Evaluation of Small-Diameter Timber for Value-Added Manufacturing - A Stress Wave Approach

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Abstract: The objective of this research was to investigate the use of a stress wave technology to evaluate the structural quality of small-diameter timber before harvest. One hundred and ninety-two Douglas-fir and ponderosa pine trees were sampled from four stands in southwestem Oregon and subjected to stress wave tests in the field. Twelve of the trees. six Douglas-fir and six ponderosa pine. were harvested and sawn into logs and lumber. The mechanical properties of wood were then assessed by both stress wave and static bending techniques in the laboratory. Results of this study indicated a significant difference in stress wave time (SWT) between Douglas-fir and ponderosa pine trees and between two stands of each species. SWT of Douglas-fir trees increased slightly as tree diameter at breast height (DBH) increased: whereas. SWT of ponderosa pine trees decreased significantly as DBH increased. The statistical analysis also revealed good relationships between SWT of trees and modulus of elasticity (MOE) of logs and lumber produced from the trees as the two species were combined. However, the strength of the relationships was reduced within the species because of small sample size and narrow property range.

INTRODUCTION

Throughout the United States. past management practices have created thousands of acres of forest densely stocked with small-diameter trees. These stands are at increased risk of insect and disease attack and have higher Catastrophic fire potential. Increased management emphasis on forest health and bio-diversity has forced land managers to seek economically viable stand treatments such as thinning to improve the stand condition. Economical and value-added uses for removed small-diameter timber can help offset forest management cost, provide economic opportunities for many small, forest-based communities, and avoid future loss caused by catastrophic wildfires. However, the variability and lack of predictability of the strength and stiffness of standing timber cause problems in engineering applications. It is essential to develop cost-effective technologies for evaluating the potential structural quality of such materials.

The traditional log-to-product manufacturing process fails to recognize a tree's full value. The process occurs in a series of mostly independent steps (trees, to logs, to lumber, to parts), each optimized for its own outputs. The ultimate end use is rarely a consideration during intermediate processing stages. By identifying final product potential before timber harvest, we hope to 1) enhance resource utilization efficiency, 2) make it economically viable for secondary wood products manufacturers to utilize small-diameter timber, and 3) facilitate stand management activities by identifying small-diameter timber value.

This study is pan of the project "Evaluation of small-diameter timbers for value-added manufacturing: An integrated approach" conducted jointly by Oregon State University, USDA Forest Service Forest Products Laboratory, and USDA Forest Service PNW Research Station. The overall goal of the project was to design, construct, and deliver a system by which communities and forest industries may efficiently recognize value-added wood products potential in small diameter trees. The specific Objective of this study was to investigate the use of a stress wave nondestructive evaluation technique to assess the potential structural quality of small-diameter timbers before timber harvest.

MATERIAL AND METHODS

A total of one hundred and ninety-two Douglas-fir *(Pseudotsuga menziesii)* and ponderosa pine *(Pinus ponderosa)* trees were sampled for stress wave evaluation at four different stands in southwestern Oregon. The stands were located in the Applegate Ranger District on the Rogue River National Forest. Stand A (Yale Twin) was a 70 year old even-aged stand consisting primarily of Douglas-fir with some madrone and a small compliment of ponderosa pine. The stand had a mean diameter of 6.4 inches (16.3 cm) and a quadratic mean diameter of 7.4 inches (18.8 cm). Stand B (Toe Top) consisted of a sparse stand of 90-year-old trees (primarily ponderosa pine) with a 65 year old under-story of Douglas-fir, smaller ponderosa pine, madrone, and an occasional incense cedar. It had a mean diameter of 6.0

inches (15.2 cm) and a quadratic mean diameter of 7.8 inches (19.8 cm). Both stand A and B were slow grown and stagnant, and the trees marked for thinning and testing had small branches. Stand C (Squaw Ridge) was a 40-year-old even-aged ponderosa pine stand with a minor compliment of Douglas-fir. The trees were vigorous and fast-growing, with large crowns and large branch diameters. The stand had a mean diameter of 8.7 inches (22.1 cm and a quadratic mean diameter of 9.4 inches (23.9 cm). Stand D (No Name) was a mixture of Douglas-fir and ponderosa pine, with some madrone peristing in the understory. Tree age ranged from 35 to 40 years. The stand had a mean diameter of 7.2 inches (18.3 cm) and a quadratic mean diameter of 8.0 inches (20.3 cm).

All sampled trees were subjected to stress wave tests in the field. Douglas-fir trees were evaluated in stands A and B, and ponderosa pine trees were evaluated in stands C and D. Trees of each stand were classified into six diameter classes that had a mean diameter at brew height (DBH, measured outside bark) of 5, 6, 7, 8, 9, and 10 inches (12.7, 15.2, 17.8, 10.3, 22.9, and 25.4 cm) respectively. A random sample consisting of eight trees per diameter class was subjected to stress wave tests in each of the four stands.

A recently developed stress wave technique was used io conduct in-situ tests on sampled trees (Wang 1999, Wang et al 2001). The testing system consisted of two accelerometers, two spikes, a hand-held hammer, and a portable scopemeter (Figure 1). Two spikes were imbedded in the trunk at 45° to the trunk surface, one spike at each end of the section to be assessed with a span of 4 ft (1.2 m). The spikes were pounded into the stem about one inch (2.5 cm), which was deep enough for the tips to penetrate the bark and reach the sapwood. The Accelerometers were mounted on the spikes using two specially designed clamps. A stress wave was introduced into the tree in the longitudinal direction by impacting the lower spike with a hammer. The resulting signals were received by start and stop accelerometers and recorded on the scopemeter as waveforms. The stress wave time (SWT, the time for a stress wave to travel through the distance between two spikes) was determined by locating the two leading edges of the waveforms on the scopemeter (Wang et al 2001). Six measurements were obtained on each tree, three on each of two sides.

After field tests, one tree per diameter class was felled in stands B (Toe Top) and C (Squaw Ridge), resulting in a sample of six Douglas-fir and six ponderosa pine trees ranging from 5 to 10 inches (12.7 to 25.4 cm) in DBH. These felled trees were then bucked into IO-foot (3.0 m) long logs and transported to Michigan Technological University in Houghton, Michigan for laboratory tests. For each log, the green weight and diameters (at two ends and the middle of the log) were measured and the green density was determined accordingly. All logs were then evaluated using longitudinal stress wave and static bending methods to obtain stress wave time and static modulus of elasticity (MOE) of the logs. A detailed description of the instrumentation and analysis procedures for log tests is given by Wang et al. (2002).

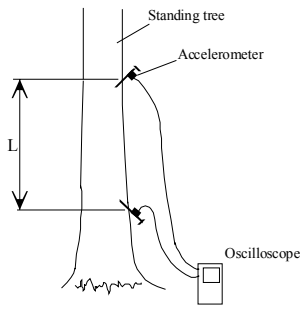


Figure 1. Schematic of experimental setup used in field test (L = test span).

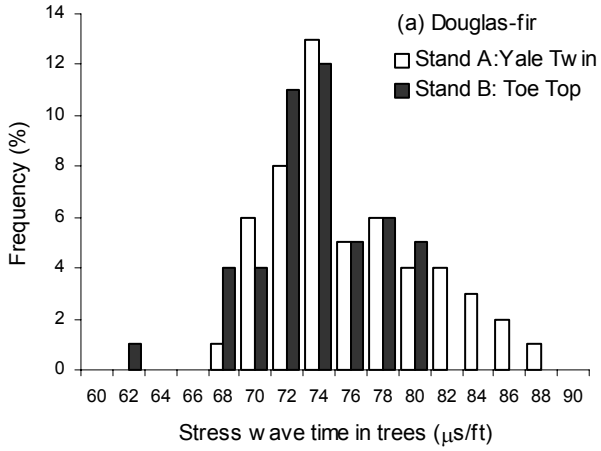
To validate the stress wave analysis of trees and logs, all logs were sawn into 2- by 4-in. (51 by 102-mm) and 2- by 6-in. (51- by 152-mm) dimension lumber on a portable horizontal band sawmill for further assessment in terms of structural quality. Sawing pattern for each log was diagrammed so that the location of each piece of lumber within each log could be tracked. Each piece of lumber received a unique identification number associating it with its location within the log and tree from which it was sawn. The lumber was stickered and stacked for air-drying until they reach the moisture content of approximately 15 percent. When dry, the lumber was planed to industry standard thickness and width for surfaced dry lumber. Longitudinal stress wave and static bending tests were also conducted on lumber at both green and dry conditions.

RESULTS AND DISCUSSION

Stress Wave Time in Standing Trees

The stress wave time in standing trees was the average value of six measurements from each tree and was reported on the unit per length basis (time/length). Lower stress wave time corresponds to higher stress wave speed (length/time). The descriptive statistics of tree measurements (SWT and DBH) from all tree samples are given in Table 1. Figure 2 shows histograms of stress wave time distribution for four different stands.

The difference between Douglas-fir and ponderosa pine can he easily distinguished in terms of stress wave time. The mean SWT of ponderosa pine trees is about 21 percent higher than that of Douglas-fir trees, which means stress waves travel much slower in ponderosa pine than in Douglas-fir trees. In general, this result is in agreement with the strength and stiffness difference between the two species as given in the Wood Handbook (FPL 1999), which states the modulus of rupture (MOR) and modulus of elasticity of ponderosa pine are about 34 percent lower than those of Douglas-fir (green condition).



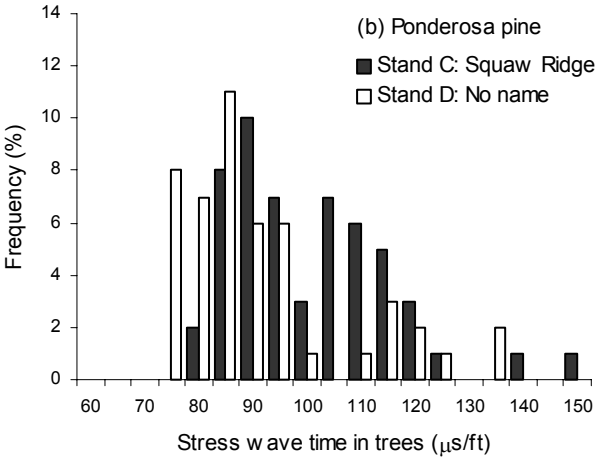


Figure 2. Histograms of stress wave time (SWT) distribution for Douglas-fir and ponderosa pine trees.

The SWT of ponderosa pine trees also shows much higher variation than the SWT of Douglas-fir trees. The standard deviation of SWT is 4.50 ms/ft (14.8 ms/m) for Douglas-fir (stand A and stand B combined), and 16.17 ms/ft (53.0 ms/m) for ponderosa pine (stand C and stand D combined). This might suggest a larger variation in strength and stiffness properties of ponderosa pine compared to those of Douglas-fir.

The statistical comparison analysis showed significant SWT differences between two stands of each species, which imply a potential difference in strength and stiffness between the stands. But this could not he substantiated due to the lack of mechanical property data of all tested standing trees.

The relationship between SWT and DBH of standing trees is shown in Figure 3. For better illustration, stress wave rimes in trees were analyzed in terms of diameter classes. The data points are mean values of SWT for eight trees in each class, and the error bar indicates the standard deviations (±1 standard deviation).

The SWT in Douglas-fir trees increased slightly as DBH of the trees increased. The trend is more evident in stand A (Yale Twin) than in stand B (Toe Top). The SWT for stand A increased about 12 percent as DBH changed from 5 in. to 10 in. (12.7 to 25.4 cm). The SWT-DBH relationship for ponderosa pine trees was quite different from Douglas-fir. As shown in Figure 3(b), the SWT in ponderosa pine trees decreased significantly as DBH of the trees increased, especially in stand C (Squaw Ridge) where the SWT dropped 24 percent when the DBH increased from 5 in. to 10 in. (12.7 to 25.4 cm). The causes for the different functional relationships between SWT and DBH for Douglas fir and ponderosa pine trees are not fully understood yet. Huang (2000) reported that, for the same age trees, stress wave time is lower for trees with slower growth rate or narrower rings. This might explain the SWT-DBH trend found in Douglas

Table 1. Diameter at breast height and stress wave time of standing trees. [a]

		Sample	DBH(in.)				SWT(μs/ft)			
Species	Stand	No.	Mean	Min	Max	SD	Mean	Min.	Max.	SD
Douglas-fir	A	48	7.4	4.7	10.3	1.71	75.2	67.3	87.0	4.79
	B	48	7.5	4.6	10.2	1.76	72.8	60.8	79.2	3.83
Ponderosapine	C	48	7.6	4.8	10.3	1.76	98.9	77.3	150.0	14.94
	D	48	7.6	4.7	10.1	1.77	89.2	71.3	134.3	16.12

[a] 1 in. = 2.54 cm, 1 μs/ft = 3.28 μs/m.
DBH, diameter at breast height.
SWT, stress wave time.
SD, standard deviation.

fir trees. For ponderosa pine trees, the opposite SWT-DBH trend could he more related to other factors such as the characteristics of tree forms (size and frequency of branches), proportion of mature and juvenile wood in the cross section as well as moisture content.

Relationship Between Stress Wave Time in Trees and Log Properties

Stress wave time in standing trees was measured in the lower part of the stem, which tracks to the butt log after harvesting and cutting. In this study, a total of 42 10-ft. 13.0-in) long logs were obtained from 12 harvested trees. The number ofthe logs produced from each tree varied from 3 to 5 for Douglas-fir and from 1 to 4 for ponderosa pine as a result of the difference in tree height. The diameter of the logs (average value of diameters measured at two ends and the middle) ranged from 4.3 to 10.0 in (10.9 to 25.4 cm for Douglas-fir and from 4.4 to 9.8 in. (11.2 to 24.5 cm) for ponderosa pine. The physical and mechanical properties (density, stress wave time, and static MOE) of logs are summarized in Table 2. Note that all these properties were determined in green and un-debarked logs.

Figure 4 shows the relationship between SWT of trees and SWT ofthe butt logs cut froin the trees. A linear regession analysis indicated a strong correlation (R^2= 0.95) when two species were considered as a single population. The strength of the relationship was weakened when the two species were considered separately (R^2 = 0.61 for Douglas-fir. R^2= 0.85 for ponderosa pine). This was presumably due to the small sample size (n=6) and limited property range for samples of each species. it was found that SWT measured in standing trees was about 10 and 22 percent lower than SWT of loss for Douglas-fir and ponderosa pine, respectively. This could be a systematic difference caused by different stress wave approaches. It has been reported that the stress wave speedmeasured in trees could be dominantly controlled by the mature wood (outer wood in the cross-section) since both wave generation and sensing occurred on the surface of the stem (Wang 1999, Huang 2000, Ikeda

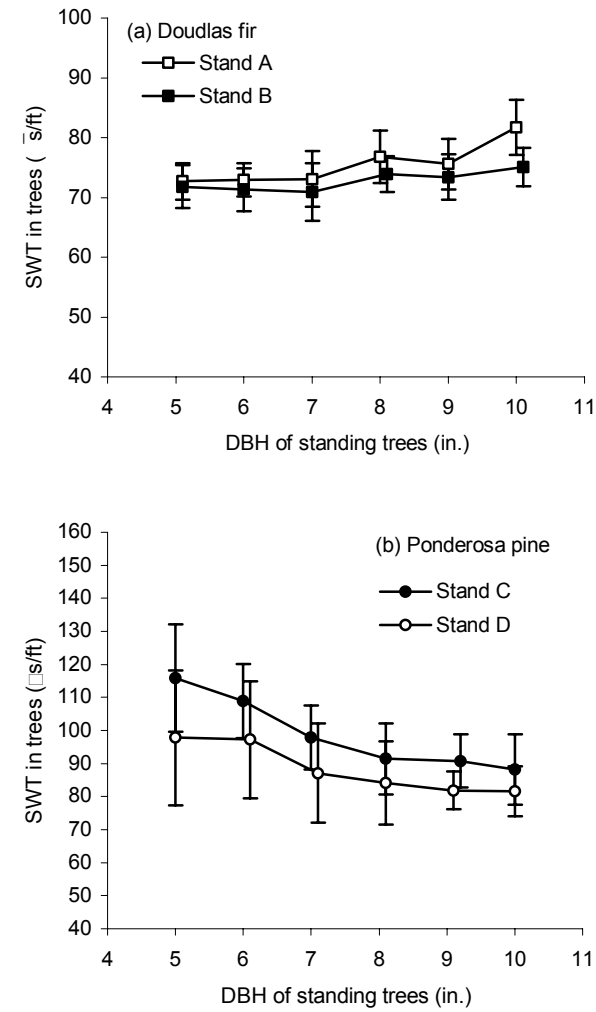


Figure 3. Relationship between stress wave time (SWT) and tree diameter at breast height (DBH).

Table 2. Physical and mechanical properties of logs. [a]

Species	No. of	Density (lb/ft³)				Stress wave time (μs/ft)				MOE (10^6 lb/in²)			
	logs	Mean	Min.	Max.	SD	Mean	Min.	Max.	SD	Mean	Min.	Max.	SD
Douglas-fir	25	41.45	35.17	48.45	3.539	76.1	70.4	84.1	3.68	0.99	0.52	1.33	0.213
Ponderosa pine	17	51.75	43.12	57.55	4.310	116.3	106.0	134.7	8.84	0.57	0.33	0.79	0.149

[a] 1 lb/ft³= 16.02 kg/m³, 1 μs/ft = 3.28 ms/m, 1 lb/in² = 6895 Pa.

MOE, modulus of elasticity determined by static bending method.
SD, standard deviation

et al. 2000, and Wang et al. 2001), whereas in logs the waves were introduced into the stem from one end and sensed at the other end (Wang et al. 2002).

The relationships between SWT of trees and the average MOE of logs are shown in Figures 5. Regression analysis indicated a linear relationship between SWT of trees and MOE of logs as all samples combined. The coefficient of determination (R^2) was found to be 0.74. Again, the strength of the relationships was reduced significantly as two species were analyzed separately.

Relationship Between Stress Wave Time in Trees and Lumber MOE

A total of 81 pieces dimension lumber (2 by 4s and 2 by 6s). 49 Douglas-fir and 32 ponderosa pine, were obtained from the logs. Stress wave and static bending tests were performed on lumber in both rough-cut and dry conditions (air dried and 4-side surfaced). The moisture content (MC) of rough-cut lumber (designated as green lumber) ranged

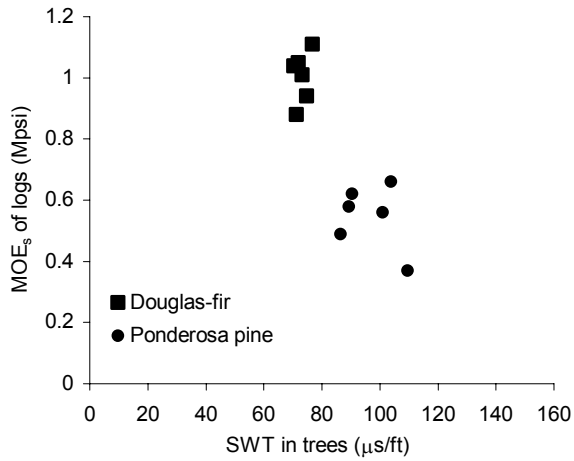


Figure 5. Relationship between SWT in frees and average MOE of logs.

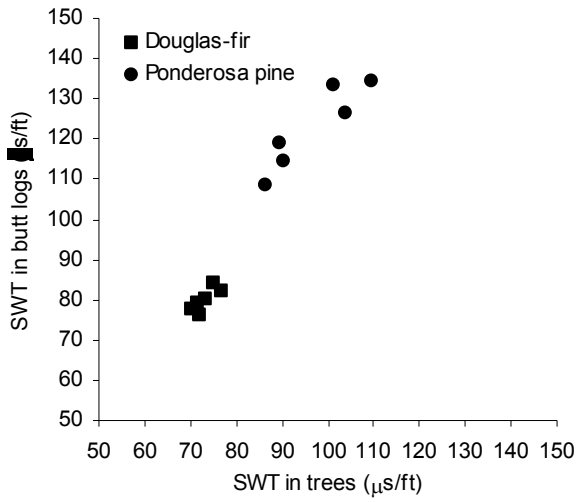


Figure 4. Relationship between SWT in frees and SWT of butt logs.

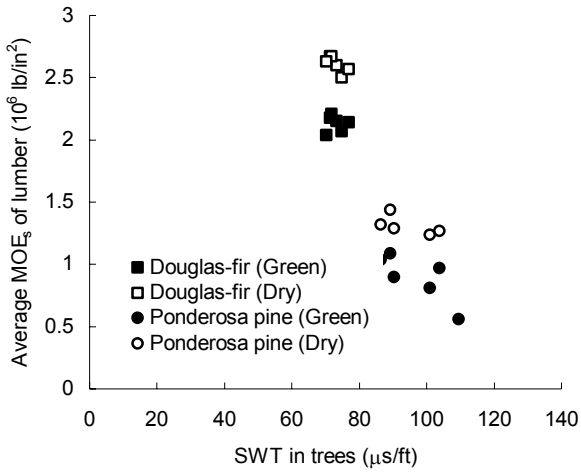


Figure 6. Relationships between SWT in trees and average MOE of lumber produced from the trees.

Table 3. Stress wave and static bending properties of lumber.

Species	Number of lumber	Rough-cut lumber (MC = 24%) SWT (μs/ft)	Rough-cut lumber (MC = 24%) MOE (10^6 lb/in^2)	Dry lumber (MC = 9%) SWT (μs/ft)	Dry lumber (MC = 9%) MOE (10^6 lb/in^2)
Douglas-fir	49	67.8 (4.0)	2.14 (12.4)	59.1 (4.3)	2.60 (11.8)
Ponderosa pine	32	115.3 (11.1)	1.06 (14.21	78.1 (11.4)	1.33 (14.5)

[a] 1μs/ft = 3.28 us/m, 1 lb/in^2 = 6895 Pa.

SWT, stress wave time.

MOE, modulus of elasticity determined by static bending method.

COV, coefficient of varation (%).

Data in parenthese represents coefficients of variation (%).

from 19 to 26 percent for Douglas-fir with an average of 24 percent and 30 to 42 percent for ponderosa pine with an average of 36 percent. The MC of dry lumber was 8 to 10 percent with an average of 9 percent for both species. which was actually lower than target MC.

The averages and coefficients of variation (COV) for stress wave and static bending properties of lumber are stiminarized in Table 3. The mean comparison results indicated a significant difference between SWT in trees and SWT in lumber. For Douglas-fir, the mean SWT in rough-cut and dry lumber decreased about 7 and 17 percent respectively conpared to the mean SWT in trees. The low SWT in lumber is mainly due to the low moisture content (the MC was below fiber saturation point for both rough cut and dried lumber). For ponderosa pine, however, the mean SWT in green lumber (rough cut) increased about 19 percent compared to that in trees. This could be caused by the different wave propagation mechanisms associated with the testing approaches used in tree and lumber measurements. As mentioned earlier, the SWT measured in trees is more controlled by the mature wood (outer wood in the cross-section) compared to the SWT measured in logs. The same interpretation could be reached for lumber. The expectation is that, given the same moisture condition, the SWT in trees would be lower than the SWT in lumber. In terms of moisture effect, since the MC of green ponderosa pine lumber was well above the FSP, the moisture has less effect on the SWT cornpared to Douglas-fir lumber. Therefore, the high SWT in ponderosa pine green lumber might be mainly due to the different wave propagation mechanism. In the case of dried ponderosa pine lumber (the MC was far below the FSP), the mean SWT decreased about 19 percent compared to that in trees because the moisture effect played a more important role compared to wave propagation mechanism.

The relationships hetween SWT in trees and average MOE of lumber produced from the trees are shown in Figure 6. In the case of Douglas-fir, both tree and lumber property range was very small. and no statistical relationship was found between SWT of trees and average MOE of lumber. In the case of ponderosa pine, the data points had a wider property range (tree and lumber) and shown a linear relationship between SWT of trees and average lumber MOE (R^2 = 0.39 - 0.63). When the two species were combined, the statistical analysis resulted in a good correlation between SWT of trees and average MOE of lumber. The coefficients of determination (R') were found to be 0.88 for green lumber and 0.86 for dry lumber.

CONCLUSIONS

A stress wave technique was used to evaluate the strucrural potential of small-diameter Douglas-fir and ponderosa pine trees. The results of the study indicated a significant difference in stress wave time between Douglas-fir and ponderosa pine trees. Stress wave time ranged from 60.8 to 87.0 ms/ft (199 to 285 ms/m) for Douglas-fir trees and 71.3 to 150 ms/ft (234 to 492 ms/m) for ponderosa pine trees. Statistical comparison analysis between stands suggested a potential difference in wood stiffness between the two stands of each species. It was found that stress wave time in Douglas-fir trees increased slightly as tree diameter at breast height increased; whereas, stress wave time in ponderosa pine trees decreased significantly as tree diameter at breast height increased. The statistical analysis resulted in good relationships between stress wave time of trees and modulus of elasticity of logs and lumber when the two species were combined. However, the statistical significance was reduced as the two species were considered separately because of small sample size and narrow property range within each species.

The data colleted for this study illustrates the potential of the stress wave technique for assessing the structural quality of small-diameter timbers in the field. Further studies are planned to develop a broader database of SWT-MOE relationship with sufficient samples for each species, and examine if species has an effect on the relationship.

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