Evaluation of small-diameter ponderosa pine logs in bending

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Abstract

Ninety-nine roundwood bending specimens were tested over the course of seven months beginning in early 2002 at the College of Engineering and Technology at Northern Arizona University in Flagstaff, Arizona. These specimens were taken from 5.0- to 12.7-inch diameter at breast height ponderosa pine trees cut during the summer of 2001 from Unit 16 of the Fort Valley Ecosystem Restoration Project located in wildland-urban interface of the Coconino National Forest. The specimens were sorted into two groups as a function of processing: hand-debarked logs known as tapered specimens and machine peeled logs known as uniform specimens. Each group of tapered and uniform logs contained both butt and tip specimens. This work provides evidence of relationships between juvenile wood and roundwood strength and stiffness. Failure mode in bending was also affected by juvenile wood. This work also shows that processing a tapered log down to a uniform log of constant diameter reduces bending strength and stiffness while increasing the percent juvenile wood in the cross section. Regardless of processing, butt logs in bending were stronger and stiffer than tip logs.

Ponderosa pine (*Pinus ponderosa*) forests of the Flagstaff, Arizona wildland urban interface (WUI) are so overstocked with small-diameter trees that resiliency has been compromised. These forests are at increased risk from attack by insects, disease, and uncontrollable wild fires (Covington 1996,1999). WUI wild fires, such as the 14,760-acre summer of 2000 Pumpkin Fire and the 16,400-acre summer of 1996 Hochderffer Fire, were fueled by heavy forest-floor debris loads and spread into the overstory canopy by the dense thickets of small-diameter trees. If left unattended, these conditions will continue to lead to more and more catastrophic, stand-replacing, soil-sterilizing fires (Pyne 1996) that threaten the community of Flagstaff.

Attention, however, requires intervention to enhance forest health thereby increasing forests' resiliency (USDA 1996, 1997). This intervention often includes alteration or restoration of the forest systems through a combination of mechanical thinning and prescribed burning activities. These intervention activities are notably incremental, costly, and generate large quantities of wood that must be removed prior to burning. A local WUI case study shows that the cost to administer and implement a restoration project was $2,036/acre, and the volume of merchantable small-diameter material removed was 1.8 truckloads/acre (Larson and Mirth 2004). These are costs that must be offset by the value of the material removed via markets or a rationalization of the increased value of well-managed forests.

The creation of suitable markets to use the removed small-diameter wood and offset treatment costs is a difficult task. Currently, the northern Arizonan market for small-diameter material is limited to products such as firewood at $26/green ton (Larson and Mirth 1999) and pallet stock at $36.5/green ton (Larson et al. 2001). These low-value products, however, barely pay for the cost to harvest and transport. They are not viable as a revenue source for funding forest treatment activities. But, when small-diameter material is used in struc-

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tural roundwood applications, its value and potential for funding forest intervention activities is significantly enhanced. Small-diameter logs in conventional post and pole applications are valued at $220/green ton (Wolfe and Moseley 2000). The market for using small-diameter material as structural roundwood, however, is an immature one that has languished for four reasons:

1. There are only a few suitable structural system designs that effectively use this material.
2. Coupled with item 1, is the lack of simple, cost-effective connectors for tying the roundwood members together.
3. These engineered systems will require precision manufacturing and tight product quality control; processes mostly unheard of in traditional roundwood markets.
4. Very little is known about the engineering properties, such as specific gravity (SG), juvenile wood, strength, and stiffness of small-diameter roundwood.

Expanding markets for the structural use of small logs will require work and innovations in all four areas. This paper, however, is limited to item 4. Specifically, this paper reports on the results of testing small-diameter ponderosa pine logs in bending and includes observations made about SG and juvenile wood.

Materials and methodology

Log selection

Test logs came from the northwest sector of an 85-acre-treatment unit, Unit 16, which was thinned in the summer of 2001. This unit is part of a 1,700-acre Greater Flagstaff Forests Partnership's Fort Valley Ecosystem Restoration Project - Phase I. It is located about five miles northwest of Flagstaff, Arizona within the Coconino National Forest.

The existing stand and leave tree mark on Unit 16 were inventoried during the summer of 2000 using a systematic strip sampling technique with a 0.89 confidence interval and a 26 percent margin of error over the Unit. The existing tree count averaged 426 trees/acre. Average tree size was 7.0 inches diameter at breast height (DBH).

In May of 2001, 80 of the soon to be harvested trees were selected for this study. The selection included 10 trees from each of eight DBH size classes ranging from 5 to 12 inches DBH. The selected trees were judged to be straight, vertical, and tall enough to produce the requisite test specimens.

The trees were hand felled on June 7, 2001, and delimbed and bucked into, whenever possible, two log sections - a butt log and a tip log with a small-end diameter inside bark (DIB) of 3 inches. Log taper measurements were recorded for each log. The mean outside and inside bark diameter-taper results for the 80 butt logs were 0.176 in./ft. and 0.130 in./ft. Similar measurements for the 74 tip logs averaged 0.178 in./ft. and 0.149 in./ft. The tip log sample demonstrated greater variability in taper measurements than the butt logs. Standard deviation (SD) for the tip and butt logs, outside bark, were 0.060 in./ft. and 0.046 in./ft., respectively. SD for inside bark were of similar magnitude.

Specimen processing

The logs were randomly sorted into two sets for further processing. Logs from trees 1 through 40 were debarked by hand with a drawknife. This debarking removed all of the outer bark along with some inner bark. Debarked logs are referred to as tapered specimens, reflecting that the specimen retains its natural white wood taper along its length. Half of the tapered beam specimens were kerfed, i.e., a radial saw cut was made parallel to the length of the log for the purpose of minimizing surface checking by relieving tension due to tangential shrinkage (Helsing and Graham 1976). This kerf was approximately 112 inch deep for the 4- and 5-inch-diameter logs and 314 inch deep for the larger logs.

Logs from trees 41 through 80 were machine processed at Indigenous Community Enterprises (ICE) to a constant diameter. These machine processed logs are referred to as uniform, indicating their uniform diametrical dimension along the length. The finished diameter size categories for the uniform logs were 4, 5, 6, 7, or 8 inches. The amount of wood that was removed due to processing was monitored. The butt and tip logs realized average diameter reductions of 17.5 percent and 2 1.2 percent, respectively.

The tapered and uniform logs were set aside, under a three-sided canopy area, for air-drying to a target moisture content (MC) of 12 percent. Eventually these logs were cut into bending specimens with a pre-test length of 16 diameters plus bearing length and trim.

Green bending modulus of elasticity

Shortly after the tapered logs had been hand debarked and prior to air-drying, 31 logs were nondestructively evaluated in bending to determine green modulus of elasticity (MOE). The logs were simply supported with a span that provided a span to depth ratio, L/d, exceeding 28. Deflection at centerline, δ, was measured three times under point loads, *P*, of 32, 113, and 179.5 pounds and a corresponding MOE in psi was calculated for each load according to Equation [**1**]. *I* is the log moment of inertia at center-span assuming a circular cross section. The green MOE per log was then established as the average of the three MOE values.

$$MOE = \frac{PL^3}{48\delta I} \text{ psi} \qquad [\mathbf{1}]$$

Dry bending tests

Log bending tests of the small tapered logs started approximately six months after hand debarking. Testing continued intermittently over a period of seven months ending with the testing of the largest uniform logs.

The bending tests were conducted using a mobile beam test machine designed and built at Northern Arizona University. This machine utilized a center-span hydraulic load head with a long stroke that permitted the testing of logs ranging in diameter, *d*, from 4 to 9.5 inches with corresponding spans, *L*, equal to *d* times 16 up to a maximum span of 152 inches. Because there are no established standard tests for simple beams of a tapered round section, test procedure utilized by Wolfe and Mosely (2000) were followed. Their procedure was a hybrid of ASTM D 198 bending test for lumber and ASTM D 1036 static test of wood poles (ASTM 1999a, 1999b).

Prior to destructive testing, specimen diameters at bearing points and center span were measured and recorded. Overhang dimensions - the length of log extending past each bearing point - was recorded. Kerfed tapered specimens were positioned into the machine such that the kerf ran along the top (relative to load head) edge of the specimen directly beneath the load head. The variable displacement deflection device set-up included the positioning of a small pin into the wood at centerline to be used as a fixed point from which to measure beam deflection. Vertical displacement was measured with an accuracy of 0.01 inch. The load was applied by hand at a rate of approximately 0.25-in./minute, while load and deflection data was automatically recorded in 3-second sampling intervals. Each failure was located and described in some detail, noting stress risers. Particular attention was given to describing the failure surface, which ranged from splintery to brash. Many believe that the splintery mode is the "preferred" mode, because it suggests ductile behavior. Brash failure is suggestive of brittle behavior and is therefore less desirable.

Shortly after the testing of each log, a full disk was cut from near the failure zone for use in measuring specimen SG, MC at time of testing, and cross-sectional radius to the first 20 rings from the pith as an indicator ofjuvenile wood. Specimen SG was determined using Method B – the volume by water immersion method, mode IV – of ASTM D 2395 (ASTM 1999c).

Very little is known about the extent and nature of juvenile versus mature wood in the small-diameter ponderosa pine resource of Northern Arizona. Voorhies and Groman (1982) examined the relationship between longitudinal shrinkage and rings from the pith for ponderosa pine logs in the 6- to 11-inch scaling diameter classes taken from northern Arizona. This study suggested that at about 20 rings from the pith, the percent longitudinal shrinkage settles down to and remains at, more or less, 0.2 percent; a shrinkage value normally expected for mature ponderosa pine. In an earlier study, however, Voorhies and Jameson (1969) concluded that the age of maturation for ponderosa pine based upon both fiber length and fibril angle is about 50 years. Based upon the above evidences, the 20-ring count from the pith radius measurement was chosen as an indicator ofjuvenile wood per specimen. This measurement was then contrasted to overall specimen radius to estimate the percentage of the specimen's cross section as possibly juvenile wood (%JW).

Bending stress at ultimate load is referred to as modulus of rupture (MOR). It is calculated according to Equation [**2**]. MOR is a function of: the critical bending moment, M_{cr}, calculated at the location of failure and accounting for span effects such as overhangs; the moment of inertia, l, also calculated at the failure location for an assumed circular cross-sectional area; and diameter, d.

$$MOR = \frac{M_{cr}(d/2)}{I}\ \text{psi} \qquad [2]$$

where:

$$I = \frac{\pi d^4}{64}\ \text{in.}^4$$

Load-deflection plots were developed for each test specimen to analyze the linear range of the specimen's behavior leading to the eventual calculation of MOE. Figure 1 is a typical plot taken from specimen 17 B, a tapered butt log specimen. MOE was calculated according to Equation [**3**], at the load-deflection point falling within the linear range. This was assumed to occur at 25 percent of the maximum-recorded centerline deflection. It was assumed, given the constant test span to depth ratio of 16, that deflection behavior was governed by bending moment and there was no need to include the effect of shear on deflection. This assumption is supported by ASTM D198 that specifies a minimum span to depth ratio of 12 for the evaluation of deflection due to bending (ASTM 1999a).

$$MOE = \frac{P_{25\%} L^3}{48 I y_{25\%}}\ \text{psi} \qquad [3]$$

Each specimen's MOR and MOE data was adjusted to a single MC of 12 percent according to ASTM D 2915 (ASTM 1999d).

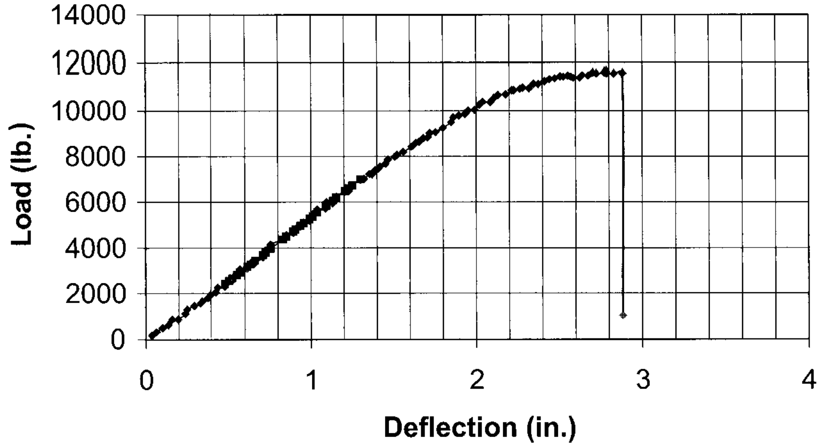

Figure 1. – Load-deflection plot for a tapered ponderosa pine log tested in single-point bending with a center-span diameter of 6.0 inches.

Bending test results

This section summarizes the most significant results of the bending test program, which included nondestructive green testing for MOE plus destructive testing of 99 dry tapered or uniform bending specimens.

Green and dry MOE

Thirty-one tapered bending specimens including both butt and tip logs were evaluated for green MOE during the early stages of the test program. The purpose was to examine the change in MOE from a green (MC greater than fiber saturation point) to a dry state (established from destructive testing and adjusted to 12% MC) and to compare green MOE group statistics to published values established from clear wood testing.

The green MOE mean of 1.12×10^6 psi and SD of 0.21×10^6 psi compare favorably to the ASTM D 2555 published clear wood values of a mean equal to 1.0×10^6 psi and a SD at 0.22×10^6 psi (ASTM 1999e).

Dry to green MOE ratios were calculated with a resulting sample mean ratio of 1.42, SD of 0.35, and the 95 percent confidence interval for the population mean ranging from 1.28 to 1.56. The D 2555 published clear wood dry-green ratio is 1.30 (ASTM 1999e). Since this test sample yielded a population prediction that captured the published parameter, it was concluded that the tested ratio was not statistically different than the published results.

Kerfing impacts

As previously noted, approximately one-half of the tapered bending specimens were kerfed for the purpose of minimizing checking. Observations made during the drying process, however, suggested that kerfing provided little added drying benefit. All logs, regardless of processing or kerfing, dried well exhibiting minor surface checking and little to no crook or twisting.

In the analyses following this one, all tapered specimens were grouped together for comparison against other treatments. This can only be done if the impact of kerfing is deemed insignificant. A two-tailed t-test on the 25 kerfed and 26 non-kerfed tapered bending specimens was completed to test for this significance. This t-test suggested that the group means were not significantly different and kerfing did not effect bending strength.

Tapered and uniform specimens

Once the question of kerfing was answered, it was possible to complete a variety of analyses making use of a tapered data set that included both the kerfed and non-kerfed results. **Table 1** contains tapered and uniform test results pooled to include tip and butt logs. This pooling was done to enable conclusions to be drawn about log processing, to compare these test results to published data, and to provide guidance on possible base design values.

Pooled one-tailed t-tests of the MOR and MOE results showed that the tapered and uniform group means are statistically different at the 99.97 percent and 89.45 percent confidence levels, respectively. This result confirms the suspicion that machining to a uniform diameter by removing the outer, mature wood fiber has the detrimental effect of reducing specimen strength and stiffness. Processing decreased mean MOR and MOE by 20.3 percent and 10.0 percent, respectively. The cross-sectional area made up of juvenile wood increased by 24.4 percent.

Table 1 includes a 95 percent confidence interval prediction of the population mean values that can be used to compare against mean values calculated from tests on small clear specimens (ASTM 1999e). The ASTM clear wood estimate for MOR for unseasoned ponderosa pine is 5,130 psi. This value is further adjusted by 1.84 to upgrade to the dry situation (ASTM 1999e), 0.90 to reduce the small clear values to full-size log values, the square to round form factor of 1.18, and 0.75 to account for the effect of knots on clear value strength (ASTM 1999f); yielding an ASTM ponderosa pine bending strength estimate of 7,518 psi. This value compares favorably with the tapered test results that suggest a population mean falling between 7,408 and 8,812 psi.

Table 1. – Tapered and uniform bending group statistics.

	Tapered	Uniform
Number of specimens	51	48
Diameter at centerline (in.)		
Mean	5.3	5.6
Standard deviation	1.2	1.5
Moisture content (%)		
Mean	9.4	11.6
Standard deviation	1.5	2.5
Specific gravity		
Mean	0.41	0.41
Standard deviation	0.05	0.04
% of cross section juvenile		
Mean	42.1	52.4
Standard deviation	19.0	26.0
Adjusted[a] MOR (psi)		
Mean	8,110	6,457
Confidence interval at 95%	7,408 to 8,812	5,862 to 7,052
Standard deviation	2,494	2,049
Adjusted[b] MOE ($\times 10^6$ psi)		
Mean	1.55	1.44
Confidence interval at 95%	1.41 to 1.69	1.32 to 1.56
Standard deviation	0.46	0.39

[a] MOR results are adjusted to a MC of 12 percent.
[b] Established from destructive testing for a specimen set of $n = 45$ for the tapered specimens and $n = 46$ for the uniform specimens. In addition, each dry MOE value was adjusted to a MC of 12 percent.

The ASTM clear wood estimate for bending MOE for unseasoned ponderosa pine is 0.997×10^6 psi. An additional factor of 1.30 is applied to convert this green value to a dry value (ASTM 1999e); yielding an ASTM bending MOE estimate of 1.296×10^6 psi. The ASTM estimate is lower than that predicted by this testing program. As shown in **Table 1,** the tapered logs demonstrated a mean MOE of 1.55×10^6 psi with a 95 percent confidence interval ranging from 1.41 to 1.69×10^6 psi. Similarly, the uniform logs demonstrated a mean MOE of 1.44×10^6 with a 95 percent confidence interval ranging from 1.32 to 1.56×10^6 psi.

The data from **Table 1** also provides an opportunity to calculate base design values for working stress design for the tapered and uniform ponderosa pine groupings that each include butt and tip logs. These values are presented in **Table 2.** The base design values in bending, F_b, were established at the lower 5 percent exclusion limit by multiplying the group SD by 1.645 and subtracting that from the sample mean. They are further adjusted to account for duration of loading by a factor of 1.620 and an additional factor of safety of 1.300. The MOE values are derived directly from the ASTM estimate, as it is a more conservative value than these test results. The uniform logs, however, reflect an additional reduction of 10 percent, as is suggested by the earlier evidence of reduced stiffness as a function of processing.

Table 2. – Base design values[a] for seasoned small-diameter ponderosa pine logs.

Ponderosa pine logs	Design stress, F_b	Design MOE
	(psi)	($\times 10^6$ psi)
Tapered	1,900	1.3
Uniform	1,450	1.2

[a] F_b and modulus of elasticity calculated at a MC of 12 percent.

Structural wood members generally demonstrate good correlations between SG and its various properties such as MOR and MOE. When the data from all 99 bending specimens are examined for

MOR to SG relationships, a weak linear correlation is found with a coefficient of multiple determination, r^2, of 0.366. If, however, only the 5 1 tapered log results are examined, a stronger and more typical relationship is realized between MOR and SG as shown in **Figure 2.** The process of manufacturing a tapered log into a log of constant diameter not only results in strength and stiffness reductions, but it appears to disrupt the normally expected relationship between SG and strength.

Very little is known quantitatively about the impacts of juvenile wood on the structural properties of wood. It is believed that specimen strength will decrease with increases in cross sectional juvenile wood. To examine the strength to juvenile wood hypothesis, a linear regression analysis was completed for MOR versus %JW for 99 bending specimens. A weak correlation of generally decreasing MOR with increasing %JW was identified by Equation [**4**]. Separate group analyses of MOR versus %JW for the tapered and uniform groups provides no improvement in correlation over the aggregated results.

$$MOR = -5{,}280(\%JW) + 9{,}800, \quad r^2 = 0.253 \qquad [4]$$

The possible relationship between strength and stiffness is also of interest. A strong correlation permits the future estimate of strength via the nondestructive measurement of stiffness. A linear regression analysis was completed for MOR versus MOE for 99 bending specimens. As seen in Equation [**5**], the MOR to MOE correlation is weak. This is in contrast to the small-diameter log testing work of Wolfe and Moseley (2000), which shows a stronger MOR to MOE correlation where r^2 is equal to 0.53.

$$MOR = 0.0027(MOE) + 3{,}375, \quad r^2 = 0.218 \qquad [5]$$

The entire beam data set was examined for significance of failure mode. Of this set of 99 specimens, 60 failed in a splintery fashion, while the remaining 39 realized a brash failure. Only 15 of the 99 failures were observed to be triggered by single knots or clusters of knots occurring around the circumference of the log. Butt logs accounted for 14 of the 15 knot related failures. A pooled one-tail t-test of the mean MOR results showed that the splintery group was statistically, at the 99.94 percent confidence interval, 20 percent stronger than the brash group. The MOE results suffered from too large a variability in sample statistics versus the number of specimens per sample to make a valid comparison of mean values. The other parameter, however, that is statistically different, at a confidence interval of 93.6 percent, between the two failure mode groups, is %JW. This suggests that failure mode (splintery versus brash) depends to some degree on juvenile wood with the possible occurrence of a brash failure mode increasing with %JW.

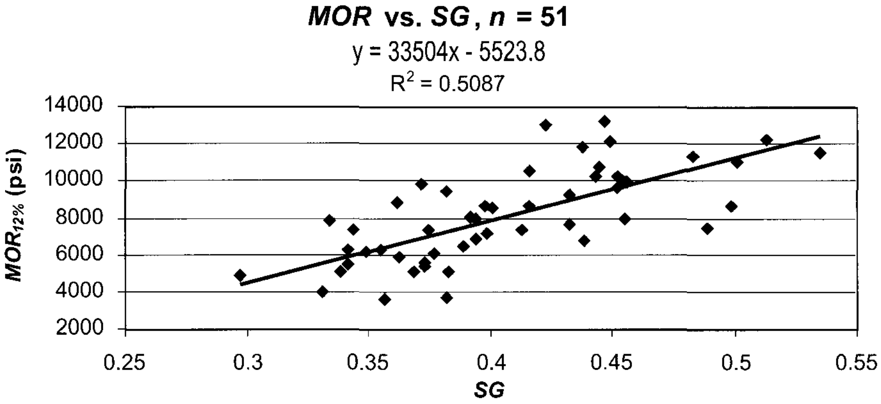

Figure 2. – MOR to SG correlation for small-diameter, tapered, dry, ponderosa pine logs.

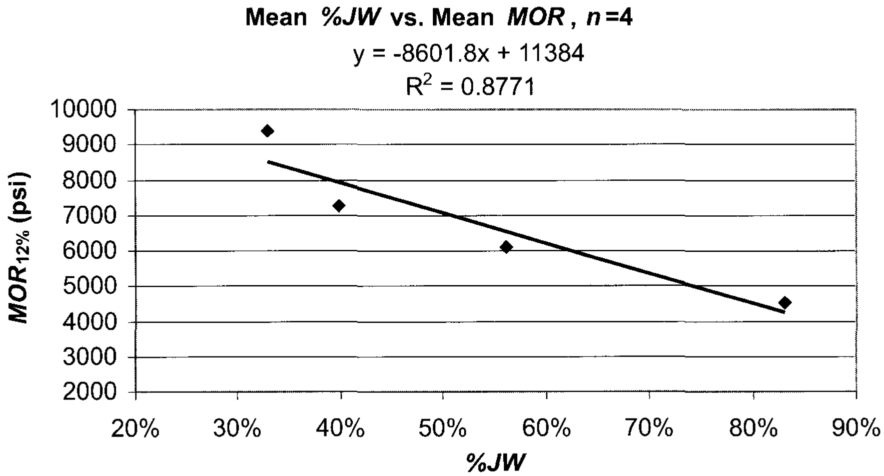

Figure 3. – Mean MOR and mean %JW for sub-groups of tapered butt, tapered tip, uniform butt, and uniform tip small-diameter ponderosa pine logs.

Butt and tip logs

The bending data was segregated into four sub-groups of tapered butt logs, tapered tip logs, uniform butt logs, and uniform tip logs to examine test results as a function of stem location. Results are presented in **Table 3.** T-testing found significant differences, at confidence intervals equal to or greater than 95 percent, between sub-group mean MOR, SG, and %JW values. The tapered specimens realize reductions in mean MOR and mean SG of, respectively, 35.1 percent and 18.2 percent between the butt and tip bending specimens. %JW increases by 70.3 percent. The uniform specimens realize similar reductions in mean MOR and mean SG of, respectively, 37.3 percent and 11.6 percent between the butt and tip bending specimens, while %JW increases by 108.8 percent. A valid statistical analysis of MOE differences could not be completed. For all samples, the MOE results suffered from the situation of large sample variability coupled with small differences in means and small sample sizes.

The change in mean %JW between butt to tip for each grouping is so significant that is was of interest to relate this mean MOR changes. **Figure 3** is a plot of these four sub-group mean results. It also presents the results of an exponential re-

Table 3. – Bending group statistics for tapered butt, tapered tip, uniform butt, and uniform tip logs.

	Tapered		Uniform	
	Butt	Tip	Butt	Tip
Number of specimens	31	20	34	14
Diameter at centerline (in.)				
Mean	5.7	4.7	6.2	4.2
Standard deviation	1.3	0.8	1.4	0.5
Moisture content (%)				
Mean	9.6	9.2	12.1	10.3
Standard deviation	1.6	1.2	2.4	2.3
Specific gravity				
Mean	0.44	0.36	0.43	0.38
Standard deviation	0.04	0.02	0.03	0.04
% of cross section juvenile				
Mean	33.0	56.2	39.8	83.1
Standard deviation	12.6	18.8	13.4	23.4
Adjusted[a] MOR (psi)				
Mean	9,405	6,101	7,245	4,541
Confidence interval at 95%	8,672 to 10,137	5,283 to 6,919	6,625 to 7,864	3,816 to 5,226
Standard deviation	1,999	1,753	1,776	1,264
Adjusted[b] MOE ($\times$ 10^6 psi)				
Mean	1.64	1.41	1.46	1.39
Confidence interval at 95%	1.48 to 1.80	1.14 to 1.68	1.33 to 1.59	1.10 to 1.68
Standard deviation	0.40	0.53	0.36	0.48

[a] MOR results are adjusted to a MC of 12 percent.

[b] Established from destructive testing for a specimen set of n = 28 tapered butt specimens, n = 17 tapered tip specimens, n = 33 uniform butt specimens, and n = 13 uniform tip specimens. In addition, each dry MOE value was adjusted to a MC of 12 percent.

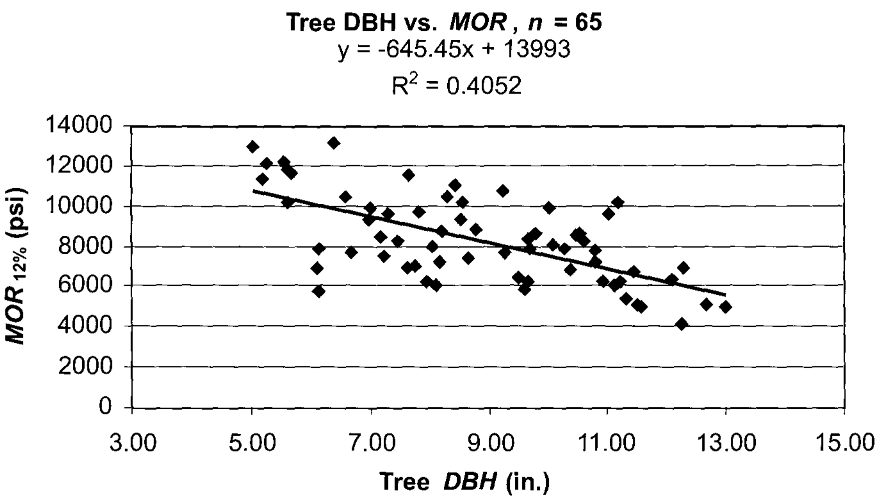

Figure 4. – MOR to tree DBH correlation for small-diameter ponderosa pine butt logs.

gression analysis. **Figure 3** suggests a strong relationship between MOR and %JW for the sub-group means.

Other property correlations were explored within the sub-groupings. In most cases, these correlations were best represented, as indicated by better r^2 values, with the full specimen grouping of n = 99 as reported on earlier. There was, however, one strongly apparent relationship regarding size effect that was unique to the butt logs. Butt log bending specimen strength decreased as the size of its originating tree increased. This is shown in **Figure 4** for the all butt logs, regardless of processing. The addition of tip logs weakens the MOR to DBH relationship. Perhaps this is an indication that size effect becomes less dominating or even overwhelmed when %JW increases, as is the case for the tip logs.

Conclusions

Ninety-nine roundwood bending specimens were tested in the dry condition over the course of seven months beginning in early 2002 at the College of Engineering and Technology at Northern Arizona University in Flagstaff, Arizona. These specimens were taken from 5.0 to 12.7 inches DBH ponderosa pine trees cut from Unit 16 of the Fort Valley Ecosystem Restoration Project located in wildland-urban interface of the Coconino National Forest. The specimens were sorted into two groups as a function of processing: hand-debarked logs known as tapered specimens and machine peeled logs known as uniform specimens. Each group of tapered and uniform logs contained both butt and tip specimens. The following is a summary of the key results from this testing program.

Processing logs to a uniform diameter removes the outer mature wood and leads to a decrease in mean MOR and mean MOE of 20 percent and 10 percent, respectively, in comparison to the tapered specimen results. Measurements of the raw butt and tip logs prior to and after machine processing showed average diameter reductions of 17.5 percent and 2 1.2 percent.

As the amount of juvenile wood within the cross section increases, MOR, MOE, and SG decreases. In addition, failure mode changes from a splintery mode associated with ductile behavior to a brash one associated with brittle behavior.

Tapered tip logs realize a reduction in mean MOR and SG of 35 percent and 18 percent, respectively, in comparison to tapered butt logs. %JW, as indicated by the cross-sectional radius measured from the pith to the first 20 rings, increases for tip logs versus butt by 70 percent. Uniform tip logs realize a reduction in mean MOR and SG of 37 percent and 12 percent, respectively, in comparison to uniform butt logs. %JW increases from butt to tip logs by 109 percent.

Butt logs, regardless of processing, demonstrate a size effect where MOR decreases as the originating tree DBH increases and the corresponding specimen center-span diameter gets bigger. Tip logs, which contain a larger amount of juvenile wood than butt logs, do not exhibit a size effect. It is believed that the juvenile wood in these tip logs dominates bending behavior; overwhelming other strength reducing characteristics such as knots that contribute to the size effect phenomenon.

The MOR test results of the congregated tapered bending specimens compared well to the ASTM mean estimates for dry ponderosa pine of 7,518 psi. The corresponding test mean, adjusted to 12 percent MC, was 8,110 psi. The mean bending MOE, however, exceeded the ASTM estimate for the tapered logs. The dry-green MOE ratio was 1.42 with a 95 percent confidence interval ranging from 1.28 to 1.56. The ASTM dry-green ratio for ponderosa pine is 1.30.

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