Stress wave nondestructive evaluation of Douglas-fir peeler cores

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Abstract

With the need for evaluating the utilization of veneer peeler log cores in higher value products and the increasing importance of utilizing round timbers in poles, posts, stakes, and building construction components, we conducted a cooperative project to verify the suitability of stress wave nondestructive evaluation techniques for assessing peeler cores and some mechanical properties of lumber that might be derived from peeler cores. Longitudinal stress waves were used to evaluate peeler cores from 111 Douglas-fir stems. Supplementary dynamic and static tests were thenconducted on2 by4 lumber sawn from the cores. Stress wave testing of peeler cores was found to be a good predictor of static and dynamic modulus ofelasticity (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. Nonetheless, based on past experience, the data derived could establish a means for classifying peeler cores into three stress classes, which would have higher levels ofconfidence for assigned bending and tensile design strength. For lumber stress wave MOE compared with peeler core stress wave MOE, the coefficient ofdetermination (r^2) value was 0.8 1. In the comparison oftransverse vibration MOE of lumber with stress wave MOE, peeler cores had a corresponding r^2 of 0.72. Comparison of statically determined tensile MOE of the lumber with stress wave MOE ofthe cores showed an 9 of 0.70, but for ultimate tensile strength ofthe lumber taken as one large group compared with stress wave MOE, the r^2 was only 0.38. For statically determined modulus ofrupture ofthe derived lumber taken as a single group compared with dynamic stress wave MOE of the peeler cores, the r^2 was 0.32.

The USDA Forest Service Forest Products Laboratory (FPL) has been developing nondestructive evaluation (NDE) techniques to assist in the grading of logs. In previous publications, we have reported on experimental techniques developed for log NDE studies. One technique utilized mechanical impact to induce a stress wave in wood specimens. We observed wave propagation in the specimens by placing an accelerometer on the wood surface and displaying its output on a digital storage oscilloscope. This enabled us to examine fundamental relationships between wave propagation characteristics and wood properties. The development of this technique led to a series of studies focused on the application of stress wave NDE methods to grading of logs.

Ross et al. (1997) examined the relationship between log NDE measurements and the quality of lumber obtained from balsam fir and eastern spruce logs. They observed useful relationships, with the relationship being exceptionally strong for eastern spruce logs. Green and Ross (1997) found similar results in a series of studies using the same technique with Douglas-fir, western hemlock, and south-

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Table 1. — Properties of Douglas-fir peeler cores and lumber. [a]

	Peeler core	Lumber					
		MOE					
Value	MOE_{sw}	MOE_{sw} [b]	MOE_{v} [b]	MOE_{B} [c]	MOE_{T} [d]	MOR	UTS
	---------- ($\times 10^6$ psi) ----------					---- ($\times 10^3$ psi) ----	
Mean	1.42	1.31	1.32	1.26	1.69	5.853	3.826
Minimum	0.84	0.77	0.67	0.67	1.06	2.510	0.595
Maximum	2.44	1.88	2.08	2.22	2.67	1.150	8.417
SD	0.297	0.253	0.280	0.320	0.360	1.784	1.636
COV (%)	20.9	19.3	21.1	24.9	21.3	30.5	42.7
r	--	--	0.90	0.68	0.84	0.57	0.61
r^2	--	--	0.81	0.47	0.70	0.32	0.37

[a] Testing methods: MOE_{sw} = stress wave MOE (green condition), MOE_{v} = transverse vibration MOE (dry), MOE_{B} = static bending MOE (dry), and MOE_{T} = tension MOE (dry); MOR (dry, edgewise); UTS (dry, parallel to grain); SD = standard deviation; COV = coefficient of variation; *r* = correlation coefficient; r^2 = coefficient of determination.
[b] Average of types A and B 2 by 4 lumber.
[c] Type A 2 by 4 lumber.
[d] Type B 2 by 4 lumber.

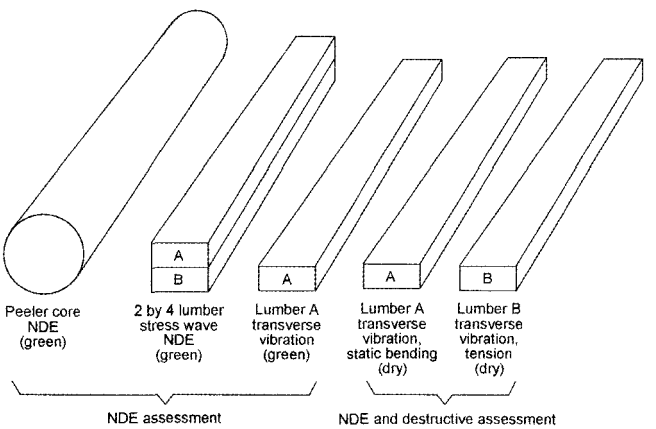

Figure 1. — Study flowchart.

ern pine logs. Pellerin et al. (1989a, 1989b) compared stress wave modulus of elasticity (MOE_{sw}) of roundwood with ultimate tensile stress, MOE in tension, MOE in compression parallel to grain, shear parallel to grain, tension perpendicular to grain, compression perpendicular to grain, and hardness of lumber for different varieties of lodgepole pine grown at different elevations.

Wang et al. (2000) followed the work of Green and Ross (1997) on Douglas-fir, hemlock, and southern pine with studies on red maple logs and reported that logs with high stress-wave grades produced high-grade lumber. In more recent work, Ross et al. (1999) reported on the use of longitudinal stress wave NDE techniques to evaluate logs for potential veneer quality. They found strong relationships between log NDE measurements and MOE of veneer obtained from the logs.

The objective of the study reported here was to evaluate longitudinal stress wave NDE techniques to assess peeler core quality.

Materials and methods

We obtained 111 Douglas-fir peeler cores from a wood products manufacturer in the Pacific Northwest region of the United States. All peeler core specimens were 2.6 m (8.5 ft.) long and 15 cm (6 in.) in diameter.

A schematic of the experiment is shown in **Figure 1.** Each core was weighed, and the speed of longitudinal stress waves that traveled through the core was measured in the green condition using the experimental setup shown in **Figure 2.** The MOE of each core was then calculated from stress wave speed and wood density based on the basic stress wave formula:

$$MOE_{sw} = C^2\rho \quad \textbf{[1]}$$

where:

MOE_{sw} = stress wave modulus of elasticity (Pa, psi)

C = stress wave speed measured in peeler core (m/sec., ft./sec.)

ρ = density of peeler core (kg/m^3, pcf), with both mass and volume measurements under moisture content at time of test

Each core was then cut into two 40- by 90-mm (nominal 2- by 4-in.) lumber specimens (designated as lumber A and lumber B) for further NDE and destructive assessments. The MOE of each lumber specimen was first determined using the same stress wave NDE techniques (measurement of speed of propagated wave through wood). Next, a transverse vibration test (measurement of resonant frequency of wood vibrating as a simply supported beam with center loading), executed on only A boards, was applied by a commercially available testing machine. All specimens were dried to equilibrium at conditions that resulted in final moisture contents of 6 to 7 percent. Both A and B specimens obtained from each peeler core were evaluated dry using transverse vibration NDE. A detailed description of the instrumentation and testing procedure of this technique is given in a previous publication (Ross et al. 1991).

To obtain static bending properties of the peeler cores, the A specimens from each core were tested to failure in bending in accordance with ASTM D 198 (ASTM 2003). Static bending MOE and modulus of rupture (MOR) for the A specimens were determined based on the load-deflection curves obtained from bending tests. Similarly, the B specimens from each core were tested to failure in tension parallel to grain to determine the tensile MOE and tensile strength of peeler cores.

Results and discussion

Table 1 shows stress wave properties of Douglas-fir peeler cores and various properties of lumber obtained from the cores. As expected, the mean values of the static properties of the lumber obtained from destructive tests were sig-

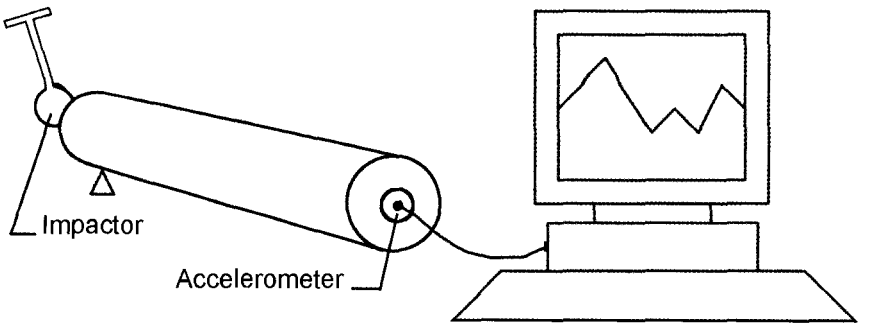

Figure 2. — Nondestructive evaluations of individual peeler cores,

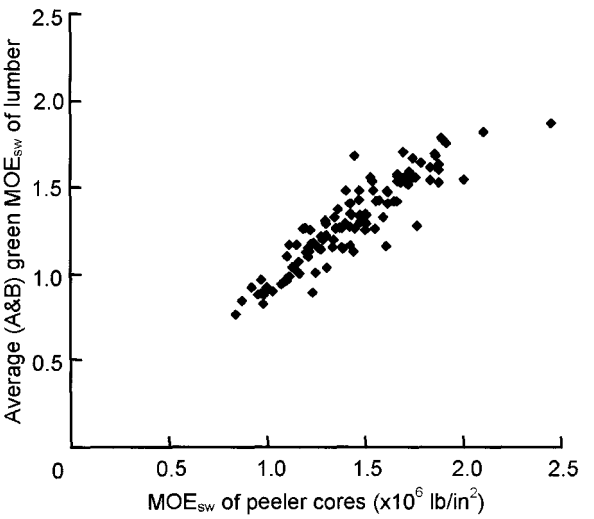

Figure 3. — Average MOE_{sw} of green lumber in relation to MOE_{sw} of peeler cores.

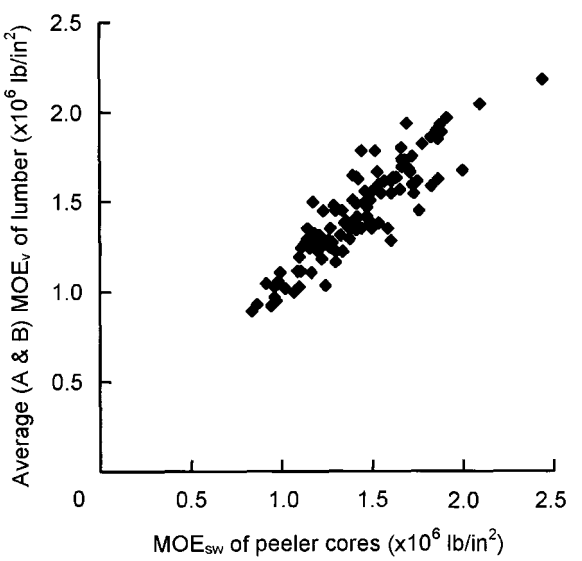

Figure 4. — Average MOE_v of dry lumber in relation to MOE_{sw} of peeler cores.

nificantly lower than the property values given in the *Wood Handbook* (USDA 1999). For example, static bending MOE of the peeler cores was 8.69×10^6 kPa (1.26×10^6 psi), which is about 35 percent lower than the value in the *Wood Handbook*. This is because a substantial portion of the high quality materials in logs is removed when they are peeled down into cores with a small diameter. The cores contain a much higher percentage of low quality juvenile wood than do whole logs.

The results indicated that the lumber cut from the peeler cores had large variability in static bending and tensile properties. Bending MOE (MOE_B) of the lumber ranged from 4.6 to 15.3×10^6 kPa (0.67 to 2.22×10^6 psi), with a coefficient of variation (COV) of 24.9 and a correlation value (r^2) of 0.47. Tensile MOE (MOE_T) of the lumber ranged from 7.31 to 18.4×10^6 kPa (1.06 to 2.67×10^6 psi) with a COV of 21.2 and an r^2 of 0.70 (in relation to core stress wave MOE). Similarly, the results of stress wave testing revealed a fairly wide range of property variability in the peeler cores. MOE_{sw} ranged from 5.8 to 16.8×10^6 kPa (0.84 to 2.44×10^6 psi) with a COV of 20.9. It appears that stress wave measurement of peeler cores can separate high and low quality materials if there is a good relationship between stress wave properties of peeler cores and mechanical properties of lumber cut from the cores.

Figures 3 and **4** show the relationships between predicted MOE_{sw} of the peeler cores and MOE_{sw} and vibration MOE (MOE_v) of corresponding lumber. The linear regression analysis indicated a strong correlation between MOE_{sw} of peeler cores and MOE_{sw} and MOE_v of lumber. The correlation coefficients were 0.91 and 0.90, corresponding to r^2 values of 0.83 and 0.90, respectively. This indicates that more than 80 percent of the variation was accounted for by the correlation.

Results from a series of statistical analyses comparing NDE measurements of peeler cores with the flexural and tensile properties of the lumber are summarized in **Table 2.** Correlation coefficients obtained from these analyses indicated that MOE_{sw} of the peeler cores is a relatively good predictor of both static bending and tensile strength moduli of the lumber. **Figures 5** and **6** show plots of MOE_{sw} of the peeler cores versus static bending (MOE_B) and tensile MOE (MOE_T) of lumber. MOE_{sw} showed a better correlation (r = 0.84) to tensile MOE than to static bending MOE (r = 0.68). Note that static bending tests on type A specimens were conducted in edgewise loading in this study. The results obtained from this type of testing would likely be more sensitive to lumber edge defects such as edge knots than is

Table 2. — Results of regression analyses relating MOE_{sw} of peeler cores to static bending and tensile properties of lumber.[a]

Lumber property	Regression equation	Correlation coefficient	Standard error
Bending property (edgewise)			
MOE_B	$MOE_B = 0.244 + 0.7191\ MOE_{sw}$	0.68	0.230
MOR	$MOR = 963.7 + 3447.3\ MOE_{sw}$	0.57	1464.7
Tensile property			
MOE_T	$MOE_T = 0.246 + 1.0199\ MOE_{sw}$	0.84	0.198
UTS	$UTS = -959.1 + 3371.5\ MOE_{sw}$	0.61	1301.3

[a] MOE_B = static bending MOE; MOE_T = tension MOE; standard error = standard error of estimate.

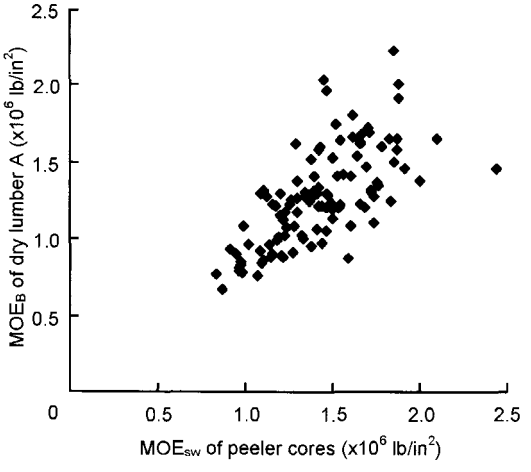

Figure 5. — MOE_B of dry lumber in relation to MOE_{sw} of peeler cores.

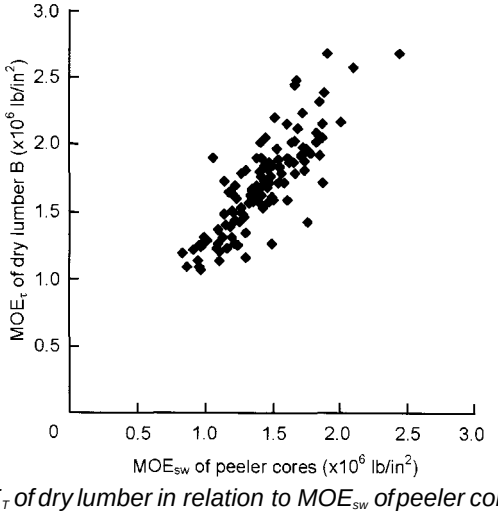

Figure 6. — MOE_T of dry lumber in relation to MOE_{sw} of peeler cores.

testing with flatwise loading. This could add variability to bending property values and therefore affect the correlation with NDE measurements of peeler cores.

For relationships of MOE_{sw} of peeler cores to maximum load properties of lumber, the correlation coefficients were 0.57 for MOR and 0.61 for ultimate tensile strength (UTS). For 8-cm- (3-in.-) diameter lodgepole pine, Pellerin et al. (1989a) found a correlation coefficient of 0.5248 for UTS with MOE_{sw} in tests on 81 specimens.

Divos and Tanaka (1997) derived correlation coefficients between dynamic bending MOE and UTS and dynamic longitudinal MOE and UTS. Dynamic bending MOE was determined through vibration induced by a gentle impact between the nodal points of a beam. Dynamic longitudinal MOE was determined by inducing a gentle impact at the end of a specimen. The specimens were 2 by 4 lumber of mixed *Picea* and *Pinus* species. The correlation coefficients were 0.565 for dynamic bending MOE and UTS and 0.599 for dynamic longitudinal MOE and UTS.

For 15- and 23-cm- (6- and 9-in.-) diameter lodgepole pine, Pellerin et al. (1989b) found an r^2 of 0.541 for UTS with MOE_{SW} and a correlation coefficient of 0.745 for MOR with MOE_{SW} in tests on 81 specimens. In our tests, the regression models accounted for less than 40 percent of the observed variation. This is in agreement with the results of other studies (Aratake et al. 1992, Aratake and Arima 1994, Sandoz and Lorin 1994).

Despite the relatively low correlations between MOE_{SW} and MOR and between MOE_{SW} and UTS, our experience indicates that MOE_{SW} results could be used to assign peeler cores to three separate strength groups. Strength values within the different groups could then be estimated with greater confidence.

Conclusions

This study showed that stress-wave-predicted MOE of peeler cores is a good predictor of both dynamic and static MOE of lumber obtained from the cores. Very strong relationships were shown between stress wave MOE of the peeler cores and dynamic MOE (stress wave MOE and vibration MOE) as well as static MOE (bending MOE and tensile MOE) of the lumber. However, the correlations between stress wave MOE of the peeler cores and the bending and tensile strength (MOR and UTS) were low. Nonetheless, based on past experience, the results of the tests to evaluate MOR and MOE do provide a basis to segregate specimens into perhaps three mechanical strength classes, to further reduce within-class variability.

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