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* Lamb.), red pine (*Pinus resinosa* Ait.), Douglas-fir (*Pseudotsuga menziesii*), and ponderosa pine (*Pinus ponderosa* Dougl. ex Laws), 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 contributes significantly to MOE prediction when used in conjunction with the fundamental wave equation. The newly developed multivariable prediction model relating static MOE to stress-wave speed, log density, and log diameter was found to better predict MOE during stress-wave evaluation of logs than did the fundamental wave equation. This could allow for the prediction of static bending properties of logs using the longitudinal stress-wave technique at levels of accuracy previously considered unattainable.

Keywords: Stress wave, nondestructive evaluation, modulus of elasticity, logs, diameter.

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 al. 1998). In addition to these applications, recent studies have shown that longitudinal stress-wave methods can be used to nondestructively evaluate the modulus of elasticity (MOE) of logs (Arima et al. 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 was 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 material affects longitudinal stress-wave behavior and thus can cause inaccurate prediction of MOE (Meyers 1994; Wang et al. 2002). 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.

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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:

$$MOE_d = C^2 \rho \tag{1}$$

where MOE, is dynamic MOE (apparent MOE) (Pa), C is wave speed (m/s), and ρ is 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, wood temperature, as well as the dimensional size and geometrical form of material.

Many investigations have dealt with the effects of moisture content, temperature, grain angle, and knots on stress-wave behavior in wood. Stress-wave speed has been shown to decrease as either moisture content or temperature of wood is increased (James 1961; Burmester 1965; Gerhards 1975). Dynamic MOE calculated from wave speed and wood density increases as moisture content 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 in large, short wood members.

The size (in cross section and length) and geometrical form of wood have also been recognized as critical factors to the application of the fundamental wave equation for property prediction. Theoretically, the one-dimensional wave equation (Eq. 1) is developed based on uniaxial stress. However, in a real case, there is 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 et al. (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 (nominal 2- by 12-in.) lumber was cut down to 51 by 152 mm (nominal 2 by 6 in.) and 51 by 76 mm (nominal 2 by 3 in.), Porter et al. 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 the wave propagation path with respect to longitudinal direction.

Wave propagation in a log can be further affected by the variation of wood properties in the radial direction, which is related to species, moisture gradient, and the diameter of the log. As a wave travels through a log in the longitudinal direction, the outer portion of the log (mature wood) may have a dominating effect on the propagation of the wave because of the tendency of the stress wave to seek out the high MOE zone for its path (Wang et al. 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 because the outer portion of a log usually has higher stiffness than does the log as a whole (mature wood and juvenile wood). 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 (*Cryptomeria japonica* D. Don) was 29% 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 was 19 to 37% 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 the overestimation of log dynamic MOE have not been reported.

MATERIALS AND METHODS

In two previous studies, 201 logs, including 109 jack pine (*Pinus banksiana* Lamb.), 50 red pine (*Pinus resinosa* Ait.), 25 Douglas-fir (*Pseudotsuga menziesii)*, and 17 ponderosa pine (*Pinus ponderosa* Dougl. ex Laws), were nondestructively evaluated. 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 (Wang et al., 2003). These logs were harvested at the Rogue River National Forest in southwestern Oregon after field stress-wave evaluation was conducted in trees. Although this study was designed mainly to investigate the use of a stress-wave system to assess the potential structural quality of standing timber, the same experimental procedures as used in the first study were employed to evaluate the MOE of Douglas-fir and ponderosa pine logs. In both studies, the green weight and the diameter of each log were measured before stress-wave testing, and the green density was determined accordingly.

Geometrically, these logs are typically a cylindrical form with a taper. Although the cross section of most logs was basically in round form, irregular shape and curved stems 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 was used as the diameter index for analysis. The term diameter used throughout this paper thus refers to the average diameter of a log.

After the physical measurements, each log was evaluated using a longitudinal stress-wave technique to obtain an estimate of dynamic MOE of the log. The experimental setup for stress-wave measurements on the logs is illustrated in Fig. 1. An accelerometer was attached to one end of the log, near the center of the cross section. A stress wave was introduced to the log through a hammer impact on the opposite end, and the resulting stress-wave signals were recorded with a personal computer. Figure 2 shows a typical time domain signal observed by the computer in testing logs. The waveform consisted of a series of

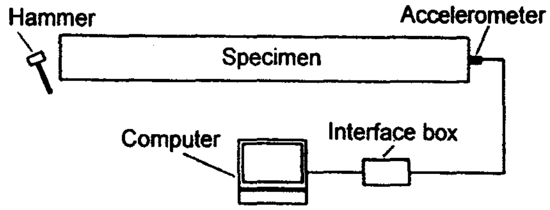

FIG. 1. Experimental setup for stress-wave measure-

equally spaced pulses, which indicate the reverberation of the stress wave within the log. The amplitude of the time signal decreased with each successive passing of the wave. The stress-wave speed C in a log was determined by coupling measurements of the stress-wave transmission time Δt (the time between two consecutive pulses of a waveform observed) and the length of the log (L):

$$C = \frac{2L}{\Delta t} \tag{2}$$

Static bending tests were then performed on the logs using a Metriguard (Pullman, WA) Model 3 12 bending proof tester to obtain the static MOE of logs. The span between two supports was set at 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

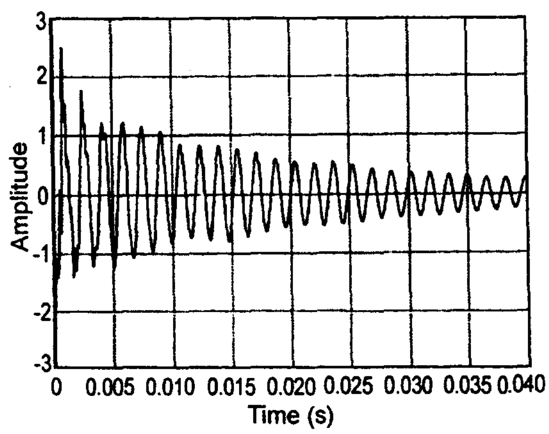

FIG. 2. Time history of a typical stress waveform observed in a treated pile section.

log through two bearing blocks. Deflection was measured at the midspan of a log. The log under test was first preloaded to 445 N (100 lb), and the deflection was set to zero. This procedure was used mainly to improve the contact between log, supports, and bearing blocks and to eliminate the effect of bark on the deflection measurement. The log was then loaded to 5.08-mm (0.2-in.) deflection. The load value corresponding to this deflection was then recorded. Static modulus of elasticity (MOE_s) of a log was then calculated by the following equation:

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

where P is load; a, distance from the end support to nearest load point; L, log span; δ, midspan deflection; and I, moment of inertia.

The moisture contents (MC) of jack pine and red pine logs were determined from three 2.5-cm- (1-in.-) thick disks cut from the tree stems using the oven-dry method (ASTM D-4442) (ASTM 1999; Wang et al. 2002). For Douglas-fir and ponderosa pine logs evaluated in the second study, no moisture samples were cut from logs at the time of testing because of the limitation of log length and because end drying occurred during the long-distance transportation and storage. The MCs were therefore measured on the boards using a resistance-type moisture meter (two pin electrodes) after the cutting.

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 and lengths, we did not intend 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 MCs of red pine logs ranged from 84 to 156% with an average of 115%; the MCs of jack pine logs were from 22 to 89% with an average of 49%. The specific gravities calculated based on the average MC and green density were 0.40 for red pine and 0.43 for jack pine, which were in a good agreement with the values given in the Wood Handbook (0.41 and 0.40, respectively) (Forest Products Laboratory 1999). For ponderosa pine and Douglas-fir logs, no MC information was collected at the time of testing. The MCs measured on boards cut from these logs ranged from 30 to 42 percent for ponderosa pine and 19 to 26% for Douglas-fir. A substantial moisture loss had occurred by the

TABLE 1. *Physical characteristics of green logs at the time of testing.*

Species	No. of logs	Diameter cm (in.)			Density g/cm^3 (lb/ft^3)			Moisture content[a] (%)		
		Average	Min.	Max.	Average	Min.	Max.	Average	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)	118	–	–
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)	48	–	–

*The average moisture content for ponderosa pine and Douglas-fir logs was estimated from the average green density of logs and the specific gravity of wood given in the Wood Handbook (Forest products Laboratory 1999).

time of testing the boards (rough cut) due to dry weather and waiting time. We estimated the MCs of logs at the time of testing were about 118% for ponderosa pine and 48% for Douglas-fir based on the green density and the specific gravity given in the Wood Handbook (0.38 for ponderosa pine and 0.45 for Douglas-fir).

Effect of log diameter on modulus of elasticity

Figure 3 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 here was determined using the one-dimensional wave equation (Eq. (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 Fig. 3 are mean values of the log MOE for each diameter class, and the error bars indicate standard deviations (±1 standard deviation).

It is clear that both static and dynamic MOE of red pine logs decreased continuously as log diameter increased. The steady decrease of static MOE with increasing log diameter was presumably due to the difference in tree growth rate. The logs of each species evaluated in this study were cut from trees that were planted in approximately the same year. For trees of the same age, bigger trees resulting from higher growth rate would generally produce wood of lower density and lower stiffness (Zhang 1995; Zhang and Morgenstern 1996; Koubaa et al. 2000).

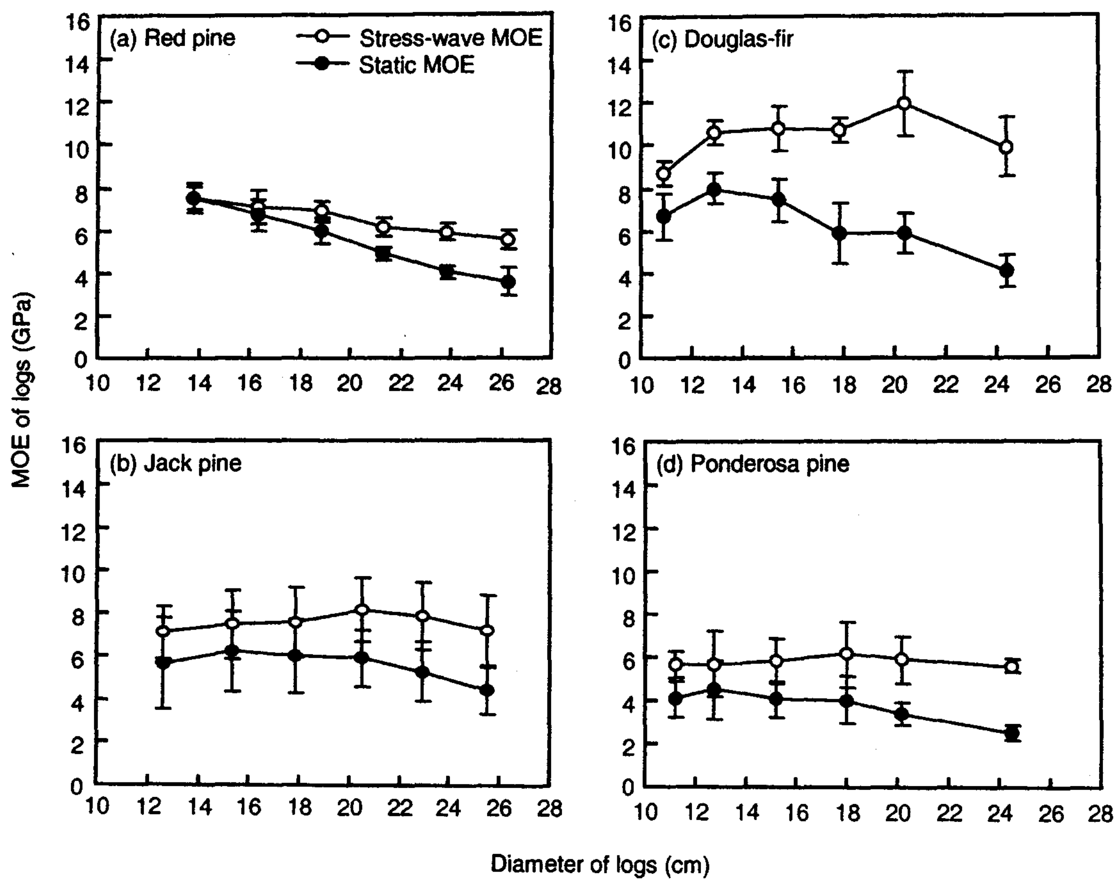

FIG. 3. Modulus of elasticity (MOE) of logs as a function of log diameter.

Although the dynamic MOE of red pine logs decreased steadily with increasing log diameter, it apparently had a different functional relationship with log diameter than did static MOE—dynamic MOE decreased at a much slower rate with increasing diameter than did static MOE. In other words, the dynamic MOE deviated from static MOE progressively as log diameter increased.

For jack pine, Douglas-fir, and ponderosa pine logs, static MOE also decreased with increasing log diameter except for the first diameter class (small logs). However, dynamic MOE didn't show a clear steady trend as log diameter increased. Also, 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 might be partially attributed to the significant differences in geometrical forms of the logs. Of all species tested, red pine logs were the most consistently round and straight in the 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 affect 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

$$\Delta = MOE_d - MOE_s \tag{4}$$

Figure 4 shows MOE deviation as a function of log diameter. The MOE deviation increased 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 Eq. (1) due to diameter effect. Also, in general, 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 would be overestimated by 0.16 GPa (23,200 lb/in^2) for every centimeter 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 with the pine species, and therefore, for Douglas-fir, an overestimation of about 0.32 GPa (46,400 lb/in^2) would be expected per centimeter increase in diameter. The mechanism responsible for the MOE deviation is not yet clear. It is possible that 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. This deviation would make it difficult to use longitudinal stress-wave techniques for a reliable assessment of log stiffness.

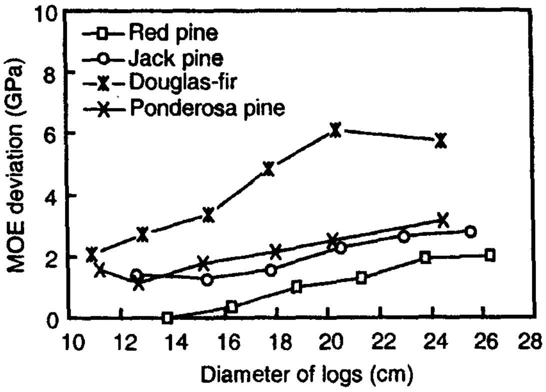

FIG. 4. Modulus of elasticity (MOE) deviation as a function of log diameter.

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 that uses stress-wave speed (C) and gross density (ρ) as predictive parameters without considering log diameter effect. Model 2 is a multivariable 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 ($y = ß_0 + ß_1 x$ or $MOE = ß_0 + ß_1 C^2 \rho$).

In general, the stress wave MOE of logs was very closely correlated with the static MOE for all species except for Douglas-fir (Fig. 5). The correlation coefficients are reported in Table 2. Stress wave and static MOE were better correlated for red pine logs than for the logs of the other three 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 causing errors in density and MOE determination. Also, the plotted data points in Figure 5 were more heavily concentrated below the 45 degree line than above, which indicates that the one-dimensional wave 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 multivariable regression model relating static MOE to three NDE parameters: stress wave speed *C*, gross density r, and log diameter *D.* The mathematical regression model used in this analysis was assumed to be of the following form:

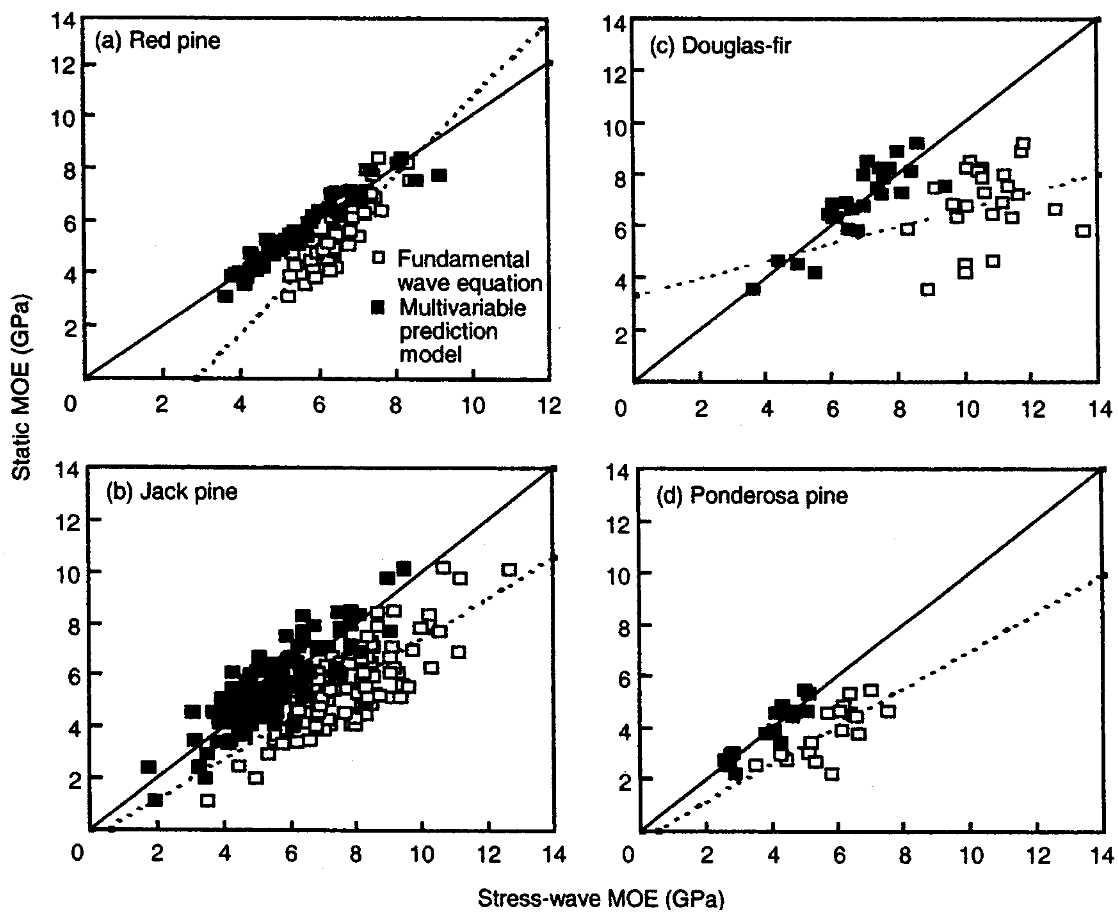

FIG. 5. Relationships between stress-wave-predicted modulus of elasticity (MOE) and static MOE of logs.

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

where, MOE' is the predicted modulus of elasticity of a log; *a*, *b*, and *c*, the least-squares fitted parameters.

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

CONCLUSIONS

Log diameter has a significant effect on stress-wave propagation in logs. Dynamic MOE of logs determined from a one-dimensional wave equation deviated from static MOE progressively as log diameter increased. The MOE deviation observed increased in proportion to the increase of the diameter of logs for all species tested. Also, log diameter had an interactive effect that contributed significantly to MOE prediction when used in conjunction with the fundamental wave equation. The newly developed multivariable regression model relating static MOE to stress-wave speed, gross density, and log diameter was found to better predict MOE during stress wave evaluation of logs than did the fundamental wave equation. This could allow for the prediction of static bending properties of logs using the longitudinal stress-wave technique at levels of accuracy previously considered unattainable.

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Table 2. *Results of statistical analysis of two prediction models for modulus of elasticity (MOE).*[a]

	Prediction Model 1: MOE = $ß_0 + ß_1\,(C^2\rho)$			Prediction Model 2: MOE' = $a\,(C^2\,\rho)^b\,D^c$			
Species	$ß_0$	$ß_1$	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

[a] $ß_0$, $ß_1$ are least-square fitted parameters in model I; a. b, care least-square fitted parameters in model 2; R^2 is coefficient of determination; *C* is wave speed; r is gross density; D is log diameter.

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