Diameter Effect on Stress-Wave Evaluation of Modulus of Elasticity of Logs

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Abstract

Recent studies on nondestructive evaluation (NDE) of logs have shown that a longitudinal stress-wave method can be used to nondestructively evaluate the modulus of elasticity (MOE) of logs. A strong relationship has been found between stress-wave MOE and static MOE of logs, but a significant deviation was observed between stress-wave and static values. The objective of this study was to investigate the effect of log diameter on stress-wave evaluation of MOE of logs and to develop a new stress-wave model by relating stress-wave MOE to log diameter for static MOE prediction. A total of 201 small-diameter logs, including jack pine (*Pinus banksiana*), red pine (*Pinus resinosa* Ait.), Douglas-fir (*Pseudotsuga menziesii*), and ponderosa pine (*Pinus ponderosa*), were nondestructively evaluated. The results of this study indicate that the longitudinal stress-wave technique is sensitive to the size and geometrical imperfections of logs. As log diameter increases, the deviation between stress-wave MOE and static MOE increases. It was also found that log diameter has an interactive effect that contributed significantly when used in conjunction with the fundamental wave equation. The newly developed multi-variable prediction model relating static MOE to stress-wave speed, log density, and log diameter was found to be a better predictor for static MOE of logs than the fundamental wave equation. This could allow for the prediction of static bending properties of logs using longitudinal stress-wave technique at levels of accuracy previously considered unattainable.

Introduction

Longitudinal stress-wave (LSW) nondestructive testing techniques are frequently used in the forest products industry to evaluate various wood and wood-based materials and products. Several significant examples of the use of LSW techniques include grading of veneer for laminated veneer lumber products (Sharp 1985), in-place assessment of timbers in structures (Ross and Pellerin 1994), and decay detection in trees (Mattheck and Bethge 1993; Yamamoto et a1 1998). In addition to these applications, recent studies have shown that longitudinal stress-wave method can be used to nondestructively evaluate the modulus of elasticity (MOE) of logs (Arima et a1 1990; Aratake et al 1992; Aratake and Arima 1994; Sandoz and Lorin 1994; Ross et al. 1997, 1999; Wang 1999; Wang et al. 2001,2002). A strong relationship has been found between stress-wave determined dynamic MOE and static bending MOE of logs, but a significant deviation was also observed between dynamic and static values. It has been postulated that the dimensional size (cross section and length) and geometrical form of a log affects longitudinal stress-wave behavior and thus can cause inaccurate prediction of MOE of the log. The purpose of this study is to investigate the effect of log diameter on stress-wave evaluation of logs and to develop a new stress-wave model by relating stress-wave properties to log diameter for static MOE prediction.

Background

Predicting the MOE of logs with longitudinal stress-waves has received considerable research effort in recent years in terms of log grading or log sorting. Typically, the MOE of a log is determined from the one-dimensional wave equation:

$$MOE_d = C^2 \rho \qquad [1]$$

where:

MOE_d = dynamic modulus of elasticity (apparent MOE) (Pa),
C = wave speed (m/s) and
ρ = gross density (kg/m^3).

This fundamental wave equation was developed for idealized elastic materials in the form of a long slender rod (Meyers 1994; Bucur 1995). Its application in wood materials can be affected by many factors, such as grain angle, knots, wood moisture content (MC), wood temperature, as well as the dimensional size and geometrical form of materials.

Many of the investigations have dealt with the effects of MC, temperature, grain angle, and knots on stress-wave behavior in wood. Stress-wave speed has been shown to decrease as either MC or temperature of wood is increased (James 1961; Burmester 1965; Gerhards 1975). Dynamic MOE calculated from wave speed and wood density increases as MC increases above the fiber saturation point (FSP) (Galligan and Courteau 1965; Gerhards 1975; Sobue 1993). Gerhards (1982) studied the effects of knots on stress waves in lumber and found that wave speed was slowed through knots and the curved grain around knots. Gerhards also suggested that, in lumber with cross grain and knots, the stress wave does not propagate with a normal wave front as supposed by the long-slender-rod theory but has a wave front that leads in the direction of the grain and lags across the grain or through knots. This non-normal wave front causes some problems in timing stress waves, particularly over large' wood members that have a short length.

The size (cross sectional size, length) and geometrical form of a wood material have also been recognized as critical factors to the application of the fundamental wave equation for property prediction. Theoretically, the one-dimensional wave Equation [1] is developed based on uniaxial stress. However, in a real case, one has radial inertia and a wave interaction with the external surfaces (free surfaces) of the material (Meyers 1994). Radial inertia is caused by the kinetic energy of the material flowing radially outward as the material is compressed. This effect, controlled by the dimensional size of materials, could have a significant bearing on the interpretation of stress-wave properties. Porter (1972) first noted from experiments that stress-wave speed could be affected by the dimensional size of the material in lumber testing. As a 51- by 305-mm (2 by 12's) lumber was cut into 51- by 152-mm (2 by 6's) and 51- by 76-mm (2 by 3's), he observed a continuous increase in wave speed. Although the change in wave speed may not be significant, it may introduce a significant change in dynamic MOE calculated from wave speed and wood density since dynamic MOE is proportional to C^2. Wang (1999) investigated stress-wave behavior in red pine logs and found that high diameter to length ratio could cause significant changes in wave propagation path with respect to longitudinal direction.

Wave propagation in a log can be further affected by the variation of wood properties in radial directions, which is a factor related to species, moisture gradient, as well as the diameter of a log. As a wave travels through a log in longitudinal direction, the outer potion of the log (mature wood) may have a dominating effect on the propagation of the wave (Wang 2000). Given the same dimensional size and same global elastic properties, this effect could lead to a higher stress-wave speed in a log than that in a rod of homogeneous material. The MOE of the log could therefore be overestimated. Iijima et al. (1997) examined the relationship between logs and sawn lumber and found that mean dynamic MOE of Sugi logs was 29 percent higher than the static MOE of lumber (green) sawn from the logs. Similarly, Wang et al. (2002) evaluated MOE of red pine and jack pine logs and found that dynamic MOE of logs were 19 to 37 percent greater than the static counterpart of lumber.

The effect of dimensional size on stress-wave prediction of wood properties is still not fully understood, especially for large wood members. Quantitative analyses of overestimation in dynamic MOE of logs have not been reported.

Materials and Methods

A total of 201 logs, including 109 jack pine (*Pinus banksiana*), 50 red pine (*Pinus resinosa* Ait.), 25 Douglas-fir (Pseudotsuga menziesii), and 17 ponderosa pine (*Pinus ponderosa*), were nondestructively evaluated in two previous studies. The first study evaluated jack pine and red pine logs and aimed at comparing different NDE techniques for assessing log quality in terms of flexural strength and stiffness (Wang et al. 2002). These logs came from trees that were grown on the Ottawa National Forest and the Lake Superior State Forest in Northern Michigan. Douglas-fir and ponderosa pine logs were evaluated in a second study. These logs were harvested at the Rougue River National Forest in southwestern Oregon after field stress-wave evaluation was conducted in trees. Although this study was mainy designed to investigate the use of a stress-wave system to assess the potential structural quality of standing timbers, the same experimental procedures as used in the first study have been employed to evaluate the MOE of Douglas-fir and ponderosa pine logs. In both studies, the green weight and the diameters of each log were measured before stress-wave testing and the green density was determined accordingly.

In geometry, these logs are typically in a cylindrical form with a taper **(Fig. 1).** Although the cross section of most logs was basically in round form, irregular shape and curved stem did occur in some logs. To obtain a better estimation of the diameter and gross density of the logs, we measured diameters at both ends and the middle of each log. The average diameter determined from three measurements using Equation [2] was used as the diameter index for analysis. The term "diameter" used throughout the paper thus refers to the average diameter of a log.

$$D = \frac{1}{3}(D_{e1} + D_{e2} + D_m) \qquad [2]$$

where:

D = average log diameter (cm);
D_{e1} = log diameter measured at one end (cm);
D_{e2} = log diameter measured at other end (cm);
D_m = log diameter measured at the middle of a log (cm).

Following the physical measurements, each log was evaluated using a longitudinal stress-wave technique to obtain an estimate of dynamic MOE of the log. A detailed description of the experimental setup for longitudinal stress-wave testing of logs is given by Wang et al. (2001). The stress-wave speed in a logwas determined by coupling measurements of the stress-wave transmission time and the length of the log. Dynamic MOE was then calculated using Equation [1].

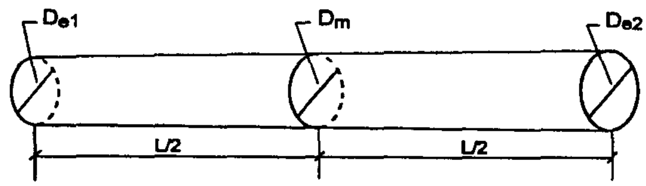

Figure 1. ~ Configuration of a log,

Static bending tests were then performed on the logs using a Metriguard Model 312 Bending Proof Tester to obtain the static MOE of logs. The span between two supports was set as 2.93 m (115.5 in.). The distance from loading point to the nearest support was 0.98 m (38.5 in.), one third of the span. A load was applied to the log through two bearing blocks. Deflection was measured in the central region, a zone of pure bending without shear deformation. The log under test was first preloaded to 445 N (100 lb.) and the deflection was set to zero. This procedure was mainly used to improve the contact between log, supports, and bearing blocks and eliminate the effect of bark on the deflection measurement. The logwas then loaded to 5.08 mm (0.2 in.) deflection. The practical load value corresponding to this deflection was then recorded. Static MOE (MOE,) of a log was then calculated by the following equation:

$$MOE_s = \frac{Pa\,(3L^2 - 4a^2)}{48\delta I} \qquad [3]$$

where:

P = load,
a = distance from the end support to nearest load point,
L = log length,
δ = midspan deflection,
I = moment of inertia.

The MC of jack pine and red pine logs were determined from three 2.5-cm-thick (1-in.-thick) disks cut from the tree stems using the ovendry method (ASTM D-4442). For Douglas-fir and ponderosa pine logs evaluated in the second study, a significant moisture loss had already occurred by the time of testing, mainly due to the long-distance transportation and storage. The moisture contents were therefore measured on the boards using a moisture meter immediately after the cutting.

Table 1. ~ ***Physical characteristics of logs at the time of testing.***

Species	Number of logs	Diameter cm (in.)			Density cm/g³ (lb/ft.³)			Moisture content (%)		
		Ave.	Min.	Max	Ave.	Min.	Max.	Ave.	Min.	Max
Red pine	50	20.0 (7.9)	11.2 (4.4)	25.8 (10.2)	0.85 (53.0)	0.77 (48.0)	0.91 (56.7)	115	84	156
Jack pine	109	20.0 (7.9)	11.9 (4.7)	27.9 (11.0)	0.65 (40.4)	0.46 (28.7)	0.86 (53.7)	49	22	89
Ponderosa pine	17	15.7 (6.4)	10.8 (4.4)	23.9 (9.7)	0.83 (51.8)	0.69 (43.1)	0.92 (57.6)	36	30	42
Douglas-fir	25	15.4 (6.3)	10.5 (4.3)	24.5 (10.0)	0.66 (41.5)	0.56 (35.2)	0.78 (48.5)	24	19	26

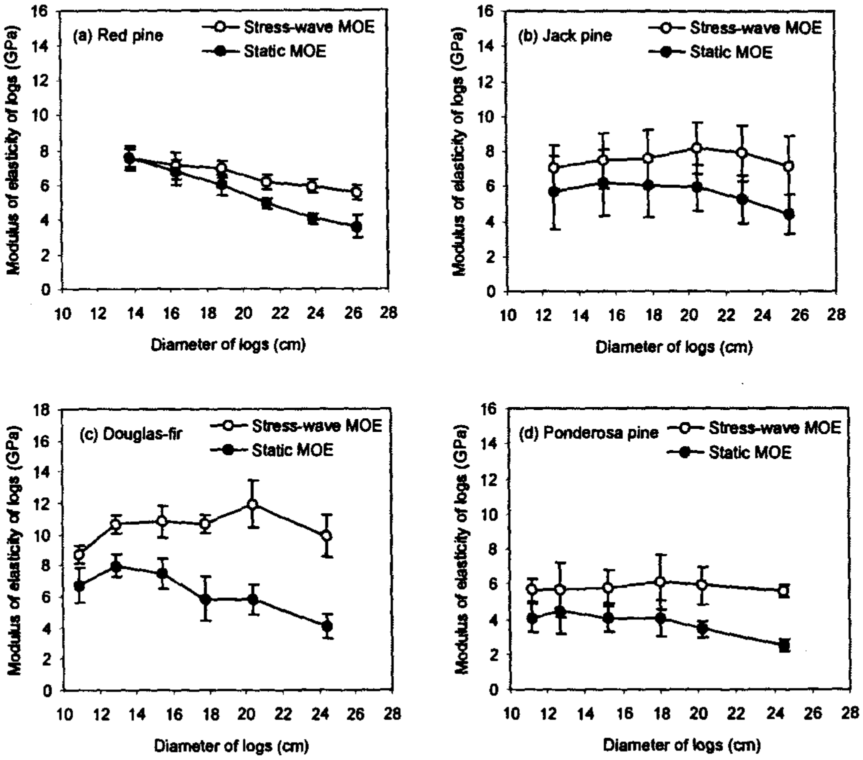

Figure 2. ~ *MOE of logs as a function of log diameter.*

Results and Discussion

Physical Properties of Logs

The physical characteristics of the logs at the time of testing are summarized in **Table 1.** The diameter of the logs tested was in the range of 11 to 28 cm (4.3 to 11 in.), which is a typical diameter range for small-diameter timber (Wolfe 2000). The length of red pine and jack pine logs was 3.66 m (12 ft.) and that of ponderosa pine and Douglas-fir logs was 3 m (9.8 ft.). Although the logs tested have different diameter to length ratios due to the variation in diameters or lengths, we were not intended to address how the length of a log would affect the stress-wave behavior in this study.

The logs were in different moisture conditions at the time of testing: the MC ranged from 84 to 156 percent for red pine logs, 22 to 89 percent for jack pine logs, 30 to 42 percent for ponderosa pine logs, and 19 to 26 per-Cent for Douglas-fir logs. For red pine, jack pine, and ponderosa pine logs, the average MC exceeded the FSP (about 30%). It was also noted that the Douglas-fir and ponderosa pine logs, as well as some of the jack pine logs, had dried significantly by the time of testing. Especially for Douglas-fir logs, the MC were already dried to below the FSP due to long-distance transportation and storage.

Effect of Log Diameter on MOE

Figure 2 shows both static and dynamic MOE of logs as a function of the diameter of logs. The dynamic MOE (also designated as stress-wave MOE) of logs were determined using one-dimensional wave Equation [1]. To quantitatively analyze the effects of log diameter on stress-wave and static properties, we grouped the logs of each species into six diameter classes. The data points shown in **Figure 2** are mean values of the log MOE for each diameter class, and the error bar indicates the standard deviations (±1 standard deviation).

It is clear that both static and dynamic MOE of red pine logs decreased continuously as log diameter increased. However the dynamic MOE apparently had a different functional relationship with log diameter compared to static MOE - it decreased in a much slower rate with increasing diameter. In other words, the dynamic MOE deviated from static MOE progressively as log diameter increased.

For jack pine, Douglas-fir, and ponderosa pine logs, the static MOE also decreased with increasing log diameter except for the first diameter class (small logs). However, the dynamic MOE didn't show a clear steady trend as log diameter increased. It was also noted that both static and dynamic MOE of jack pine, Douglas-fir, and ponderosa pine logs had a high variation in each diameter class. We believe that this could be contributed to the significant differences in geometrical forms of the logs. Of all species tested, red pine logs apparently had a better shape in terms of roundness and straightness of a stem. Jack pine, Douglas-fir, and ponderosa pine logs appeared to have a more irregular shape in cross section, a more curved stem, and more growth defects than red pine logs, which could have a significant impact on stress-wave propagation in the logs.

MOE Deviation as a Function of Log Diameter

The diameter effect on stress-wave prediction of log MOE can be further illustrated by analyzing the deviation between dynamic MOE and static MOE. Here, the MOE deviation is defined as:

$$\Delta = MOE_d - MOE_s \qquad [4]$$

Figure 3 shows MOE deviation as a function of log diameter. It can be seen that MOE deviation increases in proportion to the increase of the diameter of logs for all species tested. This clearly indicated that the MOE of logs could be substantially overestimated by stress-wave Equation [1] due to diameter effect. It was also noted that the general shapes of the MOE deviation and log diameter curves were very similar for all pine species (red pine, jack pine, and ponderosa pine). As an approximate estimation based on a linear regression fit, the MOE of logs overestimated by 0.16 GPa (23,200 psi) for every cm's increase in diameter, starting from the diameter of about 14 cm. Douglas-fir appeared to have much larger MOE deviations in all diameter classes compared to the pine species and an overestimation of about 0.32 GPa (46,400 psi) would be expected per cm's increase in diameter. This deviation would make it difficult to use longitudinal stress-wave techniques for a reliable assessment of log stiffness. The mechanism responsible for the MOE deviation is not clear yet. It is possible that

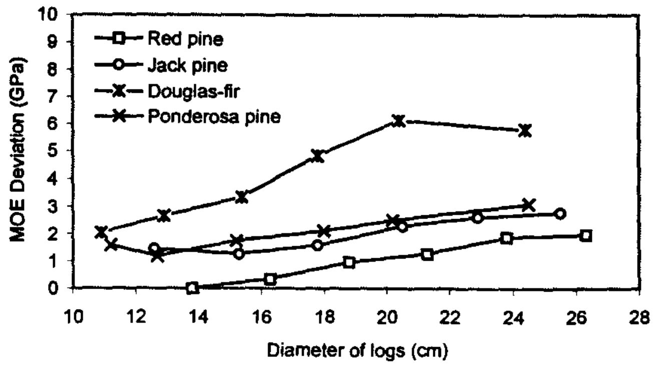

Figure 3. ~ *MOE deviation as a function of log diameter.*

the overestimation of MOE was caused by the effect of log diameter on wave propagation through the log and the tendency of stress waves to seek out the high MOE zone for its path.

MOE Prediction Models

We compared two stress-wave prediction models for evaluating the MOE of logs, with and without considering diameter effect. Model 1 is the fundamental wave Equation [1] that uses stress-wave speed (*C*) and gross density (ρ) as predictive parameters without considering log diameter effect. Model 2 is a multi-variable regression model that uses stress-wave speed (*C*), gross density (ρ), and log diameter (*D*) as predictive parameters. The relationships between stress-wave predicted MOE and static MOE were then examined through statistical analysis.

Prediction Model 1 - Fundamental Wave Equation

We first used the fundamental wave equation as a prediction model to assess the MOE of the logs (designated as stress-wave MOE). The relationship of stress-wave MOE to static MOE was represented using a linear regression model ($y = \beta_0 + \beta_1 x$, or $MOE = \beta_0 + \beta_1 C^2\rho$).

In general, the stress-wave MOE of logs was very closely correlated with the static MOE for all species except for Douglas-fir **(Fig. 4).** The correlation coefficients were reported in **Table 2.** Of the logs evaluated, the red pine logs produced a better correlation than the logs of other species. As mentioned earlier, this could be attributed to the geometrical differences between species. It appeared that the longitudinal stress wave is sensitive to the geometrical imperfections of logs. Irregular shape (not round in cross section and curved in stem) of logs could cause errors in diameter measurements, thus cause errors in density and MOE determination. It was also noted that the plotted data points in Figure 4 were more heavily concentrated below the 45° line than above, which indicated that one-dimensional wave

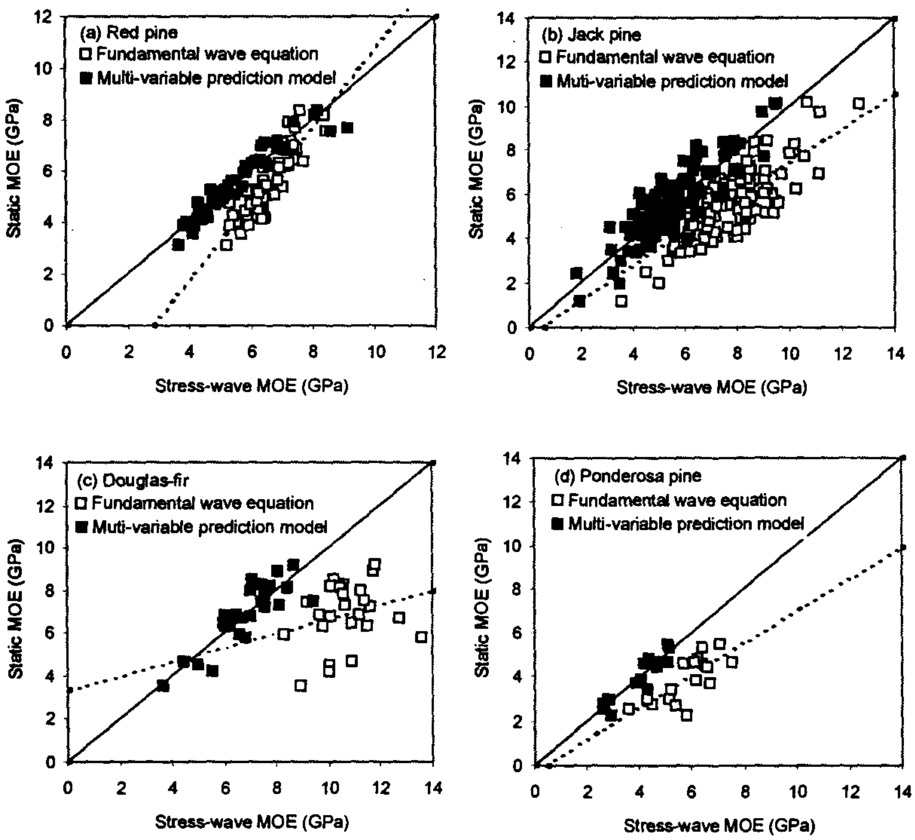

Figure 4. ~ *Relationship between stress-wave predicted MOE and static MOE of logs.*

Table 2. ~ *Results of statistical analysis of two prediction models.*

	Prediction Model 1: MOE = $\beta_0 + \beta_1 (C^2 \rho)$			Prediction Model 2: MOE = $a (C^2 \rho)^b D^c$			
Species	β_0	β_0	R^2	*a*	*b*	*c*	R^2
Red pine	-4.127	1.4740	0.75	3.6890	0.9078	-0.7326	0.92
Jack pine	-0.444	0.7883	0.60	1.9725	1.1957	-0.5060	0.73
Douglas fir	3.323	0.3313	0.07	2.9470	1.3852	-0.8952	0.79
Ponderosa pine	-0.362	0.7345	0.55	3.5858	1.0522	-0.6459	0.87

equation yielded higher MOE values than its static counterpart.

Prediction Model 2 - Multivariable Regression Model

The results discussed in the previous section demonstrated the importance of log diameter as a predictive parameter. In an effort to obtain a better prediction of MOE of logs, we developed a multi-variable regression model relating static MOE to three NDE parameters: stress wave speed *C*, gross density ρ, and log diameter *D*. The mathematical regression model used in this analysis was assumed to be of the following form:

$$MOE' = a\,(C^2\,\rho)^b\,D^c \qquad [5]$$

where:

MOE′ = the predicted MOE of a log;

a, *b*, and *c* = the least-square fitted parameters.

Model (5) with stress-wave speed C, gross density ρ, and log diameter *D* as predictor variables was fitted to the experimental data for each species by means of the least squares method. The MOE of logs predicted by this model was then compared against the static MOE of the logs. Results of the regression analyses and values for the least-square fitted parameters in the model are summarized in **Table 2.**

The relationships between stress-wave predicted MOE using the multi-variable model (5) and the static MOE of logs for four species are also shown in **Figure 4,** as a comparison to the MOE relationships with prediction model 1. The results clearly indicated that a strong relationship existed between stress-wave predicted MOE with multi-variable model and static MOE for all species. Compared with the fundamental wave equation, a significant improvement was achieved in the multi-variable model. The coefficient of determination R^2 increased from 0.07 to 0.75 for the prediction model 1 to 0.73 to 0.92 for the prediction model 2. This implied that the diameter of a log had an interactive effect that contributed significantly when used in conjunction with stress-wave speed and gross density.

Conclusions

Based on the results of this study, we conclude the following:

1. Log diameter has a significant effect on stress-wave propagation in logs. Dynamic MOE of logs determined from one-dimensional wave equation deviated from static MOE progressively as log diameter increased. It was found that the MOE deviation increased in proportional to the increase of the diameter of logs for all species tested.
2. The longitudinal stress wave is sensitive to the geometrical imperfections of logs. Round and straight logs produce better correlation between stress-wave MOE and static MOE.
3. Log diameter had an interactive effect that contributed significantly when used in conjunction with stress-wave speed and gross density. The developed multi-variable regression model relating static MOE to stress-wave speed, gross density, and log diameter was found to be a better predictor for static modulus of elasticity of logs. This could allow for the prediction of static bending properties of logs using longitudinal stress-wave technique at levels of accuracy previously considered unattainable.

References

Aratake, S., T. Arima, T. Sakoda, Y. Nakamura. 1992. Estimation of modulus of rupture (MOR) and modulus of elasticity (MOE) of lumber using higher natural frequency of log in pile of logs. Possibility of application for sugi scaffolding board. Mokuzai Gakkaishi. 38(11):995-1001.

Aratake, S. and T. Arima. 1994. Estimation of modulus of rupture (MOR) and modulus of elasticity (MOE) of lumber using higher natural frequency of log in pile of logs. II. Possibility of application for sugi square lumber with pith. Mokuzai Gakkaishi. 40(9):1003-1007.

Arima, T., N. Nakamura, S. Maruyama, and S. Hayamura. 1990. Natural frequency of log and lumber hit with hammer and applications for production processing. *In*: Proc. of the 1990 International Timber Engineering Conference. 1990 Oct. 23-25; Tokyo, Japan, Science Univ. of Tokyo. pp. 527-533.

ASTM. 1999. Annual Book of Standards. American Society for Testing and Materials. West Conshohocken, PA. 675 pp.

Bucur, Voichita. 1995. Acoustics of Wood. CRC Press, Inc. New York.

Burmester, A. 1965. Relationship between sound velocity and the morphological, physical, and mechanical properties of wood. Holz als Roh- und Werkstoff. 23(6):227-236.

Galligan, W.L. and R.W. Courteau. 1965. Measurement of elasticity of lumber with longitudinal stress waves and the piezoelectric effect of wood. *In*: Proc. of the 2nd Symposium on Nondestructive Testing of Wood. April. Washington State Univ., Pullman, WA. pp. 223-224.

Gerhards, C.C. 1975. Stress wave speed and MOE of Sweetgum ranging from 150 to 15 percent MC. Forest Prod. J. 25(4): 51-57.

Gerhards, C.C. 1982. Effects of knots on stress wave in lumber. USDA Forest Service, Research Paper FPL 384, Forest Prod. Lab., Madison, WI.

Iijima, Y., A. Koizumi, Y. Okazaki, and others. 1997. Strength properties of sugi (Cryptomeria japonica) grown in Akita Prefecture III: Some relationships between logs and sawn lumber. Mokuzai Gakkaishi. 43(2):159-164.

Mattheck, C. and K. Bethge. 1993. Detection of decay in trees with the metriguard stress wave timer. J. of Arboriculture. 19(6):374-378.

Meyers, Marc A. 1994. Dynamic behavior of materials. John Wiley & Sons, Inc. New York, NY.

James, W.L. 1961. Effect of temperature and moisture content on internal friction and speed of sound in Douglas-fir. Forest Prod. J. 11(9):383-390.

Porter, A.W., D.J. Kusec, and S.L. Olson. 1972. Digital computer for determing modulus of elasticity of structural lumber. Dept. of Environment, Canadian Forest Serv. WFPL Info. Rep. VP-X-99. Vancouver, B.C.

Ross, R.J. and R.F. Pellerin. 1994. Nondestructive testing for assessing wood members in structures: A review. Gen. Tech. Rep.

FPL-GTR-70 (Rev.) Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 40 p.

Ross, R.J., K.A. McDonald, D.W. Green, and K.C. Schad. 1997. Relationship between log and lumber modulus of elasticity. Forest Prod. J. 47(2):89-92.

Ross, R.J., S.W. Willits, W.V. Segen, T. Black, B.K. Brashaw, and R.F. Pellerin. 1999. A stress wave based approach to NDE of logs for assessing potential veneer quality. Part 1. Small-diameter ponderosa pine. Forest Prod. J. 49(11/12):60-62.

Sandoz, J.L and P. Lorin. 1994. Standing tree quality assessment using ultrasound. *In*: Proc. of the First European Symposium on Nondestructive Evaluation of Wood; 1994 Sep. 21-23; Sopron, Hungary. Sopron, Hungary: Sopron, Hungary Univ. of Sopron. Vol. 2, pp. 493-502.

Sharp, D.J. 1985. Nondestructive testing techniques for manufacturing LVL and predicting performance. *In*: Proc. of the 5th Nondestructive Testing of Wood Symposium; 1985 Sep. 9-11; Pullman, WA. Pullman, WA: Washington State Univ. pp. 99-108.

Sobue, Nobuo. 1993. Simulation study on stress wave velocity in wood above fiber saturation point. Mokuzai Gakkaishi. 39(3): 271-276.

Wang, X. 1999. Stress wave-based nondestructive evaluation (NDE) methods for wood quality of standing trees. Ph.D. Dissertation, Michigan Technological Univ., Houghton, MI.

Wang, X., R.J. Ross, J.R. Erickson, J.W. Forsman, G.D. McGinnis, and R.C. DeGroot. 2000. Nondestructive methods of evaluating quality of wood in preservative-treated piles. Res. Note

FPL-RN-0274. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 9 p.
Wang, X., R.J. Ross, J.R. Erickson, J.W. Forsman, G.D. McGinnis, and R.C. DeGroot. 2001. Nondestructive evaluation of potential quality of creosote-treated piles removed from service. Forest Prod. J. 51(2):63-68.
Wang, X., R.J. Ross, J.A. Mattson, J.R. Erickson, J.W. Forsman, E.A. Geske, and M.A. Wehr. 2002. Nondestructive evaluation techniques for assessing modulus of elasticity and stiffness of small-diameter logs. Forest Prod. J. 52(2):79-85.
Wolfe, R. 2000. Research challenges for structural use of small-diameter round timbers. Forest Prod. J. 50(2):21-29.
Yamamoto, K., O. Sulaiman, and R. Hashim. 1998. Nondestructive detection of heart rot of Acacia mangium trees in Malaysia. Forest Prod. J. 48(3):83-86.

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