United States
Department of
Agriculture

Forest Service

Forest
Products
Laboratory

Research
Note
FPL–RN–0274

Nondestructive Methods of Evaluating Quality of Wood in Preservative-Treated Piles

Xiping Wang
Robert J. Ross
John R. Erickson
John W. Forsman
Gary D. McGinnis
Rodney C. De Groot

Abstract

Stress-wave-based nondestructive evaluation methods were used to evaluate the potential quality and modulus of elasticity (MOE) of wood in used preservative-treated Douglas-fir and southern pine piles. Stress wave measurements were conducted on each pile section. Stress wave propagation speeds in the piles were then obtained to estimate their MOE. This was followed by a sequence of tests conducted on octagon-shaped cants, on boards, and on small, clear wood specimens obtained from the piles. Statistical regression analyses revealed a strong correlation between the stress-wave-based MOE (MOE_d) of piles and octagons and the corresponding flexural properties of boards and small, clear wood specimens determined by transverse vibration and static bending techniques, respectively. The results also indicated that used preservative-treated wood piles still contain material that has potential for use in exterior structural applications.

Keywords: nondestructive evaluation, piles, recycling

March 2000

Wang, Xiping; Ross, Robert J.; Erickson, John R.; Forsman, John W.; McGinnis, Gary D.; De Groot, Rodney C. 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.

A limited number of free copies of this publication are available to the public from the Forest Products Laboratory, One Gifford Pinchot Drive, Madison, WI 53705–2398. Laboratory publications are sent to hundreds of libraries in the United States and elsewhere.

The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

Contents

Nondestructive Methods of Evaluating Quality of Wood in Preservative-Treated Piles

Xiping Wang, Research Scientist
Robert J. Ross, Supervisory Research General Engineer
Forest Products Laboratory, Madison, Wisconsin

John R. Erickson, Research Scientist
John W. Forsman, Assistant Research Scientist
Gary D. McGinnis, Professor
School of Forestry and Wood Products
Michigan Technological University, Houghton, Michigan

Rodney C. De Groot, Research Plant Pathologist (retired)
Forest Products Laboratory, Madison, Wisconsin

Introduction

Preservative-treated wood products are important construction materials. Preservative-treated wood piles, after removal from service, constitute a major disposal problem for managers of waterfront facilities. For example, 7,000 to 8,000 tons of mechanically or biologically deteriorated wood piles are currently removed from U.S. Naval facilities annually at a cost of at least $20 million per year (Pendleton and Hoffard 1998). While many of these piles are no longer useful because of damage on their outer layers, a considerable amount of the interior wood could be reused for other exterior applications. Examples of the options include fence posts, retaining walls, landscaping timbers, unexposed sheathing, and other general structural applications. A key component in determining the potential use for sound wood in these piles is the development of a nondestructive evaluation (NDE) method that could be used to assess the potential quality of the wood.

Stress-wave-based nondestructive testing techniques have been investigated extensively during the past few decades and have shown much promise for predicting the mechanical properties of wood. A variety of wood-based materials ranging from small, clear wood specimens to wood-based composites have been investigated. In recent years, research has been conducted to determine if longitudinal stress wave techniques could be used to determine the quality of logs. Several studies have shown a good relationship (R^2 = 0.44–0.89) between longitudinal stress-wave-based modulus of elasticity (MOE) in logs and static MOE of lumber cut from the log (Aratake and Arima 1994, Aratake and others 1992, Arima and others 1990, Iijima and others 1997, Koizumi and others 1997a,b, Ross and others 1997, Sandoz and Lorin 1994). However, no effort has been expended to investigate the use of these techniques to evaluate the potential quality of used preservative-treated wood pilings. The objective of this study was to investigate the use of longitudinal stress wave NDE methods to assess the quality of used preservative-treated wood piles removed from service.

Materials

Nine used creosote-treated wood piles (six Douglas-fir (*Pseudotsuga menziesii*) and three southern pine (*Pinus* spp.), designated DF1 to 6 and SP1 to 3) were removed from U.S. Navy shore facilities and used for this study. The first batch of piles (five Douglas-fir) were cut on-site into approximately 6-ft (1.8-m) sections and transported to the Institute of Wood Research (IWR) at Michigan Technological University (MTU), in Houghton, Michigan. The second batch of piles (one Douglas-fir and three southern pine) was transported to MTU in the whole length, and the piles were then cut into 8.5-ft (2.59-m) sections. Altogether, 57 pile sections were obtained from these used piles—44 sections from Douglas-fir and 13 sections from southern pine.

These creosote-treated piles had been used as fenders in piers and wharves. The outer portions of these piles were severely damaged mechanically or biologically during their years of service. Splits, decay, and marine borer damage were the major visual defects observed on these piles. More splits and marine borer damage were found in the Douglas-fir piles. The Douglas-fir piles ranged from 30 to 62 ft (9.14 to 18.90 m) long and 14 to 15.7 in. (35.6 to 39.9 cm) in diameter (butt), with creosote penetrating into the wood from 0.25 to 2 in. (0.64 to 5.1 cm) deep. The southern pine piles ranged from 40 to 47 ft (12.2 to 14.3 m) long and 14.5 to 15.75 in. (36.8 to 40.0 cm) in diameter (butt), with creosote penetrating into the wood from 1.5 in. (3.8 cm) to near the pith, depending on the pile.

Experimental Procedure

Figure 1 shows the experimental procedures we used. Longitudinal stress wave NDE methods were used to assess the piles and the octagon cants cut from them. Transverse vibration and static bending tests were performed on boards and small, clear wood specimens obtained from the octagons.

To obtain an estimate of the maximum yield of solid wood, we selected 18 sample sections from the piles that contained less creosote and cut them into octagon-shaped cants, thereby removing most of the creosote-treated outer shell. This outer shell material was saved for another study, which was on remediation and potential use of this material in the manufacture of composite board material. Stress wave measurements were conducted on each pile section and each octagon-shaped cant. Samples of shells and sawdust were provided for creosote content analysis. Octagon cants were then sawed into 4/4 (1-in., 2.5 cm) boards, followed by a series of stress wave, transverse vibration, and static bending tests (destructive) on boards and small, clear wood specimens cut from boards to obtain an estimate of MOE of boards to correlate with the E-rating values obtained from piles and cants.

Figure 2a shows a typical sawing scheme we used to obtain boards from octagon cants. One-inch boards were sawn from octagon cants with the board width increasing from either side to the middle. This sawing scheme allowed the maximum yield of solid wood from the piles. The number of boards obtained from the octagon cants may change because of the different diameters of the pile sections. Figure 2b shows the cutting of the small, clear wood specimens from the boards. From two middle boards and two side boards, 1- by 1- by 16-in. (25.4- by 25.4- by 406-mm) small, clear specimens were cut. The 12 shaded specimens shown in Figure 2b, 2 from each sideboard, 4 from each middle board, were used to conduct static bending tests for destructively determining the wood strength and stiffness. In addition, to investigate the variation of stress wave and static properties of wood in the radial direction within the cross section of piles, all small, clear wood specimens that we obtained from the two middle boards of the pile sections designated DF6B and S2B (B designates the second section from the butt end of the pile) were nondestructively (stress wave) and destructively (static bending) tested.

Stress Wave Measurements

Figure 3 shows the experimental setup for stress wave measurements. The specimens (pile sections and octagon-shaped cants obtained from selected pile sections) were laid on the ground and tested in the longitudinal direction. Longitudinal stress waves were generated on one end using a hand-held hammer with the accelerometer (Model 3021, Columbia Research Labs, Inc., Woodlyn, Pennsylvania) attached to the opposite end. Following a mechanical impact, a stress wave propagates back and forth along the length of the specimen. The stress wave signals were detected by the accelerometer, and the waveform was monitored and recorded by a personal computer. Figure 4 shows a typical stress waveform obtained by monitoring the propagation of longitudinal stress waves in a pile section. The stress waveform consists of a series of equally spaced pulses whose magnitude decreases exponentially with time. The stress wave speed (SWS) can be determined by coupling measurements of the time Δt between pulses and the length L of the specimen by

$$\text{SWS} = 2L/\Delta t \quad (1)$$

Based on stress wave measurements, the dynamic MOE (MOE_d) of piles and cants may be calculated using a one-dimensional wave equation:

$$\text{MOE}_d = (\text{SWS})^2 \rho \quad (2)$$

where ρ is the density of the specimen.

Density Determination

After stress wave measurement, each pile section and octagon cant was weighed with a scale. For the pile sections, diameters of both large and small ends were measured and the bulk volume of the pile section was calculated using the following equation:

$$V_{\text{pile}} = (\pi/12)\, L\, (D_1^2 + D_2^2 + D_1 D_2) \quad (3)$$

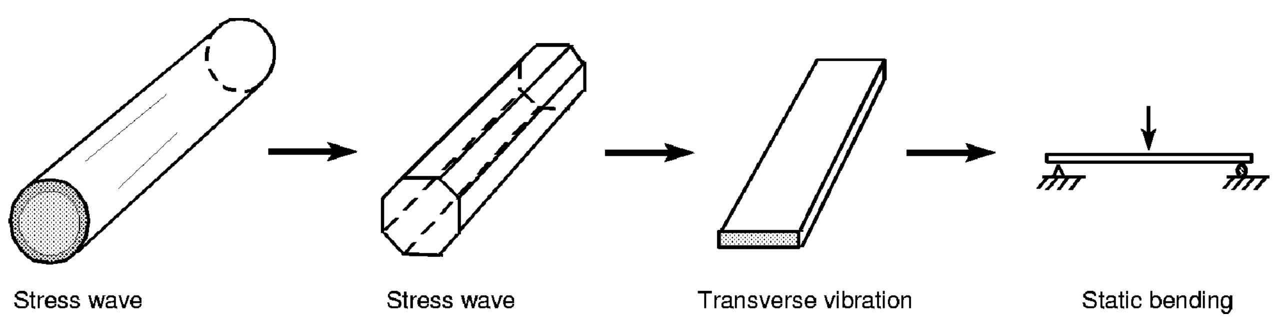

Figure 1—Experimental procedures.

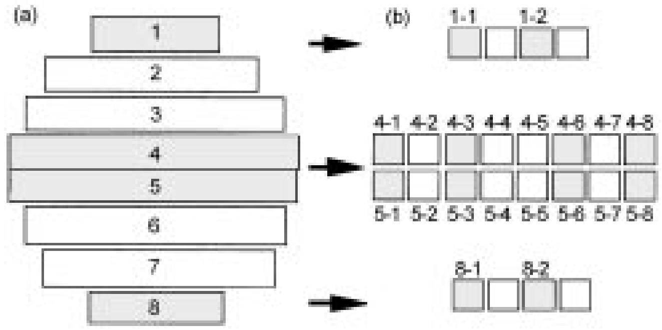

Figure 2—(a) Boards sawn from octagon cant and (b) small, clear wood specimens cut from two side boards and two middle boards.

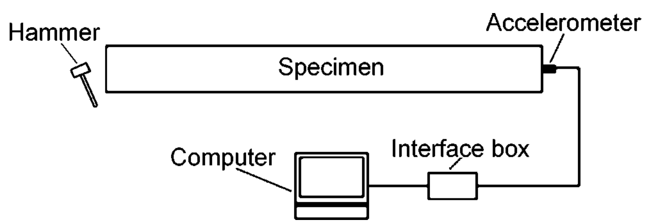

Figure 3—Experimental setup for stress wave measurement.

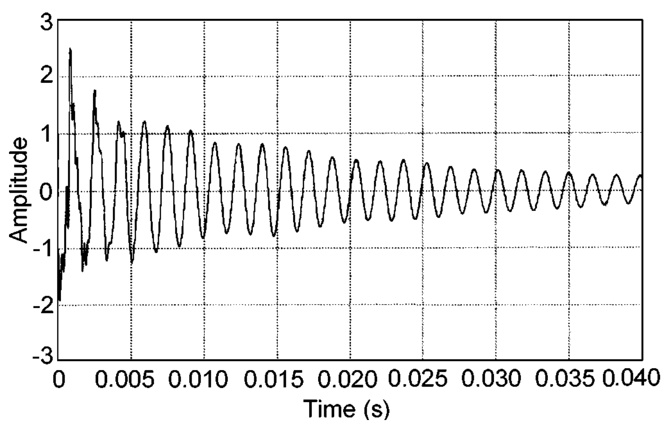

Figure 4—Time history of a typical stress waveform observed in a treated pile section (SP1C).

where D_1 is the diameter of the large end, D_2 the diameter of the small ends, and L the length of pile section. For octagon cants, the circumference of the cant was measured at two ends and the bulk volume was calculated as

$$V_{\text{octgon}} = \frac{\sqrt{3}}{2}\left(\frac{l}{6}\right)^2 L \tag{4}$$

where l is the average circumference of an octagon cant and L is the length of the cant. Then the density was determined using the bulk weight and bulk volume.

A disk was cut from the middle section for each pile to investigate its density distribution and determine the moisture content of the piles. The disks were wrapped with a plastic bag tightly and brought back to the laboratory. Nine small samples (1 by 1 by 1 in (25.4 by 25.4 by 25.4 mm)) were immediately cut from each disk, four from the outer part, four from the middle part, and one from the center of the disk.

Transverse Vibration Tests

Transverse vibration technique was used to obtain an estimate of the MOE of boards cut from the octagon cants. As a potential lumber grading method, the transverse vibration testing technique measures natural frequencies of the vibration in a very short time, which in turn provides the MOE of the test material since the natural frequencies of a member are governed by its MOE and other easily measured parameters of test specimens (Ross and Pellerin 1994). Previous results revealed a very strong relationship between transverse-vibration-determined MOE (MOE_v) and static MOE (MOE_s) with a correlation coefficient $r = 0.99$ (Ross and others 1991). In this study, a Metriguard Model 340 E-computer (Pullman, Washington) was used to conduct transverse vibration tests on all boards obtained from the octagon cants. The board under test was supported at one end by a knife-edge support and at the opposite end by the load-cell transducer with a load bottom. The dimensions of the boards were physically measured, and the weight and natural frequency of the boards were automatically determined using the load-cell transducer interfaced to the Metriguard E-computer. The MOE_v of boards was then determined by the following equation:

$$\text{MOE}_v = \frac{f_r WL^2}{2.46 I \text{g}} \tag{5}$$

where f_r is natural frequency (Hz),

W, weight of board (lb (kg)),

L, span of board between supports (in. (m)),

I, moment of inertia (in^4 (m^4)), and

g, gravitational constant (386 in/s^2 (9.8 m/s^2)).

Static Bending Tests

Static bending tests were performed on a limited number of small, clear wood specimens (1 by 1 by 16 in. (25.4 by 25.4 by 406 mm)) obtained from selected octagon cants using a SATEC Universal Testing Machine. These tests were conducted according to ASTM D143 standards (ASTM 1988). The specimen was supported at two ends on a round block resting on a relatively stiff steel L support, loaded across a 14-in. (356-mm) span. A load was applied at the center of the specimen using a bearing block of steel. A deflectometer was used to measure the deflection of the specimen. A computer data acquisition system was used to monitor the process of the bending test and record the test data. An average value from all 12 specimens for each pile was assumed to be the average value for static bending of the solid wood in the piles.

Results and Discussion

Physical Properties of Used Creosote-Treated Piles

Table 1 summarizes the various physical characteristics of creosote-treated piles used in this study. The average moisture content of the piles ranged from 12.7% to 59.3% for the Douglas-fir piles and 22.7% to 88.6% for the southern pine piles. The moisture contents of Douglas-fir piles DF1, DF2, and DF3 as well as southern pine pile SP3 were below fiber saturation point (about 30%). Whereas for Douglas-fir piles DF4, DF5, and DF6 and southern pine piles SP1 and SP2, the average moisture contents exceeded or were close to the fiber saturation point. The significant difference in moisture content from pile to pile may imply different service conditions or service history. According to the information provided by the U.S. Navy, Douglas-fir DF4, DF5, and DF6 and southern pine SP1 and SP2 were older piles, and Douglas-fir DF1, DF2, and DF3 and southern pine SP3 were relatively newer piles. This can be reflected by their moisture content differences. The older piles have higher moisture contents than the newer piles, and they also exhibit more moisture content changes in a radial direction than the newer piles. Further investigation indicated that the outer layer of a pile has lower moisture content than the middle layer or center part of the pile. This may be caused by natural drying effects after removal from the waterfront facilities.

Density of material is an important component in the determination of stress-wave-based dynamic MOE (MOE_d). In this study, densities of used piles were determined in two different ways. Bulk density values for the Douglas-fir piles ranged from 32.01 to 53.10 lb/ft^3 (0.51–0.85 g/cm^3), and those for the southern pine piles ranged from 49.15 to 53.63 lb/ft^3 (0.79–0.83 g/cm^3). Density values obtained from small samples ranged from 29.18 to 52.02 lb/ft^3 (0.47–0.83 g/cm^3) for the Douglas-fir piles and 49.69 to 58.78 lb/ft^3 (0.80–0.94 g/cm^3) for the southern pine piles. This indicated that bulk density values are basically in agreement with the average density values of small samples cut from the piles.

Board MOE and Stress Wave Properties of Piles and Octagon Cants

Stress wave speeds (SWS) measured in piles and octagon cants are summarized in Table 2. After the piles were cut into octagon cants by removing creosote-treated outer layers, the wood density decreased 6.2% to 26.1% for Douglas-fir piles and 18.6% for southern pine pile SP1. The SWS measured in octagons increased 2% to 19.1% for Douglas-fir and about 12% for southern pine compared with that measured in pile sections This supports the hypothesis that creosote penetrated into wood has a significant attenuation effect on stress wave propagation. It was also found that defects, such as splits (if crossing the wave propagation line), decay, and marine borer damage have strong negative effects on stress wave propagation in piles.

Table 3 shows dynamic MOE (MOE_d) of piles and octagons determined by stress wave methods and the MOE of boards determined by the transverse vibration method. It can be seen that the stress-wave-based MOE_d of piles and octagons tended to be higher than the average MOE of boards sawn

Table 1—Physical characteristics of creosote-treated Douglas-fir and southern pine piles

Pile no.	Length of pile (ft)[a]	Number of sections	Moisture content (%) Average	Minimum	Maximum	Bulk density (lb/ft^3)[a]	Depth of creosote penetration (in.)[a] Minimum	Maximum
Douglas-fir								
DF1	57.4	10	14.8	11.0	17.8	35.21	0.25	2.00
DF2	62.2	11	12.7	9.9	15.2	37.39	0.25	2.00
DF3	40.5	7	13.2	10.7	15.2	32.01	0.25	2.00
DF4	38.1	7	34.1	25.6	56.9	37.02	0.25	1.00
DF5	29.1	6	42.1	28.1	62.5	53.10	1.00	7.00
DF6	36.0	4	59.3	45.5	85.1	51.30	1.50	4.00
Southern pine								
SP1	46.0	5	28.2	17.9	43.8	49.15	2.00	6.50
SP2	47.0	5	88.6	39.5	153.9	53.63	2.50	6.00
SP3	39.5	4	22.7	18.5	26.8	53.51	[b]	[b]

[a] 1 ft = 0.3 m; 1 lb/ft^3 = 16.01 kg/m^3; 1 in. = 25.4 mm.
[b] Fully penetrated.

Table 2—Stress wave speeds in piles and octagon cants

Pile no.	Stress wave speed (ft/s)[a,b] Pile	Octagon cant
Douglas-fir		
DF1	16,657	17,051
DF2	16,939	17,257
DF3	14,977	15,322
DF4	15,479	15,965
DF5	12,162	14,485
DF6	13,612	14,265
Southern pine		
SP1	12,671	14,249
SP2	10,682	11,923
SP3	10,971	—

[a]Average value of all sections obtained from each pile.
[b]1 ft/s = 0.31 m/s.

from piles but were close to the MOE of the bark-side boards cut near the outer surface of the piles. (The maximum value of board MOE in Table 3 is the MOE of the bark-side board.) The same phenomenon was observed in further investigations on the variation of SWS and MOE in the middle boards cut from piles. This may imply that the stress waves tend to lead in the outer portion of wood (towards the bark) while they travel through piles or octagons.

The results of these experiments indicated that used preservative-treated wood piles still contain wood of good quality. The MOE of boards obtained from used piles ranged from 0.89×10^6 to 2.42×10^6 lb/in^2 (6.14 to 16.68 GPa) for Douglas-fir and 1.17×10^6 to 1.94×10^6 lb/in^2 (8.07 to 13.37 GPa) for southern pine. Static bending tests conducted on small, clear wood samples cut from boards support these results. Therefore, it should be possible to remove some of the damaged outer shell wood and reuse the center core for other exterior applications.

Relationships Between Stress Wave Properties and Flexural Properties

Results obtained from various regression analyses are summarized in Table 4. Correlation coefficients obtained from these analyses indicate that good relationships existed between stress wave properties of piles and octagons and the corresponding flexural properties of boards and small, clear wood specimens.

Figure 5 shows stress-wave-based MOE_d of piles compared with stress-wave-based MOE_d of octagons that were cut from piles. It can be seen that a strong correlation existed between the MOE_d of piles and that of octagons. This revealed that the stress wave properties of used piles could reflect the properties of solid wood within the piles, although creosote and surface defects in used piles have effects on stress wave propagation and stress wave measurements as mentioned before. Figures 6 and 7 show the relationships between stress-wave-based MOE_d of piles and octagons and the average MOE of boards determined by the transverse vibration method. Good correlation (r = 0.85 to 0.91) was found between stress wave MOE_d and board MOE. It was also observed that MOE_d of piles has better correlation with the MOE of a bark-side board than with the average MOE of boards.

Table 3—Stress-wave-based MOE_d of piles and octagon-shaped cants and MOE of boards sawn from piles

	Stress wave MOE ($\times 10^6$ lb/in^2)[a]		Vibration MOE of boards ($\times 10^6$ lb/in^2)[a]		
Pile no.	Pile	Octagon cant	Average	Minimum	Maximum
Douglas-fir					
DF1	2.12	1.98	1.40	0.96	2.05
DF2	2.32	2.26	1.89	1.51	2.42
DF3	1.55	1.44	1.16	0.89	1.32
DF4	1.88	1.80	1.55	1.23	1.93
DF5	1.69	1.59	1.36	1.23	1.53
DF6	2.05	1.88	1.55	1.34	1.92
Southern pine					
SP1	1.85	1.71	1.52	1.34	1.94
SP2	1.17	1.63	1.33	1.17	1.55
SP3	1.39	—	—	—	—

[a]1 lb/in^2 = 6.895 kPa.

Table 4—Results of linear regression analyses for the correlations between MOE_d of piles and octagon cants and properties of boards and small, clear wood obtained from piles[a]

Properties of boards and small, clear wood	MOE_d	Linear regression model $Y = a + b X$			
Y	*X*	*a*	*b*	*r*	S_{yx}
Average board MOE_v	MOE_d of piles	0.3443	0.5889	0.85	0.123
Average board MOE_v	MOE_d of octagons	0.1408	0.7403	0.91	0.101
Bark-side board MOE_v	MOE_d of piles	0.0677	0.8752	0.90	0.144
Bark-side board MOE_v	MOE_d of octagons	–0.1447	1.0514	0.91	0.137
MOE_s of small,clear wood	MOE_d of piles	0.7114	0.3355	0.76	0.103
MOE_s of small,clear wood	MOE_d of octagons	0.5064	0.4669	0.85	0.084
MOR of small, clear wood	MOE_d of piles	510.24	4,133.9	0.69	1,538.9
MOR of small, clear wood	MOE_d of octagons	–757.00	5,059.0	0.68	1,566.0

[a]The small, clear wood specimens were tested in static bending according to ASTM D143 standards; MOE_d, stress-wave-based dynamic modulus of elasticity; MOE_v, modulus of elasticity determined by transverse vibration method; MOE_s, static modulus of elasticity; *r*, correlation coefficient; S_{yx}, standard error of estimate.

Regression analyses also revealed good relationships between MOE_d of piles and octagons and the static MOE and MOR of small, clear wood specimens. The correlation coefficients are listed in Table 4. It therefore can be concluded that stress-wave-based MOE_d is a good predictor for assessing the quality of wood in used piles.

Variation of Stress Wave Properties Within a Pile

The close relationships between stress wave properties of piles and octagons and the corresponding flexural properties of boards and small, clear wood obtained from piles are well recognized from the above results. To gain a better understanding of the stress wave behavior in piles and assist in the interpretation of stress wave results, it was necessary to characterize the variability of stress wave speed as well as stress-wave-based MOE_d within a pile.

The variation of stress wave speed along the length of a whole pile is shown in Figure 8. Stress wave speeds in both Douglas-fir and southern pine piles generally decreased from the larger end to the small end. However, with Douglas-fir piles, the butt section (larger end) exhibited lower values of SWS than the next several sections, whereas the top section (small end) had somewhat higher values than the section just before it. This can possibly be attributed to the different service conditions that these two sections experienced. As mentioned earlier, these preservative-treated piles were used as fenders in piers and wharves with the small end embedded in the ground under water. The wood in the small end might have experienced environmental conditions that preserved its strength. Conversely, the large end of the piles was out of the water, exposed to air and subjected to severe biological and physical factors. As a consequence, wood in the large end of used piles was more likely to suffer serious degradation. For southern pine piles, a 4-ft (1.22-m) butt section was cut off and not included in stress wave measurements because that portion was already seriously rotted.

One Douglas-fir pile section (DF6B) and one southern pine pile section (SP2B) were selected to investigate the variation of stress wave properties in radial direction within the cross section of piles. Boards and small, clear samples were coded from one side to another side through the pith. Two middle boards contained both mature wood and juvenile wood, whereas two bark-side boards were totally mature woods. Small, clear specimens were cut from two middle boards and ranged from mature wood to juvenile wood. Stress wave measurements were conducted on all boards and small, clear wood using the end-attached method.

Figure 9 shows the variation of stress wave speed in an octagon along the radial direction across the board increment. Board position 1 and 8 indicate bark side and 4 and 5 indicate middle boards. It is clear that stress waves travel faster in the bark-side boards than in the middle boards. The stress wave speed in Douglas-fir boards varied from 13,127 ft/s (4,001 m/s) at the middle board to 15,289 ft/s (4,660 m/s) at the bark-side board, and in southern pine boards, it varied from 11,332 ft/s (3,454 m/s) at the middle board to 12,628 ft/s (3,849 m/s) at the bark-side board.

Figure 10 shows the variations of stress-wave-based MOE_d and board MOE_v along the radial direction across the board increment. The variability of stress wave speed and that of stress-wave-based MOE_d is very similar along the radial direction. It can be seen that MOE_d decreased from bark-side to pith. Also, MOE_d follows the same trend with board MOE_v. The average MOE_d is about 10% to 12% higher than board MOE_v for Douglas-fir and southern pine piles. This indicates that the variations of stress wave properties reflect the inherent changes of wood mechanical properties in terms of board positions within the cross section of a pile.

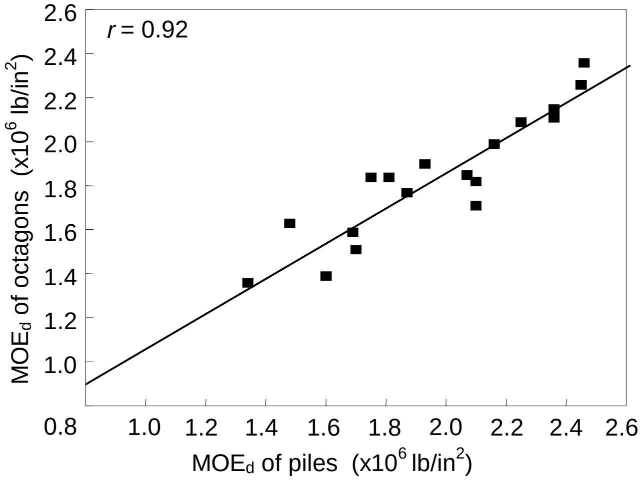

Figure 5—MOE_d of piles plotted with MOE_d of octagons (1 lb/in^2 = 6.895 kPa).

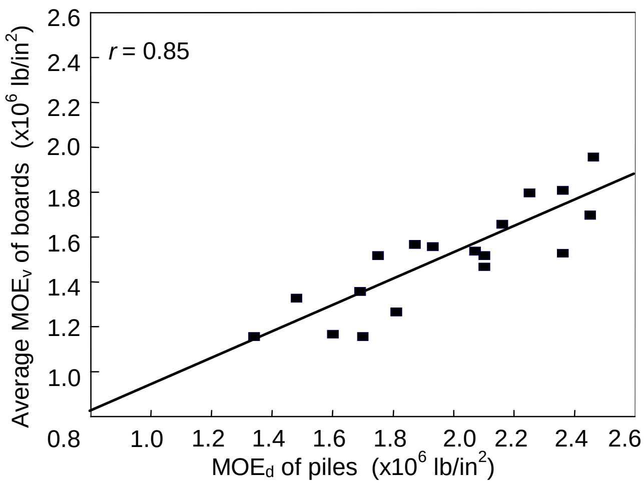

Figure 6—Average MOE_v of boards plotted with MOE_d of piles (1 lb/in^2 = 6.895 kPa).

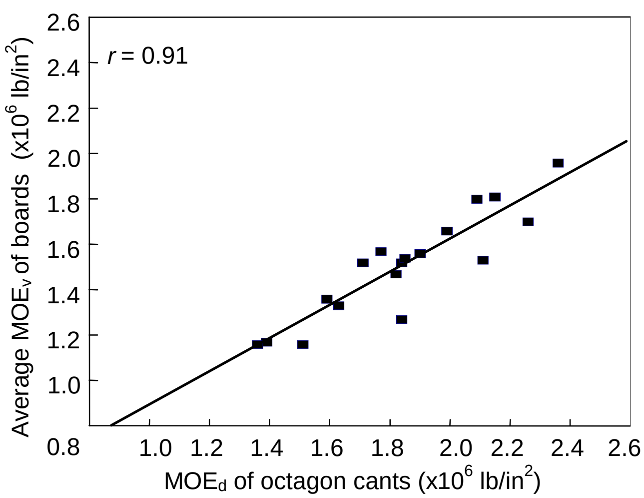

Figure 7—Average MOE_v of boards plotted with MOE_d of octagon cants (1 lb/in^2 = 6.895 kPa).

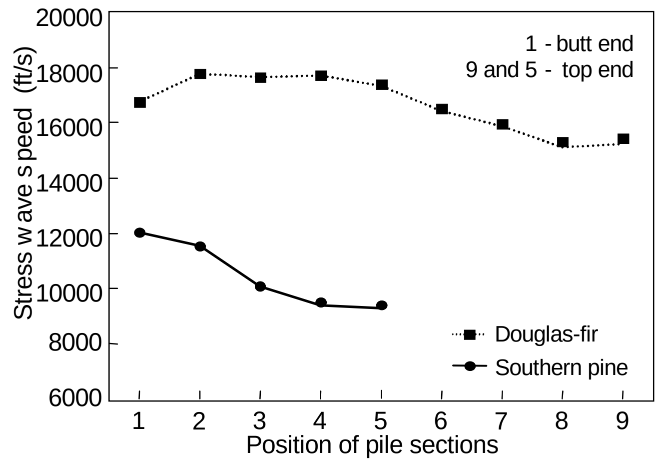

Figure 8—Variation of stress wave speed along the length of a pile (1 ft/s = 0.31 m/s).

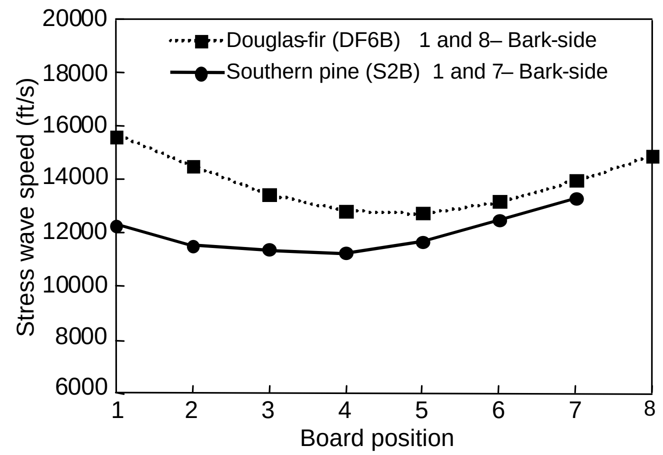

Figure 9—Variation of stress wave speed in an octagon along the radial direction across the board increment (1 ft/s = 0.31 m/s).

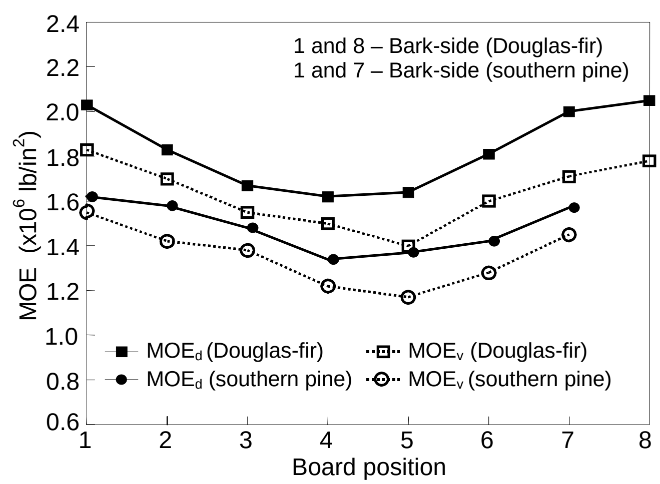

Figure 10—Variation of MOE in an octagon along the radial direction across the board increment (1 lb/in^2 = 6.895 kPa).

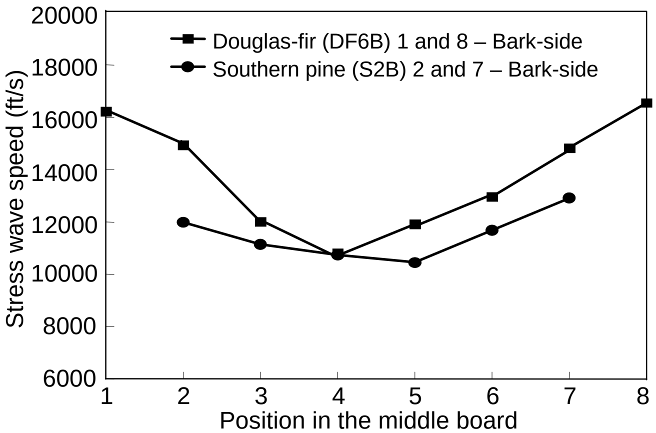

Figure 11—Variation of stress wave speed (SWS) in the middle board along the radial direction (1 ft/s = 0.31 m/s).

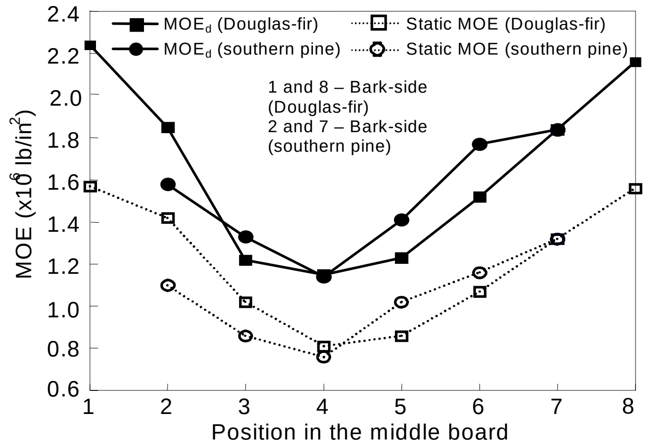

Figure 12—Variation of MOE in the middle board along the radial direction (1 lb/in^2 = 6.895 kPa).

The variations of stress wave speeds in the middle boards along the radial direction are shown in Figure 11. Compared with the variation of SWS in octagons, much larger variation of SWS was observed in Douglas-fir boards, where SWS in the middle board varied from 10,988 ft/s (3,349 m/s) at pith to 16,017 ft/s (4,882 m/s) at bark-side. This implies that larger variations in mechanical properties of wood may exist along the radial direction. For the southern pine section, SWS in the middle boards varied from 10,646 ft/s (3,245 m/s) at pith to 12,283 ft/s (3,744 m/s) at bark-side, which is close to the variation observed in the octagon. It can be seen that stress wave propagation in the southern pine piles and boards was greatly influenced by creosote penetration.

Figure 12 shows the variations of stress-wave-based MOE_d and static MOE of small, clear wood in the radial direction of the middle board. Both MOE_d and static MOE of small, clear wood exhibit significant variations in the radial direction. MOE_d and static MOE both continuously decrease from bark side to pith. For both Douglas-fir and southern pine piles, MOE_d of the small, clear wood shows the same trend with static MOE.

When these results are compared with the stress wave properties of piles and octagons, it is apparent that the SWS measured in the piles and octagons tends to be higher than the average SWS measured in the boards and small, clear wood but they are close to the SWS in the bark-side board and bark-side small, clear wood. The same result can be found for stress-wave-based MOE_d of piles and octagons. This agrees with the results previously observed. It therefore can be concluded that stress waves tend to lead in the outer portion of wood (towards the bark) while they travel through piles or octagons.

Conclusions

Longitudinal stress wave NDE methods were applied to used preservative-treated wood piles to assess the potential quality of the wood in them. Based on the results in this study, the following conclusions can be drawn:

1. Longitudinal stress wave methods can be used to evaluate the potential quality of wood in used preservative-treated piles removed from service. Although creosote and surface defects in used piles have effects on stress wave propagation in piles, good correlation was found between stress-wave-based MOE_d of piles and corresponding flexural properties of boards and small, clear wood specimens obtained from the piles.

2. Stress wave properties of wood in used piles vary in both the longitudinal and radial directions of the pile. Stress wave speed and stress-wave-based MOE_d basically declined from large end to small end along the length of a pile and increased from pith to bark side along the radial direction in the cross section of a pile. The results further indicated that stress waves tend to lead in the outer portion of wood (bark-side) while they travel through the piles or octagons.

3. Results indicated that used preservative-treated wood piles still retain wood of good quality. The MOE of boards obtained from piles ranged from 0.89×10^6 to 2.42×10^6 lb/in^2 (6.14 to 16.68 GPa) for Douglas-fir and 1.17×10^6 to 1.94×10^6 lb/in^2 (8.07 to 13.37 GPa) for southern pine. Static bending tests conducted on small, clear wood samples cut from boards support these results. It was therefore concluded that the resulting timber and lumber of used piles could be used for other applications.

References

Aratake, S.; Arima, T. 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.

Aratake, S.; Arima, T.; Sakoda, T.; Nakamura, Y. 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.

Arima, T.; Maruymura, T. [and others]. 1990. Natural frequency of log and lumber hit with hammer and applications for production processing. In: Proceedings, 1990 international timber engineering conference; 1990 October 23–25; Tokyo, Japan. Tokyo, Japan: Science University of Tokyo: 527–533.

ASTM. 1988. Annual book of ASTM standards. Vol. 04.09. Wood. D143. Philadelphia, PA: American Society for Testing and Materials.

Iijima, Y.; Koizumi, A. [and others]. 1997. Strength properties of sugi (*Cryptomeria jap*onica) grown in Akita Prefecture III: Some relationships between logs and sawn lumber. Mokuzai Gakkaishi. 43(2): 159–164.

Koizumi, A.; Iijima, Y. [and others]. 1997a. Strength properties of sugi (*Cryptomeria japon*ica) grown in Akita Prefecture I: Young's moduli of logs. Mokuzai Gakkaishi. 43(1): 46–51.

Koizumi, A.; Iijima, Y.; [and others]. 1997b. Strength properties of sugi (*Cryptomeria japonica*) grown in Akita Prefecture II: Mechanical properties of lumber. Mokuzai Gakkaishi. 43(2): 210–214.

Pendleton, D.E.; Hoffard, T. 1998. Management of treated wood removed from waterfront services—Options for Navy activities. Special rep. Port Hueneme, CA: Naval Facilities Engineering Service Center.

Ross, R.J.; Geske, E.A.; Larson, G.H; Murphy, J.F. 1991. Transverse vibration nondestructive testing using a personal computer. Res. Pap. FPL–RP–502. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 17 p.

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

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 p.

Sandoz, J.L.; Lorin, P. 1994. Standing tree quality assessments using ultrasound. In: Proceedings, First European symposium on nondestructive evaluation of wood; 1994 September 21–23; Sopron, Hungary. Sopron, Hungary: University of Sopron. 2: 493–502.