencia y rigidez de la madera estructural con el método de ultrasonidos combinado con parámetros de clasificación visual). Materiales de Construcción 57(288): 49-59 (bilingual in Spanish-English).
10. Grabianowski, M., Manley, B., Walker, J.C.F., 2006: Acoustic measurements on standing trees, logs, and green lumber. Wood Science and Technology 40(3): 205-216.
11. Halabe, U.B., Bidigalu, G.M., GangaRao, H.V.S., Ross, R.J., 1997: Nondestructive evaluation of green wood using stress wave and transverse vibration techniques. Mater. Eval. 55(9): 1013-1018.
12. Han, G., Wu, Q., Wang, X., 2006: Stress-wave velocity of wood-based panels: Effect of moisture, product type, and material direction. Forest Products Journal 56(1): 28-33.
13. Ilic, J., 2001: Relationship among the dynamic and static elastic properties of air-dry *Eucalyptus delegatensis* R. Baker. Holz als Roh- und Werkstoff 59(3): 169-175.
14. Ilic, J., 2003: Dynamic MOE of 55 species using small wood beams. Holz als Roh- und Werkstoff 61(3): 167-172.
15. Kabir, M.F., Daud, W.M., Khalid, K., Sidek, H.A.A., 1998: Dielectric and ultrasonic properties of rubber wood. Effect of moisture content, grain direction and frequency. Holz als Roh- und Werkstoff 56(4): 223-227.
16. Matheson, A.C., Dickson, R.L., Spencer, D.J., Joe, B., Ilic, J., 2002: Acoustic segregation of *Pinus radiata* logs according to stiffness. Annals of Forest Science 59(5-6): 471–477.
17. Oliveira, F.G.R., Sales, A., 2006: Relationship between density and ultrasonic velocity in Brazilian tropical woods. Bioresource Technology 97(18): 2443-2446.
18. Oliveira, F.G.R., Campos, J.A.O., Sales, A., 2002: Ultrasonic measurements in Brazilian hardwood. Materials Research 5(1): 51-55.
19. Oliveira, F.G.R., Candian, M., Lucchette, F.F., Salgon, J.L., Sales, A., 2005: A technical note on the relationship between ultrasonic velocity and moisture content of Brazilian hardwood (*Goupia glabra*). Building and Environment 40(2): 297-300.
20. Ross, R.J., McDonald, K.A., Green, D.W., Schad, K.C., 1997: Relationship between log and lumber modulus of elasticity. Forest Products Journal 47(2): 89-92.
21. Ross, R.J., Pellerin, R.F., 1994: Nondestructive testing for assessing wood members in structures. A review. Gen. Tech. Rep. FPL-GTR-70. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 40 pp.
22. Ross, R.J., Zerbe, J.I., Wang, X., Green, D.W, Pellerin, R.F., 2005: Stress wave nondestructive evaluation of douglas-fir peeler cores. Forest Prod. J. 55(3): 90-94.
23. Wang, X., Ross, R.J., Erickson, J.R., Ligon, J., 2000: Nondestructive evaluation of standing trees with stress wave methods. In: Proceedings of the 12$^{th}$ International Symposium on Nondestructive Testing of Wood. University of Western Hungary, Sopron. Pp 197-206.
24. Wang, X., Ross, R.J., McClellan, M., Barbour, R.J., Erickson, J.R., Forsman, J.W., McGinnis, G.D., 2001: Nondestructive evaluation of standing trees with a stress wave method. Wood Fiber Sci. 33(4): 522–533.

Petr Horáček, Jan Tipner
Mendel University in Brno
Faculty of Forestry and Wood Technology
Department of Wood Science
Zemědelská 3
613 00 Brno
Czech Republic.
Corresponding author: horacek@mendelu.cz

Khaled T. Hassan
Mendel University in Brno
Faculty of Forestry and Wood Technology
Department of Wood Science
Zemědelská 3
613 00 Brno
Czech Republic

Alexandria University
Faculty of Agriculture
Department of Forestry and Wood Technology
Alexandria
Egypt
E-mail: khaled_taha1985@yahoo.com