SMALL-DIAMETER LOG EVALUATION FOR VALUE-ADDED STRUCTURAL APPLICATIONS

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ABSTRACT

Three species of small-diameter logs from the Klamath/Siskiyou Mountains and the Cascade Range in southwest Oregon were tested for their potential for value-added structural applications. The logs were tested in bending and compression parallel to the grain. Strength and stiffness values were correlated to possible nondestructive evaluation grading parameters and compared to values derived from published values based on tests of small-diameter clear wood of the test species. For the test sample, specific gravity and static bending modulus of elasticity were good indicators of strength. Growth rate, however, was poorly correlated to specific gravity, strength, and stiffness. The results suggest that the conventionally derived design values based on published small clear strength values are appropriate for bending but nonconservative for axial compressive strength. At present, established round timber specifications, modified to place limits on the presence of crown wood, would be sufficient for selection of small-diameter structural timbers. If amore tightly controlled strength limit is desirable for a specific application, static modulus of elasticity appears to be the most reliable indicator of strength of small-diameter logs.

The Ecosystem Health Assessment of the Applegate Watershed in southwestern Oregon identified overstocked forest stands as a major cause of declining forest health (22). The primary constituent of these overstocked stands, are small-diameter trees, defined as trees with a diameter at breast height (DBH) under 9 inches (230 mm). Limited water and nutrients in these dense stands retard tree growth. Overstocked stands also provide a heavy fuel load that causes forest fires to burn longer and hotter. These factors contribute to the potential weakening of mature forests, leaving them vulnerable to insects, disease, drought, and fire.

The solution to these problems is complicated by the need for cost-effective management of timber stands. Compared to clear cutting, greater care is required to selectively remove small-diameter trees with no negative impact on the remaining timber. This means added cost, which must be compensated by the value of the timber removed or rationalized on the basis of the increased value of a well-managed timber stand. To add value requires expanding the demand for some or all of this material.

One potential value-added market for small-diameter trees is structural applications. In the conventional pole, pile, and post markets, small-diameter logs are valued at around $220/green ton. This resource is worth roughly $160/green ton when processed for dimension lumber and under $30/green ton when processed as wood chips for composites or for firewood. The low value for small-diameter logs in the dimension lumber market is compensated by the greater demand for lumber; a much greater volume of small-diameter logs is needed for lumber production compared to poles, piles, and posts. Poles have a greater net value per volume of harvested fiber because they require less processing than other uses, create less waste than lumber production, and have greater load capacity than timber sawn from the same logs. Increasing current markets for round timber therefore of-

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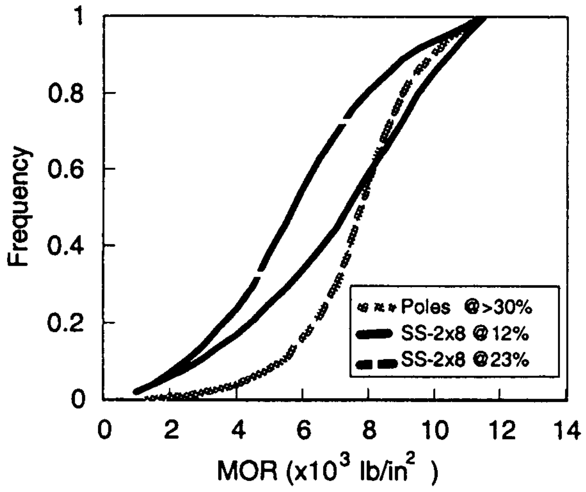

Figure 1. – MOR strength of Douglas-fir poles compared to dimension (Select Structural) lumber. 1 psi = 6.89 kPa.

fers the greatest potential for increasing the value of small-diameter logs.

Expanding markets for small-diameter logs may require improved methods of predicting strength and stiffness. Round timber bending strength is not highly correlated to visual characteristics such as knots or spiral grain, but it is well correlated to bending stiffness. A number of studies have shown a positive correlation between the speed of sound in wood and wood quality (10,14,18). Studies that deal with the speed of sound as a measure of material properties commonly refer to "stress waves" and compare materials on the basis of wave transit time for a fixed path length. Transit time is commonly measured using one or two accelerometers attached to the wood member. When a wave is introduced by means of an impact, the accelerometer monitors acceleration and amplitude variations along the wave. By identifying a characteristic point on a wave pulse, it is possible to measure the time required for the pulse to travel from one location to another (pass-through) or to travel the length of a log and be reflected back to the starting point (pulse echo). Converting transit time to velocity is often a questionable operation in wood because the true path length of the pulse cannot be measured and is assumed to be equal to the length of the piece of wood. This unknown quantity detracts from the expected precision of stress wave transit time as a prediction of relative log stiffness and strength.

To expand markets for small-diameter logs, we need data to develop design standards for structural applications. These efforts should begin by creating guidelines for grading and deriving design values for round timber from small-diameter trees harvested from overstocked stands.

OBJECTIVES AND SCOPE

This report describes a pilot study conducted to evaluate the potential for developing value-added structural products and systems from small-diameter trees. It focused on material property evaluations aimed at uses where small-diameter logs may compete with sawn timbers in structural systems. This initial study focused on evaluating properties across a range of growth rates and densities of small-diameter logs from the Applegate Watershed and the southern Cascades in southwestern Oregon.

Specific objectives included the following:

1. Comparing strength and stiffness of small-diameter logs to published values determined on the basis of standard dimension, small clear test specimens;
2. Evaluating the efficacy of using various nondestructive evaluation techniques to predict strength and assign stress grades to logs;
3. Developing guidelines for testing and evaluating small-diameter logs.

ROUND TIMBER DESIGN

One of the central problems of using round timbers in structural applications is developing adequate design standards. A number of associations maintain standards that could be used to derive design stresses for round timbers. In North America, the most widely referenced standards are published by the American Society for Testing and Materials (ASTM) and the American National Standards Institute (ANSI). Both ASTM and ANSI publish round timber specifications, giving minimum quality requirements and size classifications for round timber piles (ASTM D 25) (4) and poles (ANSI 05.1) (1). These associations also publish standards for the derivation of design stresses (2,5,6,8).

The ASTM maintains three standards related to design stresses for visually graded structural timbers: ASTM D 245, D 2899, and D 3957. ASTM D 245, while written for visually graded lumber design stresses, includes guidelines for structural timbers. ASTM D 2899 provides derivation of design stresses for timber piles; this standard is also referenced by ASTM D 3200 as the basis for construction pole design values. ASTM D 3957 covers stress values for wood members used in log buildings. While small-diameter logs fit into special-use categories such as poles, piles, and wall logs, they can also be used in applications where they will compete with sawn timbers, such as trusses, wall framing, rafters, and space frames.

Conventional roundwood design standards consider only one stress grade. In both ASTM and ANSI standards, one design stress is assigned to all timbers of a given species that meet the minimum quality requirements. In roundwood design standards, unlike lumber design standards, visual characteristics such as knots and spiral grain have little effect on the strength of unprocessed wood. **Figure 1** compares cumulative distributions of bending strengths for Douglas- fir 2 by 8 dimension lumber at 12 and 23 percent moisture content (MC) (11) to bending strength of small (< 10-in. (< 254-mm) diameter) Douglas-fir poles tested at MCs exceeding 30 percent (21). (Note: 2 by 8 = nominal 1.5 by 7.25 in or standard 38 by 184 mm.) In the drier condition, the lumber had a comparable mean strength but three times the coefficient of variation (30% compared to 10%). Consequently, there is less demand for incremental stress grades for poles, and minimum quality specifications are endomed instead for both pole and pile applications (1,4).

Nondestructive evaluation of wood using stress waves has met with varying degrees of success. Wave velocity, amplitude, and frequencies are all correlated to material properties. Velocity is the easiest parameter to deal with and has thus attracted the most attention as an indicator of wood properties. It has been shown to be useful for the detection of defects (17) (e.g., knots, decay, shake, insect damage) as well as moisture gradients (14). In uniform, isotropic materials, wave velocity is directly related to the square root of the ratio of modulus of elasticity (MOE) to density. Unfortunately, wood is neither uniform nor isotropic. Velocity predictions are complicated by natural variations in strength that are not necessarily related to changes in density, by circuitous paths that add to wave transit time, and by moisture gradients that may dampen and slow the waves (13,16,18,19). The value of stress wave velocity measurement lies in its ability to detect strength degradation, which makes it a valuable tool for pole maintenance programs. There is still some question, however, as to its value for accurately assigning strength values to freshly harvested round timbers (19).

MATERIALS AND METHODS

Bending and compression strength and stiffness were evaluated for full-log sections and correlated to tests on small specimens. Resulting values were correlated to several nondestructively evaluated properties, including specific gravity (SG), stress wave transit time, bending and compression strength, and growth rate.

LOG SELECTION

Timber stands in the Applegate portion of the Klamath/Siskiyou Mountains and plots outside the Applegate on the crest of the Cascade Range were surveyed for small-diameter stems. Log selection focused on availability, form, and wood properties. A parent sample of more than 400 trees was initially surveyed to obtain information on the species and quality of small-diameter trees available for structural components. Trees included in this survey were judged to have main stems that met the ANSI 05.1 minimum quality specification (Appendix A). Because each stem was to be cut into two test logs, the smaller knot size limitations imposed by ANSI for the lower half of a round timber were specified over the full length of the log. A wood sample was taken from the outer inch (25.4 mm) of each tree approximately 4 feet (1.2 m) from the groundline using a 0.5-inch- (13-mm-) diameter plug cutter on a battery-operated drill. These “plug” samples were sent to the Forest Products Laboratory in Madison, Wis., for evaluation of SG and growth rate.

From the parent sample, 20 trees were selected for each of three species considered abundant enough to support a local business: Douglas-fir (Pseudotsuga *menziesii),* ponderosa pine *(Pinus ponderosa),* and white fir *(Abies concolor).* The trees, ranging in age from 17 to 116 years, were selected on the basis of SG to provide a test sample that represented the full range of values found in the survey. The average ages of the trees were: ponderosa pine, 24 years; white fir, 44 years; and Douglas-fir, 49 years.

Each tree stem was cut into two logs 11 to 13 feet (3.4 to 4 m) long. The lower log was measured from the butt end, and the upper (tip) log was measured downward from a 3-inch (76mm) tip. Diameter of the butt logs ranged from 4 to 13 inches (102 to 330 mm). If an 11-foot butt log with a minimum tip diameter of 3 inches could not be cut from the stem, the matching tip log was not tested. The logs were tagged for species, plot, and tree, and then sent to the Forest Products Laboratory, where they were hand-peeled and stacked off the ground. Bending tests were conducted 6 months later and compression tests 1 year later.

SG AND GROWTH RATE MEASUREMENT

Samples were taken close to the failure location in each test phase for determining SG and growth rate. Values were calculated using dry weight and green volume. All plug samples, all full-log compression test samples, and a small sample of bending test specimens were used to assess ring count as a predictor of SG.

STRESS WAVE READINGS

For this study, stress wave transit times were measured using both pulse-echo and pass-through methods. The pulse-echo method was used for the full 8-foot (2.4-m) length of the green logs. The accelerometer had a natural frequency response in the range of 25 kHz. The average time between an initial positive rise on the time-amplitude scale was considered representative of the wave transit time. Assuming the pulse path length is twice the log length and dividing by transit time gives a low estimate of wave velocity because the actual path length is likely to be slightly greater than twice the log length. The pass- through measurements were taken just prior to the bending test using two accelerometers, each placed 16 inches (406 mm) to either side of midspan. The accelerometers were attached to nails embedded in the log surface. The nails were hammered l/2 inch (13 mm) into the log surface at an angle roughly 45 degrees to the surface and parallel to the log length, with the nailheads pointing away from one another. Accelerometer signals were monitored with an oscilloscope. Stress wave times were determined by measuring the time interval between the initial rise of the signal spike generated by hitting the nailhead with a hammer to the initial rise of the corresponding signal spike picked up through the nail on the receiving end.

Stress wave MOE (E_{sw}) values were assumed to be a function of green wood density and stress wave velocity, Using stress wave transit time, E_{sw} was calculated using the expression:

$$E_{sw} = \rho V^2 \qquad [1]$$

where ρ is green density (lb. - mass/in.^{3} = lb. - s^2/in.^{4}) and V = wave velocity (in./sec.).

Green density was estimated as the weight of wood plus the weight of water up to the fiber saturation point. Because there was no significant correlation between measured stress wave velocity and MC and because previous research (18) had shown insignificant change in wave velocity above the fiber saturation point, we assumed a maximum green density at 35 percent MC.

BENDING TESTS

Log bending tests were conducted using a center-point load on an 8-foot (2.4-m) span. Because there are no established standard tests for simple beam bending of a tapered round section, our test procedure was a hybrid of the ASTM D 198 bending test for lumber (6) and the ASTM D 1036 static test of wood poles (3). Symmetric third-point loading, which is suggested for lumber, has the advantage of providing a con-

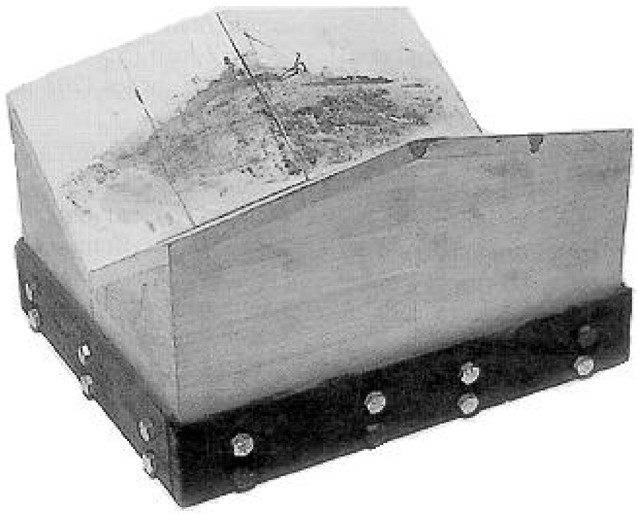

Figure 2. – Load head used to apply center-point load to surface.

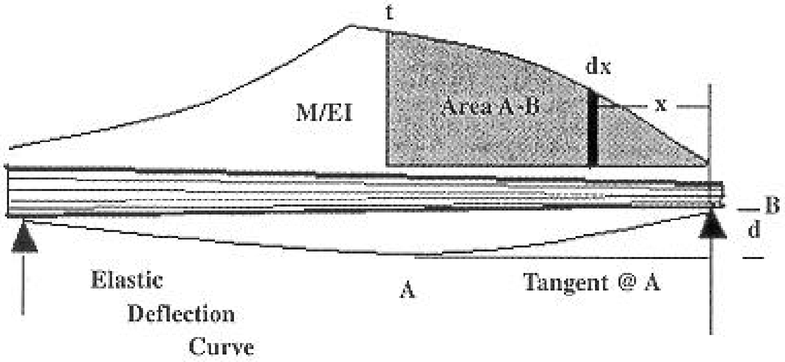

Figure 3. – Calculation of moment area. Deflection (d) equals the first moment about an axis through B of the area under the M/El curve between A and B. when A is the point of maximum deflection.

stant moment over the middle third of the span. This, in turn, has the advantage of imposing constant stress over the section between load heads when the specimen has a uniform cross section, but it is of little advantage for a tapered beam. The ASTM D 1036 test calls for applying a concentrated load at “ground line” distance from the butt end of a pole to evaluate the moment capacity for pole applications. Since we were more concerned with using the test timbers as simple beams rather than poles, we modified the ASTM D 1036 procedure by using a midspan concentrated load, under the assumption that this method of loading provided the easiest and most consistent test and analysis of beam bending for these tapered logs.

A load head with special wood contact surfaces was fabricated to apply the load **(Fig. 2).** The load head actually consisted of four planes, one per quadrant of the rectangular head. Along the axis of the head, oriented parallel to the log axis, the planes were sloped 10 degrees upward from horizontal moving away from the center; along the axis, oriented normal to the log axis, the planes were angled 30 degrees downward moving away from the center. Initial contact between the load head and the round log surface was therefore at two points 30 degrees either side of a vertical plane through the centroidal axis at midspan, which placed a slightly inward confining force component on the log as the vertical load was applied. As these points compressed, the contact areas spread more rapidly parallel to the log axis than perpendicular to it.

The log supports were similar to those specified in ATSM D 198. The logs were simply supported on an 8-foot (2.4-m) span. Each end was supported in a concave cradle that could rotate about axes both parallel and perpendicular to the test span. One end of the log was supported on rollers to limit longitudinal restraint. Load was applied at a rate of 0.4 in./min. (10 mm/min.). In most cases, failure or maximum load occurred in less than 10 minutes at less than 4 inches (102 mm) of vertical displacement.

Load was measured by a load cell between the machine head and load head. Assuming a load cell accuracy of 1 percent of the full range, we varied load cells with log size to maintain a failure load accuracy within 5 percent across the range of log sizes tested. We selected load cells that had capacities of no more than five times the capacity of the log. To facilitate the process, logs were tested by size, beginning with the largest.

MC and SG samples were taken immediately after testing. A disk was cut from the log close to the point of failure; the sample was cut square to facilitate volume measurements. The sample was weighed, ovendried, and re-weighed. This method yielded a gross measure of MC and SG.

BENDING STRENGTH

The bending strength of the logs was evaluated using simple beam theory:

$$\mathrm{MOR} = \frac{8Pl^2}{\pi D^3} \qquad [2]$$

where P is the failure load, l is the test span, and D was estimated as average of diameters measured 16 inches (406 mm) either side of the load point.

This analysis assumes that the bending stress is maximum at midspan. Of course, this requires that the bending moment, which varies linearly along the length, decreases faster than the timber section modulus moving from midspan to the tip end.

BENDING MOE

Center-point loading of a tapered round timber presents several problems that make it difficult to determine MOE accurately. Since we considered MOE to be of secondary importance for this pilot study, we made a number of simplifying assumptions that compromised the accuracy of our MOE calculations for the sake of expediency. We assumed that the poles were perfectly round, that they had a linear taper, and that MOE was constant over the pole length. In addition, and more critically, we chose to equate load head movement to center-point deflection. This required the additional compromising assumptions that error resulting from shear would be negligible for the span/depth ratios used and that measurements could be adjusted for bearing deformation using an empirically derived function of log stiffness. This measurement was considered adequate *to* give a measure of relative MOE of the correct order of magnitude and variability.

We determined MOE for the tapered logs using classic moment-area methods in which both moment and section properties are varied over the beam span. The moment-area theorem **(Fig. 3)** basically states that the deflection of any point (B) on the elastic curve from the tangent to this curve at a second point (A) is equal to the static moment about an axis through B of the area under the moment/stiffness (M/EI) diagram between A and B. If the slope of the tangent to the elastic curve at point A is zero (point of maximum deflection), this calculation gives the deflection of point A relative to point B.

A computer program was written to use the moment-area method to assess the point of maximum deflection for the range of log tapers represented by our test sample. In general, a quadratic shape function fit to the measured log diameters had a small coefficient on the x^2 term, suggesting that a linear taper was appropriate to characterize the moment of inertia for the integration. This analysis indicated that the point of maximum deflection ranged from 0.75 to 1.5 inches (19 to 38 mm) from midspan toward the tip end. We considered this range of maximum deflection to be within the range of experimental error inherent in the test method, requiring no further adjustment to approximate relative displacement of the center point. For each log we derived a constant (α), calculated as:

$$\alpha = \int_0^t x^2/I \qquad [3]$$

where t = distance from small-end reaction to point of maximum deflection and I = moment of inertia that varies as a function of log taper.

The value α, calculated as the first moment of the area under the M/EI diagram between the point of maximum deflection and the tip-end reaction about an axis through the tip-end reaction, is basically the product of beam deflection and a unit bending MOE divided by a unit load. Multiplying a by the measured slope of the load-deflection curve gives an estimate of the effective MOE of the log.

COMPRESSION TESTS

Compression tests were conducted on two samples: full-size log sections and small specimens. Specimens were cut from the test logs after the bending tests. The full-size sections were cut from the large end of each log. The small specimens were cut from only the small end of the butt logs.

FULL-SIZE SECTIONS

Full-size log sections were cut to lengths between 3 and 4 times the average log diameter. The ends were squared off to minimize problems with eccentric load. Specimens were centered between load heads of a million-pound (454,000-kg) capacity universal testing machine and loaded in compression until maximum load was exceeded. Displacement was measured as load-head movement, and strain was determined as load-head displacement divided by specimen length. After testing, disks were cut from undamaged sections and measured for MC and SG. Failures rarely occurred at the small end of the specimen, but they were often influenced by knots somewhere along the specimen length. Failure stress was calculated as maximum load divided by average cross-sectional area. MOE values were determined using linear regression to fit a straight line to the load-deformation curve between 0.4 and 0.6 times the maximum load.

SMALL SPECIMENS

We attempted to cut the small specimens from clear wood in the butt logs. However, for many logs, it was impossible to obtain sections with no knots or pith. The specimens were cut so as to minimize the effects of knots and pith. The roughsawn specimens were stored in a conditioned room at 21°C 65 percent relative humidity, until they reached equilibrium. They were then planed to 2- by 2-inch (51- by 51-mm) sections and cut 8 inches (203 mm) long with parallel ends.

The small specimens were tested following ASTM D 143, except that deformation was measured over the length of the specimen. Compressive loads were applied parallel to the grain. Loads were monitored and plotted as a function of load-head movement. The slope of the linear portion of this plot was used to determine compressive MOE (E_c). Maximum compressive stress was determined as the maximum load divided by specimen end-surface area (4 in^2 (31 cm^2)).

CROWN WOOD

Cellulose material produced in the stem of a tree during the stage of development when that portion of the stem is within the active crown of the tree has physical and mechanical properties that vary significantly from those of the material produced in portions of the stem that are well below the active crown. The term “juvenile” often used to describe this material is somewhat confusing in that at a given cross section, this wood is the oldest rather than the “youngest” part of the tree. Crown wood is a more appropriate term in that the wood properties have nothing to do with age but rather are the result of proximity to the auxin-producing active crown of the tree.

Studies have shown that strength and stiffness increase as a function of the number of annual rings from the pith up to a transition point, after which these properties remain fairly constant. Bendtsen and Senft (9) showed this “transition” point to occur within the first 20 years of growth. Their data show roughly a tenfold increase in strength and stiffness in going from the pith to the transition point.

To provide some basis for assessing the effect of crown wood on the effective section properties, we performed a set of iterative calculations to select a crown-wood portion of the total cross-sectional area (β) and an MOE ratio (γ) that resulted in the lowest variability of the effective axial stiffness. We varied b from the proportion of the area encompassed by the 10th annual ring to that encompassed by the 20th annual ring,

TABLE 1. – Summary of mean specific gravity values measured in four study phases.[a]

Species	Plug	Bending[b]	Compression	
			Full-size logs	Small specimens
Douglas-fir	0.54 (10)	0.45 (11)	0.46 (12)	0.50 (9)
White fir	0.42 (16)	0.36 (12)	0.40 (20)	0.40 (14)
Pine	0.39 (14)	0.36 (11)	0.38 (23)	0.39 (17)

[a] Values in parentheses are coefficients of variation (%).

[b] Squared-up disk represented only the center 75 percent of the *cross* section,

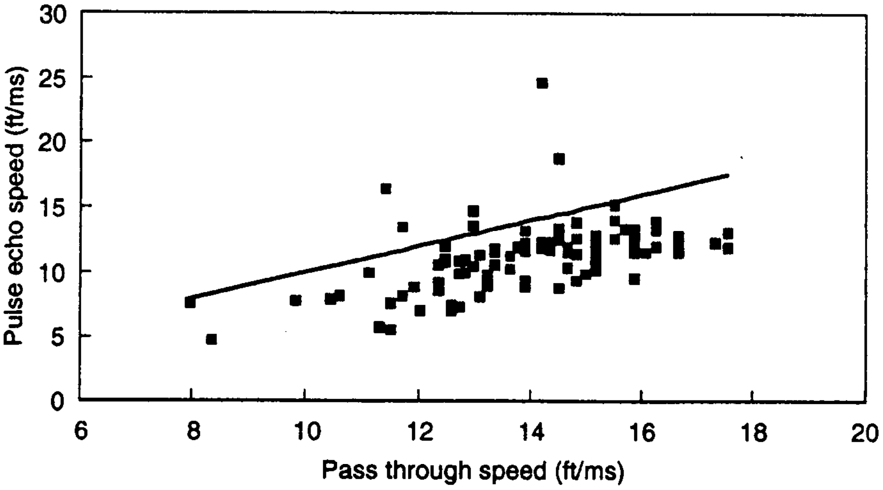

Figure 4. – Relationship of pulse-echo to pass-through stress-wave velocity. 1 foot = 0.305 m.

and we varied the effective MOE (E_e) of each crown-wood portion from 50 to 100 percent of that of the wood beyond the crown-wood range.

Assuming:

$$E_e A_t = Pl/\delta \qquad [4]$$

$$\gamma E_m \beta A_t + (1-\beta A_t)E_m = (\gamma\beta + 1 - \beta)E_m A_t$$

$$E_m = Pl/(\delta A_t(\gamma\beta + 1 - \beta)) \qquad [5]$$

The mature wood MOE (E_m) is inversely related to β and γ. We used Equation **[4]** to derive values for E_m. By estimating β as the crown-wood portion of the cross-sectional area within the 10th, 15th, and 20th annual rings and varying γ, we obtained different distribution means and variability. Assuming that the more accurate assessment of the crown-wood effect would minimize E_e variability, we selected the combination of β and γ that minimized variability. Given these measured areas, we evaluated effective section properties by assigning a range of stiffness ratios to the crown-wood regions: the lower the axial stiffness of crown wood relative to mature wood, the lower the effective section for resisting axial load. The combinations of annual ring count and stiffness ratio that resulted in the lowest variability in compressive stiffness and ultimate compressive strength were assumed to be indicators of characteristic values that might be used to visually grade small-diameter round timbers.

RESULTS

The results showed few surprises. However, they do highlight a need for standard procedures for assessing physical as well as mechanical properties of small-diameter round timbers. Bending strength values were within the range expected on the basis of published strength data, but axial compression values were slightly low. Variations in the measurement of nondestructive mechanical and material properties detracted somewhat from the value of these properties as predictors of log strength.

LOG TAPER

Log-diameter taper ranged from 0.0009 to 0.03 in./in. (0.023 to 0.76 mm); the range for butt and tip log taper was roughly the same.

SPECIFIC GRAVITY

Table 1 shows the range in SG of test samples at various phases of the study. In each case, SG was calculated as ovendry weight divided by green volume. However, the fact that samples were cut differently for each test resulted in variations that reflected within-tree variations. The bending samples represented the center 75 percent of the cross section of the logs. The full-size compression values represent the average for the entire cross section; the values for the small specimens represent the outer growth rings in the butt logs. Although roughly half (23/48) of the small specimens contained pith, their SG values were close to those of the original plug samples.

On average, SG values were close to published values (8) of 0.45, 0.37, and 0.39 for Douglas-fir, white fir, and ponderosa pine, respectively. Within-tree variations were fairly large, but average coefficients of variation (COVs) within a species were on the order of 10 to 15 percent. Douglas-fir samples had an average SG of 0.46, white fir 0.38, and ponderosa pine 0.37.

The growth rate and SG data collected for the parent sample indicate a weak relationship between these two parameters. The ponderosa pine was fairly fast grown; growth rate of the majority of specimens in this sample was 7 to 20 rings/in. and that of the slowest grown specimens was 36 rings/in. Growth rate for the white fir sample was uniformly distributed in the range of 6 to 30 rings/in.; the slowest growth rate was 38 rings/in., similar to that of ponderosa pine. The Douglas-fir sample exhibited the broadest growth rate range, extending from 6 to 52 rings/in.

STRESS WAVE VELOCITY

Figure 4 compares the stress wave velocities measured for the test logs. Stress wave velocity measured soon after the logs arrived at the Forest Products Laboratory was slightly slower than that measured immediately prior to testing. Stress wave velocity ranged from 4,800 to 25,000 ft./sec. (1,463 to 7,620 m/sec.) for the three species. For each species, stress wave velocity exceeded 18,000 ft./sec. (5,486 m/sec.) in only one or two full-length logs. The remainder of full-length logs exhibited fairly

TABLE 2. – Summary of mean strength test results for three species of small-diameter round timbers.[a]

	Static bending			Compression, full-size log sections			Compression, small specimens		
	Douglas-fir	White fir	Pine	Douglas-fir	White fir	Pine	Douglas-fir	White fir	Pine
Maximum stress (psi)									
Stem	8,820 (26)	6,730 (36)	5,410 (35)	5,000 (15)	3,860 (18)	2,490 (29)			
Butt	8,990 (24)	7,330 (30)	4,950 (21)	5,240 (17)	3,830 (17)	2,260 (31)	6,500 (12)	4,520 (14)	2,850 (14)
Tip	8,630 (27)	5,960 (40)	6,400 (44)	4,710 (10)	3,920 (29)	3,060 (14)			
Modulus of elasticity (× 10^6 psi)	1.4 (20)	1.2 (22)	0.81 (31)	0.81 (23)	0.64 (34)	0.37 (43)	1.6 (27)	0.8 (27)	0.4 (30)

[a] Values in parentheses are coefficients of variation (%). 1 psi = 6.89 kPa.

tight stress wave distributions: for pine, velocity ranged from 4,800 to 10,000 ft./sec. (1,463 to 3,048 m/sec.), for Douglas-fir from 10,100 to 15,000 ft./sec. (3,078 to 4,572 m/sec.), and for white fir from 7,600 to 14,000 ft/sec. (2,316 to 4,267 m/sec.). The range of stress wave velocity measured over the 32-inch (813-mm) gauge length at midspan prior to bending tests was slightly narrower. No velocity values exceeded 18,000 ft/sec. (5,486 m/sec.). For pine, stress wave velocity ranged from 8,300 to 15,900 ft./sec. (2,530 to 4,846 m/sec.), for Douglas-fir from 11,700 to 17,500 ft/sec. (3,566 to 5,334 m/sec.), and for white fir from 7,900 to 17,500 ft./sec. (2,408 to 5,344 m/sec.).

The higher stress wave velocities obtained immediately before testing are attributed to drying and test length. Sections taken from the logs after testing showed a steep moisture gradient for the larger-diameter logs. In many cases, fibers near the outer circumference were well below the fiber saturation point. Stress wave was greater in dry wood. For the full-log pulse-echo measurements, stress waves passed through six times as much log length as did waves measured by the pass-through method. This contributed to greater error in the path length estimate, possibly making the pulse-echo waves appear to travel slower than the pass-through waves.

BENDING TESTS

The MOR values for the three test species are compared in **Table 2.** Because of the limitations on sample size, differences observed between the butt and tip log strength values must be referenced with caution. These differences are not significant at the 0.05 level of confidence. The Douglas-fir sample consisted of 21 butt logs and 20 tip logs. The white fir sample consisted of 17 tip logs and 21 butt logs. Because of small size and numerous knots, only 7 tip logs and 15 butt logs of the ponderosa pine sample met the ANSI quality specification.

All logs failed within 15 inches (381 mm) of midspan. The majority of logs had average MC at or above fiber saturation. Most exhibited fairly linear load displacement curves up to two-thirds of the maximum load and ductile failure modes. A few of the smaller, dryer logs failed in a brittle manner. Although knots played a role in defining log load capacity, failures generally did not begin at knots.

The test procedures exhibited some sensitivity to log size. Historical data on variations in MOE (9) suggest that this property should be greater for the butt log than for the tip. However, our results showed a tendency for lower MOE in larger logs. Inspection of the logs after failure showed greater bearing deformation in the larger, stiffer logs. The lower MOE values for the larger logs are thus attributed to a combination of bearing and shear deformation.

COMPRESSION TESTS

Average compressive strength values of full-size log sections are shown in **Table 2.** Although the MC of several samples exceeded 20 percent, average MC was 15 percent at the time of testing. The average compression values are slightly below what might be expected on the basis of green clear wood values adjusted to 15 percent MC.

Crown wood constituted from 18 to 76 percent of the butt log sections. The proportion of crown wood was based on the assumption that crown wood is represented by the first 10 to 20 years of growth. For ponderosa pine, crownwood area averaged 85 to 100 percent of the cross-sectional area, depending on the definition used (10 to 20 annual rings). This proportion of crown wood was greater than that measured for either Douglas-fir or white fir; 28 percent of ponderosa pine, 9 percent of white fir, and 10 percent of Douglas-fir trees were 20 years of age or younger.

Compressive strength values of small specimens **(Table 2)** were slightly greater than those measured for full-size sections but still low compared to ASTM clear wood values. The tests indicated ductile but varied failures. Of the 60 tree stems sampled, 16 had knots in the small end of the butt log that prevented us from taking a clear sample for parallel-to-grain compression tests. Of the 44 specimens tested, 22 had small knots that were involved to some extent in the failure. Twelve specimens exhibited shear- and splitting-type failures and 9 exhibited a combination of fiber buckling and compression.

ANALYSIS

Our results suggest that the bending strength of small-diameter logs is comparable to that of timber from larger trees, but axial stress may be significantly lower than that found in trees more than 10 inches (254 mm) in diameter. Sample sizes limit the confidence that can be placed on any assessment of distribution fractiles, but mean trends suggest that for the three species tested, the mean MOR is greater than or equal to values estimated on the basis of clear wood strength and conventional design assumptions for poles and piles. Mean MOE was close to the expected value. Axial compression strength, however, fell below the conventionally derived estimates **(Table 3).** This low compressive strength was attributed to the proportion of crown wood.

SPECIFIC GRAVITY

SG values for the three species tested were well within the range expected on the basis of published values. Despite a fairly wide range in growth rates for the Douglas-fir sample, the variability of

SG was not significantly different from that determined for small clear specimens by ASTM D 2555 (8). The ASTM COV for SG ranges from 10 percent for ponderosa pine to 13 percent for Douglas-fir. Bending test specimens and small compression test specimens had COVs in this range. However, variability in SG was on the high side for the white fir and ponderosa pine full-size compression test sections.

There is normally a positive correlation between SG and strength. This correlation is often referenced indirectly as a measure of wood quality for structural applications. The correlation between SG and growth rate provides a measure that can be evaluated by visual inspection. Trees that grow slowly are generally thought to be denser than those that grow quickly. However, Megraw (15) found that growth rate and SG are virtually independent. We found this to be true, particularly at growth rates slower than 30 rings/in. Change in SG with growth rate in the plug samples appears to be positively correlated to growth rate at the low end of the scale, but regression analysis showed little correlation across the whole range. It is Megraw's (15) contention that the percentage of earlywood controls SG regardless of growth rate.

BENDING STRENGTH

Bending strength values, calculated as described in the Methods section, are shown in **Table 3** as a 95 percent confidence on the mean. These values are compared to mean values calculated from tests on small clear specimens (ASTM D 2555 (8)), adjusted for size and knots as recommended in ASTM D 2899 (7) for poles and piles. In each case, the butt logs exhibited slightly higher mean strength. However, this difference was significant (p = 0.05) only, for the white fir logs. The ASTM adjustment to mean strength includes a 10 percent reduction from the small clear value to the full-size log value and a 12 percent reduction from the butt value to the tip value (20). In all cases, mean strength values of test samples were greater than the ASTM-predicted value at the 0.05 level of significance.

TABLE 3. – Compression test results compared to ASTM predicted values.

Species	95% confidence on mean	ASTM estimate[a]
Bending strength (psi)		
Douglas-fir	7,370 to 9,420	6,900
White fir tip	4,950 to 6,970	4,637
White fir butt	6,500 to 8,160	5,270
Pine	4,720 to 6,100	4,620
Bending modulus of elasticity (× 10^6 psi)		
Douglas-fir	1.52 to 1.68	1.6
White fir	1.13 to 1.27	1.2
Pine	0.71 to 0.9	1.0
Compressive strength, full-size log sections (psi)		
Douglas-fir	4,800 to 5,200	6,500
White fir	3,720 to 4,080	5,220
Pine	2,220 to 2,780	4,780
Compressive strength, small (standard) specimens (psi)		
Douglas-fir	6,160 to 6,810	7,230
White fir	4,260 to 4,800	5,800
Pine	2,370 to 3,280	5,310

[a] ASTM D 2899 (7) based on strength of small clear wood adjusted for size and knots. Compressive strength determined for samples under 20 percent MC are compared to estimates adjusted for MC.

The bearing deformation included in the measurement of load-head movement restricted the accuracy that could be obtained for MOE calculations. By assuming that bearing deformation is insignificant for smaller (4-in.- (102-mm-) diameter) stems and that average MOE of the wood fiber that controls stiffness of the log section does not vary with log size, we were able to derive a correction for the MOE calculation on the basis of linear regression. MOE was obtained for each test specimen (see Methods). Within each species group, we assumed the following: 1) that the average value determined for 3- to 4-inch (76- to 102-mm) stems was close to the true value; and 2) that the difference between the average value and the value determined for larger stems was a function of stem diameter. Regression of the MOE difference relative to diameter for all three species gave a correction that was dependent on geometry alone. While this approach still provided some measure of variability, it controlled the mean value for each species and permitted no assessment of difference between butt and tip sections.

The adjusted test values reported in **Tables 2** and **3** indicate that average bending MOE values for the test material were close to published values (8). In combining tip and butt samples, Douglas-fir and white fir MOE values were found to be essentially equal to the tabulated values. Mean MOE of ponderosa pine was slightly lower than these values.

RELATIONSHIP OF LOG STRENGTH TO MOE

Of the nondestructive parameters surveyed, static MOE provided the greatest correlation to strength **(Fig. 5).** Static bending MOE explained 53 percent of bending strength variability and compressive MOE 58 percent of compressive strength variability. To improve these estimates, we incorporated other nondestructive evaluation parameters, including butt diameter, MC, ring count, and SG. The best prediction model explained 90 percent of strength variability for Douglas-fir logs, 69 percent for ponderosa pine, and 88 percent for white fir.

Longitudinal MOE determined on the basis of stress wave velocity had a positive but weak correlation to log strength and bending MOE. Stress wave MOE explained roughly 41 percent of variability in MOR and MOE. A plot of full-log MOR versus stress wave MOE for the 32-inch (813-mm) gauge length showed considerable scatter about the regression line. This may be explained in part by moisture gradients from the surface to the pith. It may also be that the high percentage of juvenile wood in some logs actually caused a steep transition in elastic properties, where the bending MOE measured was controlled by the outer zones and the stress wave time was strongly influenced by crown wood. The correlation coefficients for

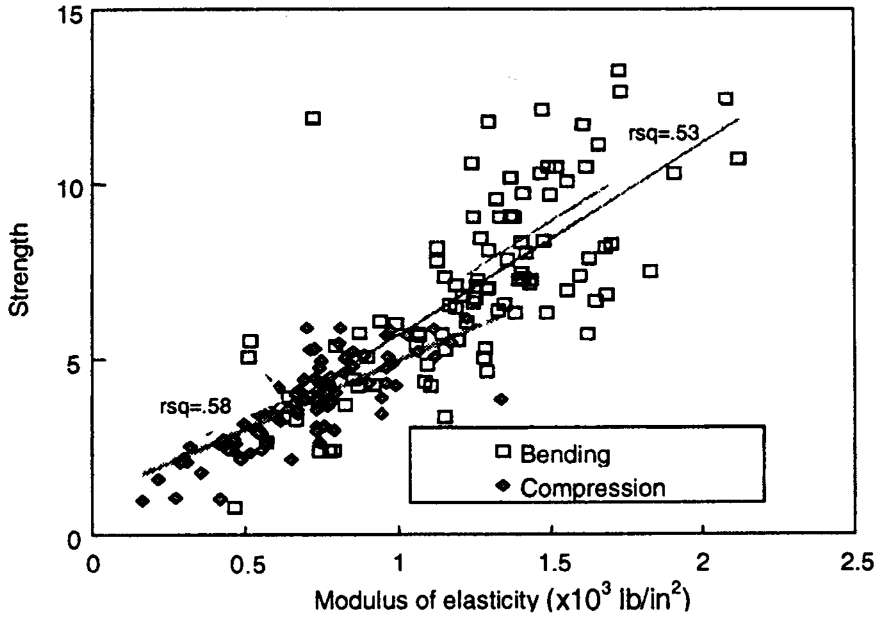

Figure 5. – Strength as a function of MOE. Plot shows compressive strength versus compressive MOE and bending strength versus bending MOE.

stress wave MOE and bending strength (0.39) and stress wave MOE and static bending MOE (0.4) found in our study are slightly low but not inconsistent with values reported by other researchers (12,16,18,19).

Our study suggests that transverse stress-wave velocity provides a better prediction parameter for MOR and MOE than does longitudinal stress-wave MOE. This is partly due to the number of parallel readings that can be made, which allow for comparison of obstructed and unobstructed paths. The use of stress-wave transit time for stress grading of logs will require multiple transverse readings. The time required for these readings may be a limiting factor when producing structural lumber for competitive markets. Given the low predictability of single stress-wave measures and the current state of technology, stress-wave velocity does not appear to offer an economically viable means of grading small-diameter logs for this use.

COMPRESSIVE STRENGTH

Full-size log compressive strength was less variable than full-log bending strength for white fir and Douglas-fir **(Table 2).** Full-log compression tests are more attractive than bending tests for evaluating log strength because they are easier to run and can easily be used to test change in strength along log length. Small-specimen strength averaged roughly 20 percent greater than full-log strength **(Table 3)**, but it explains 70 percent of the variability in full-log strength. Although the average change in compressive strength from small clear to full-sized specimens was twice that assumed in the ASTM Standard D 2899 (7) derivation of bearing loads on piles, the high correlation suggests that this method provides a viable means of predicting full-size compressive strength.

Factors that may have contributed to the observed 20 percent reduction in compressive strength of full-size sections compared to small specimens include specimen size, knots, and crown-wood proportion. Longer sections provide greater probability of stressing a weak link. Knots and crown wood played a greater role in limiting compressive strength of full-size specimens. Assuming that the crown-wood region ranges from 10 to 20 annual rings from the pith, small-diameter sections are likely to have a greater portion of this weaker wood than do larger trees. As the entire section is strained equally in compression, the more mature and stiffer outer regions carry a disproportionate share of the total load. In our study, standard-size specimens were cut primarily from regions bordering on the outer circumference, which represented the more highly stressed regions. Strength predictions based on ASTM values for small clear wood samples, however, are likely to be slightly unconservative, as they were most likely derived from tests on wood samples gathered further from the influence of crown wood in large trees.

When compressive strength and stiffness were evaluated using effective area estimates derived to minimize variability, the results varied slightly with species. For ponderosa pine, the lowest variability for MOE and ultimate compressive stress was obtained assuming that crown-wood regions are best represented by the first 20 annual rings. For white fir, the best MOE estimates were determined using 10 annual rings of crown wood. For Douglas-fir, the best MOE estimates were determined using 20 annual rings of crown wood and the best ultimate compressive strength estimates were obtained using 15 annual rings. The best estimates for the ratio of crown-wood to mature wood stiffness ranged from 0.52 for ponderosa pine to 0.74 for Douglas-fir. For ultimate compressive strength, the best estimates of the strength ratio of crown wood to mature wood ranged from 0.69 to 0.78. These differences are not significant given the sample size and variability measured.

The data indicate that the average strength of the smaller tip sections of ponderosa pine was greater than that of the butt sections **(Table 2).** However, the sample was too small to make this a valid comparison; only 6 tip sections were tested compared to 14 butt sections. Many pine tip logs were not tested because of their small diameter and large knots.

Together, compressive MOE and SG explained 65 percent of the variability in compressive strength. For purposes of grading these timbers to serve as columns, MOE and SG are the best nondestructive predictors of strength.

In attempting to correlate full-log bending to compressive strength, we found that compressive strength could explain only 35 percent of the variability in bending. Although this is an improvement over stress-wave MOE, compressive strength is not as good a predictor as bending MOE as determined in the crude manner described in this study.

CONCLUSIONS

Bending strength and stiffness of small-diameter logs of the test species compare favorably with published values for the respective species. It appears that visual inspection of such logs may be sufficient for selecting small-diameter structural timbers and assigning design bending stresses following ASTM recommendations.

MOE showed a strong correlation to strength. Bending MOE is apparently an important nondestructive evaluation parameter for stress grading of logs. When MOE was used in combination with other nondestructive evaluation parameters, such as SG, MC, and growth rate, model predictions were able to account for up to 90 percent of the variability in log strength.

Compressive strength of both the full-log sections and small (standard-size) specimens indicated that the ASTM-derived design value is non- conservative. This may have been due to the larger portion of crown wood in the small specimens. Further study is needed on the influence of crown wood on the strength of small-diameter logs to develop design recommendations based on small clear test values.

The weak correlations between stress-wave transit time and strength suggest that longitudinal stress-wave measurement will add little to strength predictions based on visual grading. The stress-wave MOE values were generally higher and more variable than expected on the basis of published MOE values for the test species. The linear regression correlations suggest that these values could be used to explain only 16 percent of the variability in log strength. Possible stress-wave error sources include equipment inaccuracy, moisture gradients, steep transition from crown to mature wood, interpretation of wave transit times, and the true relationship between MOE determined using a compressive wave and that determined using static bending. Any of these problems are likely to be worse in field evaluations than in the laboratory. Although stress-wave measurement has been shown to be effective in detecting decay or other strength-reducing defects, our results suggest that additional research is needed to render this method useful for grading sound logs for strength and stiffness.

This study provided useful information about the testing as well as the strength and stiffness of small-diameter logs. The load-head configuration developed to accommodate the rounded surface of the logs should be useful in future evaluations of the structural properties of small-diameter logs. However, future bending tests should be designed to give more accurate readings of bending deflection.

RECOMMENDATIONS

The results of this study support the premise that small-diameter logs could be used as structural elements with limited revision to current round timber specifications and design standards. If the axial compression values, which appear low by comparison to published values, are significantly affected by a relatively high proportion of crown wood, specifications for structural-use timbers should include provision for either limiting the crown-wood portion or making the appropriate adjustment to axial strength.

Another possible limit to structural timber specifications not covered in this study is the roundness of the section. Out-of-round sections add to the variability of strength and stiffness calculations. A generic model for stiffness and strength will assume a round section and a linear change in diameter along the length. Comparison of section properties of a round section to that of an ellipse with the same circumference but a 10 percent difference in orthogonal diameter shows a 12 percent difference in section modulus and a 17 percent difference in moment of inertia. Errors derived from the round section and linear taper assumptions may therefore account for a considerable portion of variability in strength and stiffness. Limits on these geometric parameters may be worth considering in future studies aimed at improving the accuracy of stress grading for small-diameter logs.

Items of importance to expanding markets for small-diameter logs (not covered in this study) involve construction details to address problems with the round form and taper. From a structural perspective, the greatest problem is connections. Connection problems include round shape, non-standard sizes, and effects of change in moisture, which result in drying checks in the outer circumference of a round timber. A number of connection details have been proposed, but there are no published values for axial and moment capacities. The problem of taper can be addressed by changing perceptions about round timbers, limiting uses to those not sensitive to taper, or modifying section properties to eliminate the effect of taper.

To encourage structural uses for small-diameter logs, research is needed to evaluate axial load and connection capacities and to develop construction details to overcome perceived problems caused by log taper and round sections.

LITERATURE CITED

1. American National Standards Institute. 1992. American national standard for wood poles: specification and dimensions. ANSI O5.1. ANSI, New York.
2. __________. 1997. National electric safety code. Inst. of Electrical and Electronics Engineers, Inc. ANSI C2. ANSI, New York.
3. American Society for Testing and Materials. 1990. Standard test methods of static tests of wood poles. ASTM D 1036-90, Vol. 4.10. ASTM, West Conshohocken, Pa.
4. __________. 1991. Standard specification for round timber piles. ASTM D 25-91, Vol. 4.10. ASTM, West Conshohocken, Pa.
5. __________. 1993. Standard practice for establishing structural grades and related allowable properties for visually-graded lumber. ASTM D 245-93, Vol. 4.10. ASTM, West Conshohocken, Pa.
6. __________. 1994. Standard method of static tests of lumber in structural sizes. ASTM D 198-94, Vol. 4.10. ASTM, West Conshohocken, Pa.
7. __________. 1995. Standard practice for establishing design stresses for round timber piles. ASTM. D 2899, Vol. 4.10. ASTM, West Conshohocken, Pa.
8. __________. 1996. Standard test methods for establishing clear wood strength values. ASTM D 2555; Standard practice for establishing stress grades for structural members used in log buildings. ASTM D 3957; Vol. 4.10. ASTM, West Conshohocken, Pa.
9. Bendtsen, B.A. and J.F. Senft. 1986. Mechanical and anatomical properties in individual growth rings of plantation-grown cottonwood and loblolly pine. Wood and Fiber 18(10):23-38.
10. Bodig, J. and J.R. Goodman. 1981. Nondestructive evaluation of wood utility poles. *In*: Proc. of 7th Wood Pole Inst., Colorado State Univ., Ft. Collins, Colo.
11. Green, D. and J. Evans. 1987. Mechanical properties of visually graded lumber. Vol. 2. Douglas-fir-Larch. USDA Forest Serv., Forest Prod. Lab., Madison, Wis.
12. Goodman, J.R., M.D. Vanderbilt, M.E. Criswell, and J. Bodig. 1981. Probability based design of wood transmission structures. Part I. Strength and stiffness of wood utility poles. EPRI EL-2040, Vol. 1, Proj. 1352-1. Electric Power Res. Inst., Palo Alto, Calif.
13. Han, W. 1994. Log quality evaluation by lengthwise ultrasonic transmission. Measurement of log quality seminar. Norwegian Inst. of Wood Technology, Oslo, Norway.
14. James, W.L. 1981. Effects of transverse moisture content gradients on the longitudinal propagation of sound in wood. FPL-RP-466. USDA Forest Serv., Forest Prod. Lab., Madison, Wis.

15. Megraw, R.A. 1985. Wood quality factors in loblolly pine. Tappi Press, Atlanta, Ga.
16. McLain, T. 1980. Probability based design of wood transmission structures. Final Rept. EPRI Proj. RP-1352. Electric Power Res. Inst., Palo Alto, Calif.
17. Nelson, R.F. and J.L. Hodgson. 1992. Wood pole inspection and maintenance. *In*: Proc. of Inter. Conf. on Wood Poles and Piles, Colorado State Univ., Ft. Collins, Colo. pp. 223-235.
18. Steiger, R. 1997. Sorting of roundwood and sawnwood using soundwaves. Holzforschung-Holzverwertung 49(2):28-35.
19. Wilson, J. 1992. NDE: Tools for the future. Presented at Southwestern Pole Conf., Nov. 26-27, 1992, Mississippi State Univ., Mississippi State, Miss.
20. Wolfe, R. 1989. Allowable stresses for the upside-down timber industry. *In*: Proc. of Inter. Conf. on Poles and Piles, Colorado State Univ., Ft. Collins, Colo.
21. Wood, L.W., E.C.O. Erickson, and A.W. Dohr. 1960. Strength and related properties of wood poles. Wood Pole Res. Program. ASTM, West Conshohocken, Pa.
22. U.S. Department of Interior, Bureau of Land Management. 1994. Applegate adaptive management area ecosystem health assessment. USDA Forest Serv., Rogue River and Siskiyou National Forests, Medford District, and USDA Pacific Northwest Res. Sta. Rogue Inst., Ashland, Oreg.

Appendix A. – ANSI O5.I Quality and Size Limitations

The ANSI 05.1 standard provides guidelines for setting minimum acceptable quality for round timbers used as utility poles. The smallest pole permitted by the ANSI standard must meet the following criteria. (Note: 1 inch = 25.4 mm; 1 ft. = 0.3048 in.)

Length:	19 ft. 6 in. from butt to minimum allowable tip circumference
Minimum tip circumference:	12 in.
Minimum circumference measured 6 ft. from butt:	15 in.
Growth rate:	6 rings/in. in outer 2 in. of radius
Straightness	
Single sweep:	Deviation 1 in. for every 10 ft. of length of line joining two points on surface
Double sweep:	Line joining midpoints at top and groundline should not pass outside body of pole
Short crook:	Prohibited: deviation from straightness that, within any 5 ft. is greater than mean diameter of crooked section
Spiral grain:	No more than 360 in 10 ft. for poles less than 30 ft. long and no more than 360 in 16 ft. for poles 35 to 45 ft. long
Single knots:	2-in. diameter on lower half of pole and 4-in. diameter on upper half
Sum of knots:	Maximum of l/3 the circumference or 8 in. within 12 in. of pole length
Shake:	Must be further than 2 in. from surface and more than 2 ft. from butt
Defects	
Compression wood:	None in outer in. of radius
Bark inclusions:	2 in. deep