

Grading and properties of small-diameter Douglas-fir and ponderosa pine tapered logs

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Abstract

Approximately 375 Douglas-fir and ponderosa pine logs, 3 to 6 inches in diameter, were tested in third-point bending and in compression parallel to the grain. The moisture content at time of test was about 14 percent. Good correlations were found between the modulus of elasticity (MOE) in static bending and those obtained by transverse vibration. Good correlations were also found between modulus of rupture (MOR) and MOE. A species independent relationship was established between ultimate compression stress parallel to the grain and MOR. A mechanical grading system previously developed for 9-inch diameter logs was shown applicable to small-diameter logs.

There is currently heightened interest in the use of round timbers for structural applications. This interest arises from two perspectives: 1) a desire for more precise grading procedures for the relatively large round timbers used as structural members in large timber structures such as lodges, churches, and high-end log homes, and 2) a desire to use smaller diameter round members as structural elements in community centers, schools, and timber bridges. These latter types of structures, generally constructed of logs 4 to 7 inches in small-end diameter, have been termed "round-wood engineered structures."¹ Increased construction of round-wood engineered structures could provide additional value-added uses for material mechanically thinned from at-risk forests in the western United States (LeVan-Green and Livingston 2001). Compared to sawing lumber from small-diameter logs, using the logs as structural elements has several perceived advantages:

- Logs are less susceptible to warp during drying,
- Processing costs are lower,

- Geometric considerations indicate that the load carrying capacity of a round member is two to four times that of the largest rectangular member that could be cut from it, and
- Structurally graded round members may have higher economic value than the lumber that could be cut from them.

The primary objective of this paper is to evaluate the application of a proposed mechanical grading system for 9-inch diameter logs to smaller logs that are 3 to 7 inches in diameter. A secondary objective is to compare test results for small diameter logs to properties assigned by visual grading. The information presented in this paper is limited to two species (suppressed growth Douglas-fir (*Pseudotsuga menziesii*) and

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Table 1. - Limits on knot size and slope of grain and allowable properties for visually graded Douglas-fir and ponderosa pine sawn round timbers.^a

Grade ^b	Maximum knot size	Maximum slope of main	Allowable properties ^c					
			Douglas-fir			Ponderosa pine		
			Fb	E	Fc ^d	Fb	E	Fc ^d
Unsawn, Dense	1/2 diameter	1:15	2400	1.6	1300	--	--	--
Unsawn	1/2 diameter	1:15	2050	1.5	1150	1400	1.1	800
No. 1, Dense	1/3 diameter	1:14	1950	1.6	1050	--	--	--
No. 1	1/3 diameter	1:14	1700	1.5	950	1150	1.1	650
No. 2, Dense	1/2 diameter	1:10	1650	1.6	900	--	--	--
No. 2	1/2 diameter	1:10	1400	1.5	800	975	1.1	550
No. 3, Dense	3/4 diameter	1:6	1100	1.3	575	--	--	--
No. 3	3/4 diameter	15	925	1.2	525	625	0.8	350

^aTP 1995, 2006. Rules apply to all dimensions.

^bOther limits on grade characteristics are given in TP 1995.

^cF_b = 5th percentile MOR/2.1, lb/in²; E = mean MOE, in millions of lb/in².

^dF_c = 5th percentile UCS/1.9, lb/in². Allowable properties for compression parallel to the grain are increased by 10 percent for compression parallel to the grain (TP 2006). Care must be taken to assure that the timber is sufficiently seasoned (dry) before full load is applied

“plantation” grown ponderosa pine (*Pinus ponderosa*)) that were debarked (and therefore were tapered), and then tested at about 14 percent moisture content. A future paper will look at the impact of machining to a constant diameter on the grading and properties of these logs.

Background

Visual grading of round timbers

ASTM Standard D3957 (ASTM 2006) provides procedures for establishing stress grades for structural members used in log homes (Burke 2004). The standard addresses grading and property assignment for two types of structural members used in log buildings: wall logs and round timber beams. Only the standard applied to round timber beams are evaluated in this study.

Properties of two types of round timber beams are addressed in D3957: unsawn and sawn round timbers. The only grade assigned to unsawn round timbers is named “Unsawn,” and it is primarily intended for bending or truss members. Sawn round timbers have a flattened surface that is sawn or shaved along one side and they are also primarily intended for use as bending members. The sawn surface is limited to a penetration of no more than 0.30 of the radius of the round log. This limits the reduction in the cross section to less than 10 percent. Timber Products (TP 1995) has developed structural grading rules for three grades of sawn round timbers: No. 1, No. 2, and No. 3.² Logs of all grades may also be used as compression members. Logs used in this application do not usually have a flattened surface. As with the visual grades of dimension lumber or structural timbers, the grade description of structural logs is a combination of limits on characteristics that affect strength and characteristics that might affect serviceability for the intended application, but not necessarily strength. **Table 1** summarizes the limits on knot size and slope of grain for four TP grades. In addition, there are limits on potential decay associated with knots, shake, splits, and compression wood. Examples of serviceability factors include limits on lack of “roundness” and excessive warp or wane.

² Although not used in this study, visual grades also have been developed by the Log Homes Council, with properties derived by ASTM D3957 procedures.

Allowable properties for sawn round timbers are derived from clear wood data, modified by strength ratios set forth in ASTM D3957 and D2899 (ASTM 2006). This clear wood approach is therefore very similar to the ASTM D245/D2555 (ASTM 2006) procedures once used to derive allowable properties for all dimension lumber in the United States and still used for structural timbers. Allowable properties in bending (F_b), modulus of elasticity (MOE) and compression parallel to grain (F_c) for Douglas-fir and ponderosa pine logs are given in **Table 1**. Allowable properties are also established for tensile strength parallel to grain (F_t), strength in compression perpendicular to grain (F_{cp}) and shear strength parallel to the grain (F_v).

Mechanical grading of 9-inch diameter logs

In a previous study, the technical basis was established for mechanical grading 9-inch diameter logs (Green et al. 2006). The material for this study was 236 logs of the Englemann spruce (*Picea Engelmannii*)-alpine fir (*Abies lasiocarpa*)-lodgepole pine (*Pinus contorta*) species grouping (ES-AF-LP). The logs were cut from fire-killed trees and were at a moisture content of about 15 to 17 percent at time of test. Bending tests were conducted on 169 logs and short column compression tests on 67 logs. The relationships between properties are the basis for the mechanical grading of structural lumber. For machine stress rated lumber bending strength is estimated from modulus of elasticity. The coefficient of determination (r^2) between MOE determined by transverse vibration (E_v) and determined by static test in third-point bending (MOE) was 0.83 for these 9-inch diameter logs. The r^2 value for the correlation between modulus of rupture (MOR) and E, was 0.53, and that between MOR and MOE was 0.68. These correlations are similar to the results expected for softwood dimension lumber (Green and McDonald 1993) and thus confirmed the potential for mechanical grading these logs for structural applications. The 90 percent lower confidence limit on the MOE-MOR relationship excludes 5 percent of the data on the lower side of the regression, and provides the regression equivalent to the 5th percentile traditionally used to assign properties to visually graded lumber.

Stepwise regression indicated that if MOE is measured, then addition of characteristics such as knot size and slope of grain provide only a marginal increase in the ability to predict MOR. In the initial phase of the study (Green et al. 2004) the r^2 value between MOR and MOE increased from 0.61 to 0.67 with the addition of knot size (RMSE increased from 647 psi to 696 psi). These results agree with results reported by Ranta-Maunus (1999) for small-diameter logs from European species. It was recommended that MOE be the primary sorting criteria for the proposed grading system but that the maximum allowable knot size and slope of grain be limited to those allowed in No. 3 visual grade; knot size $\leq$ 3/4 of the diameter and slopes $\leq$ 1 in 6. Factors that might effect serviceability such as degree of roundness and warp were also set at the limits given for the No. 3 visual grade.

Computer simulation indicated that the proposed mechanical grading system could give higher yields for an equivalent set of properties than was available through visual grading (Green et al. 2006). For example, a No. 1 visual grade of ES-AF-LP is assigned an MOE of 1.1 million psi and an allowable bending strength of 1,100 psi. The yield of No. 1 logs in the study was 54.4 percent. The predicted yield of a mechanical grade having an MOE of 1.1 million psi was 97 percent. The allowable bending strength of this grade was estimated to be 1,200 psi. With the potential advantages of mechanical grading demonstrated for larger logs, it was decided to develop similar technical requirements for logs 3 to 6 inches in diameter.

Effect of diameter on properties of small-diameter logs

Ranta-Maunys (1999) summarizes the results of a major European study on the bending and compression parallel to the grain properties of 3- to 6-inch diameter logs of six softwood species. The logs are tested in bending using simple supports and 3rd-point loading. When all species are grouped, a correlation of -0.16 is found between MOR and log diameter ($r^2=0.03$) and a correlation of -0.02 between MOE and diameter. For individual species, no consistent trends were found between MOR and log diameter for larch (*Larix*, sp), Scot pine (*Pinus sylvestris*), Douglas-fir, and Norway and Sitka spruce (*Picea abies* and *Picea sitchensis*, respectively). They also conducted short-column compression tests using an unsupported free span of six times the log diameter. The correlation between compression strength and log diameter was only 0.02. Additional discussion of these results is given in Green et al. (2004).

Larson et al. (2004a, 2004b) conducted bending and compression tests on 5- to 12.7-inch diameter lodgepole pine logs. For the bending tests, about half the 100 available logs were machined to a constant diameter and the rest were just debarked and tested with their natural taper. The logs were tested as simply supported beams with a center point load. If only butt logs were considered, the relationship between MOR and tree diameter had an r^2 value of 0.41. They stated, however, that if the properties of the tip logs are added to the regression then the correlation is weakened and speculated that the apparent size effect may be weakened as the percentage of juvenile wood increases. They found only a weak correlation between compression strength and log diameter.

Materials and methods

Selection and processing

The logs used in this study came from the Hayfork Ranger District on the Shasta-Trinity National Forest, about 40 miles west of Redding, California. For each species, the original sampling design called for 60 trees each in 4- and 6-inch diameter breast height (DBH) and 40 trees in the 8-inch DBH class. The ponderosa pine logs were from tree thinnings from the "Jones Burn Plantation." These trees were planted by the Forest Service in 1960 at a spacing of about 10 feet. The target spacing after thinning was 15 to 18 feet between trees. The 218 ponderosa pine trees selected for this study ranged in size from 4 to 8 inches DBH, but some trees in the plantation have been measured at 18 inches DBH. The Douglas-fir was removed from a stand of predominately mixed conifers similar in composition to those reported in a previous study of lumber

properties (Green et al. 2005a). These suppressed trees were about 70 years old and were being removed to help clean up a blow down area. Approximately 160 Douglas-fir trees were selected, with diameters ranging from about 4 to 8 inches. Because taper was greater in the plantation grown ponderosa pine than in the suppressed Douglas-fir, additional ponderosa pine trees were selected in an effort to keep the total number of logs to be tested similar for the two species. For both species, crooked and defective trees were excluded.

To ensure that the logs were still in the green condition at the time of initial property measurement the trees were cut a few weeks prior to initiation of the study. The harvested tree-length logs were hauled to a sorting yard maintained by the Hayfork Watershed Research and Training Center and piled with the bark left on the logs until measurements were made. At the beginning of the study, the tree-length logs were cut into one to three mill-length logs of approximately 12.5 feet each. The mill-length logs were then numbered to allow identification of the species, the tree from which the log was cut, and the position of the log in the tree. The age of each tree-length log was determined by counting the rings on the butt end of the bottom log. Just prior to non-destructive testing the mill-length logs were debarked and measurements taken of log length, and large and small end log diameter. A modulus of elasticity for each log was obtained in transverse vibration (E_{tv}) using a prototype machine developed for this study (Murphy 2000).

The debarked logs were then stacked in the sort yard in Hayfork and allowed to air dry for about three months (Simpson and Wang 2003). While drying, the logs were sorted into three groups for each species. The sorting was done on the basis of ranked green E, value such that each group had approximately the same range and mean E_{tv} value. After air drying to approximately 15 percent MC, two groups of logs were shipped to the Forest Products Laboratory in Madison, Wisconsin, and one group to the University of Idaho in Moscow, Idaho. One of the two Madison groups was to be tested in bending and the other in compression parallel to the grain. The group sent to the University of Idaho was machined to a uniform diameter (dowelled) before testing in bending. The results for these dowelled logs are reported separately (Gorman et al., in preparation).

At the FPL the logs were stored in a humidity room maintained at 72 °F and 67 percent RH for about 6 months prior to testing. The logs were then graded as sawn round timbers by a qualified grader of Timber Products Inspection (TP 1995). At that time TP grading rules did not provide for grading Douglas-fir logs as Dense,³ so this determination was not recorded. Measurements were taken of small and large end log diameters, and information recorded on grading characteristics such as knots and slope-of-grain. Other characteristics, such as number of annual rings included in the log, cross-sectional area of the log, and percentage of the log cross-section within the first 20 annual rings were recorded for future analysis. Two nondestructive evaluation measurements were taken on each log while it was simply supported at the ends. The MOE was determined by placing a dead load in the middle of the

³ For Douglas-fir to qualify as Dense, a member must average on one end or the other not less than six annual rings per inch and one third or more of summerwood. Pieces that average less than four annual rings per inch may qualify as Dense if they average one half or more of summerwood.

span, E_{dead} . This was done by placing a 23-lb pre-load on the log and then measuring the incremental deformation 60 seconds after an additional 50-lb dead load was applied. Deflections at midspan were measured with a linear variable displacement transducer (LVDT) to the nearest 0.0001 inch. Then the E_{iv} measurement was taken using the prototype E-tester.

Testing

Static bending tests were conducted using a universal testing machine, with the logs tested in third-point bending according to ASTM D198 (ASTM 2006). Third-point loading was chosen to correspond with procedures used for lumber and timbers in ASTM D198, and to better agree with procedures being used in a large testing program on small-diameter logs recently completed in Europe (Ranta-Maunus 1999). The span to depth ratio varied with log diameter. To keep the span to depth ratio in a range from about 19:1 to 29:1 the logs with midspan diameters greater than 4.5 inches were tested on an eleven-foot span and the smaller logs tested over a seven-foot span. A rate of crosshead motion of 1.0 inch per minute was chosen to achieve an average time to failure of about 3 min. Load-deflection plots were obtained for each specimen for calculation of MOR and static MOE. After testing, a 1-inch-thick section of each specimen was removed from each end of the log and one from an area close to the location of failure to determine moisture content and specific gravity according to ASTM D2395 and D4442 (ASTM 2006). The disks from each log were scanned for later determination of other growth characteristics such as growth rate and the percentage of the cross-section that was juvenile wood (defined as the first 20 years of growth).

Tests in compression parallel to the grain followed procedures given in ASTM D 198 (ASTM 2006), with lateral supports provided at 12 inches from the ends of the log and at 24-inch spacing in the middle of the log. To facilitate handling, each full-length log was cut in half and each half tested. The average length of the logs at test was 98 inches. The logs were loaded at a rate of crosshead movement of approximately 0.1 inch inches per minute to limit times to failure to 5 to 12 min. Following testing, a 1-inch-thick cross-section was cut from near failure of each log for measuring oven-dry moisture content and specific gravity (ASTM D 4442 and D 2395) and for measuring growth characteristics.

Results and discussion

Data presented here for all properties were obtained from tests of dry logs. A separate paper focuses on the effects of moisture content on log properties (Green et al. 2007).

Visual grading

Bending. — **Table 2** shows the number of logs tested in this study by mean log diameter class, and the mean flexural properties for the Unawn grade. Class specification indicates the smallest log in the class, thus diameter class 3 logs are from 3.00 to 3.99 inches in diameter. For MOE there is no consistent change in property with change in log diameter for either species. For Douglas-fir, the MOR, the strength of the logs in

Table 2. — Variation of flexural properties of small-diameter logs by species and log diameter.

Diameter class ^a (inches)	Douglas-fir				Ponderosa pine			
	Sample size		Unawn ^b		Sample size		Unawn ^b	
	All grades	Unawn	MOE	MOR	All grades	Unawn	MOE	MOR
3	35	31	2.43	13.16	32	21	1.12	5.59
4	29	27	2.33	12.15	33	27	1.16	5.44
5	20	13	2.39	12.27	21	17	1.19	5.48
6	7	7	2.24	12.20	8	6	1.19	5.55
7	--	--	--	--	2	2	1.19	5.96

^aClass 3 has logs with midspan diameters from 3.00 to 3.99 inches, Class 4 from 4.00 to 4.99, etc.

^bModulus of rupture (MOR) is given in units of 10^3 psi and modulus of rupture (MOE) in units of 10^6 psi.

the 3-inch diameter class is about 8 percent greater than that of the logs in the larger diameter classes, but except for this difference there is little change in MOR with increasing diameter. For ponderosa pine the MOR drops about 3 percent for logs in the 4-inch diameter class compared to the 3-inch diameter logs but thereafter increases consistently as log diameter increases. However the differences in MOR with log diameter were not statistically significant at the 95 percent confidence level. Thus based on our results, and those of Ranta-Maunus (1999), previously discussed, we conclude that flexural properties do not vary significantly by log size for the range of log diameters tested in this study.

Table 3 summarizes the bending results by visual grade. The average moisture content of the logs is about 13.5 percent. The average specific gravity of the suppressed growth Douglas-fir is 0.49, which is about the same as that assigned to Douglas Fir-Larch in the National Design Specification (AF&PA 2005). The specific gravity of the ponderosa pine is 0.40, lower than the species average of 0.43. The sample sizes for most of the grades are too small to draw firm conclusions about property differences between grades. In general, the mean MOE and MOR values of the No. 2 and No. 3 grades are lower than those of the Unawn and No. 1 grades, suggesting at least some ability of the visual grading system to separate the logs into groups having distinct properties. Also, as might be expected, the coefficient of variation for both the MOR and MOE of the suppressed growth Douglas-fir tends to be smaller than that of the plantation grown ponderosa pine.

For the Unawn grade, the MOE measured for the Douglas-fir data in **Table 3**, after combining all diameter classes and rounded according to the procedures of ASTM D245, is 2.4 million psi. This is much higher than the assigned value of 1.5 million psi (**Table 1**). The allowable Fb value from the test data (rounded product of 5th percentile MOR / 2.1) is 4,250 psi, also much higher than the assigned value of 2,050 psi, and would be higher than that for the Unawn, Dense grade. For ponderosa pine, the comparisons would be a measured MOE of 1.2 million psi versus assigned value of 1.1 million. For Fb the measured value is 1,650 psi versus an assigned value of 1,440 psi. Thus all the values assigned by the D3957 procedure for the Unawn grade are below the test values measured in this study, especially those for suppressed growth Douglas-fir. For the other grades there is not enough data to estimate strength properties at the 5th percentile level. For MOE the best that can be said is that there is no indication that assigned values are non-conservative.

The first 20 years of growth were used as an indication of the juvenile wood core in both the Douglas-fir and ponderosa

Table 3. - Flexural properties of visually graded 3- to 7-inch Douglas-fir and ponderosa pine round timbers.

Species	Grade	Sample size	Moisture content (percent)	Specific gravity (OD/OD) ^a	Modulus of elasticity (10 ⁶ lb/in ²)		Modulus of rupture (10 ³ lb/in ²)		5th
					Mean	COV ^b	Mean	COV ^b	
Douglas-fir	Unsawn	78	13.6	0.49	2.372	14.2	12.578	15.8	8.877
	No. 1	5	13.2	0.49	2.438	6.9	13.387	15.8	--
	No. 2	6	13.6	0.48	2.135	12.1	12.009	14.6	--
	No. 3	2	13.4	0.40	1.760	--	9.646	--	--
Ponderosa pine	Unsawn	73	13.7	0.40	1.158	20.9	5.514	26.1	3.467
	No. 1	4	13.8	0.45	1.160	26.4	6.220	29.7	--
	No. 2	8	13.8	0.39	1.075	25.3	5.279	23.9	--
	No. 3	11	13.7	0.38	0.962	25.6	5.286	20.0	--

^aOD/OD is specific gravity based on oven-dry weight and oven-dry volume.

^bCOV is coefficient of variation (percent).

Table 4. - Variation in ultimate compression stress (UCS) by log diameter and species of small-diameter logs tested in compression parallel to the grain.

Diameter class ^a (inches)	Douglas-fir			Ponderosa pine		
	Sample size	Unsawn	UCS ^b	Sample size	Unsawn	UCS ^b
2	0	0	--	2	2	2.638
3	26	25	4.567	27	25	2.372
4	28	24	5.038	35	28	2.518
5	18	18	5.345	28	23	2.626
6	11	9	5.557	7	6	2.673
7	4	3	5.053	--	--	--

^aClass 3 has logs with midspan diameters from 3.00 to 3.99 inches, 4 from 4.00 to 4.99, etc.

^bUltimate compress stress (UCS) is in units of 10³ lb/in².

pine butt logs (Voorhies and Groman 1982, Shuler et al. 1989, Jozsa and Middleton 1994). For the suppressed growth Douglas-fir, the average percent of the cross-sectional area taken up by the first 20 rings was 34.5 percent, with 75 percent of the logs having less than 50 percent of the cross section composed of juvenile wood. This is in contrast to the ponderosa pine logs where the average juvenile wood content was 73.5 percent, and the 75th percentile log already contained 100 percent juvenile wood. The high juvenile wood content of the ponderosa pine and the low juvenile wood content of the Douglas-fir contribute to the large difference in properties of the logs for the two species.

The two species also exhibited different types of failure. The suppressed growth Douglas-fir logs failed with the expected “splintery” failure. After the maximum load had been reached these logs were still able to support some load. Virtually all the plantation grown ponderosa pine failed suddenly in a “brashy” manner and many totally separated at the failure location. Although the ponderosa pine exhibited properties in excess of the assigned allowable values, this type of failure might be of concern for some applications (e.g. structural systems where there is little load sharing between members). A more detailed investigation of the effect of juvenile wood on log properties will be discussed in a later paper (Gorman et al., in preparation).

Compression parallel to the grain. — **Table 4** summarizes the variation in UCS by log diameter class. Again, only the Unsawn grade has sufficient logs to observe trends between log properties and diameter. If we do not include the results for the 2-inch diameter class, which has only two logs, and the 7-inch class with only 3 logs, then distinct patterns are observed. Unlike MOR, UCS for both species increases as the diameter increases from the 3-inch class to the 6-inch class. For Douglas-fir the increase is about 22 percent and for ponderosa pine the increase is about 13 percent. Overall, however, the relationship is not significant at the 95 percent confidence level.

This lack of significance may be partly a function of the small sample sizes for some diameter classes. Larson et al. (2004b) found a weak correlation between UCS and log diameter for small diameter ponderosa pine logs. Ranta-Manus et al. (1998) concluded that log diameter did not correlate well with UCS. We conclude that our results indicate that there is a weak tendency for UCS to increase with increasing log diameter.

Table 5 summarizes compression properties by log grade. The MOE in compression parallel to the grain was not measured in this study. With the overwhelming majority of the logs falling in the Unsawn grade it is difficult to draw any conclusions about the ability of the visual grading system to sort logs by UCS. Comparisons can be made, however, with tested versus assigned allowable compression strengths for the Unsawn grade. Allowable compression strength parallel to the grain (F_c) can be calculated as the 5th percentile UCS value (**Table 5**) divided by 1.9 (ASTM D245). For Douglas-fir, the calculated F_c value for the Unsawn grade from the test data is 1,900 psi and the assigned value is 1,150 psi (**Table 1**). For ponderosa pine the experimental data would yield an allowable compression strength of 800 psi and the assigned value is also 800 psi. The experimental results for Douglas-fir are about 73 percent higher than the assigned value and the experimental results for ponderosa pine meet the assigned value.

Property relationships

Relationships between mechanical properties are used extensively in assigning mechanical properties to both mechanically graded lumber and to visually graded lumber. The technical basis for a mechanical grading system has historically been the relationship between bending strength and stiffness, and relationships between bending strength and strength in compression and tension parallel to the grain (ASTM D6570). For visually graded lumber, relationships between bending strength and tensile strength parallel to the grain, and between bending strength and compression strength parallel to the grain, are used to reduce sampling and testing costs (ASTM D1990).

Alternative estimates of MOE. — Previous research had shown that E, of 9-inch diameter ES-AF-LP logs machined to a uniform diameter had a good correlation ($r^2 = 0.95$) with the MOE derived by a simple center span dead load (Green et al.

Table 5. - Properties of visually graded 3- to 7-inch Douglas-fir and ponderosa pine round timbers in compression parallel to the grain.

Species	Grade	Sample size	Moisture content (percent)	Specific gravity (OD/OD) ^a	Ultimate compression stress (10 ³ lb/in ²)		
					Mean	COV ^b	5th
Douglas-fir	Unsawn	79	13.8	0.490	5.024	16.9	3.621
	No. 1	2	14.4	0.475	5.484	--	--
	No. 2	4	13.8	0.525	5.793	7.1	--
	No. 3	2	14.2	0.515	6.186	--	--
Ponderosa pine	Unsawn	84	14.0	0.384	2.536	18.1	1.704
	No. 1	3	14.0	0.377	2.324	12.3	--
	No. 2	8	14.1	0.389	2.432	12.0	--
	No. 3	4	14.0	0.372	2.368	22.2	--

^aOD/OD is specific gravity based on oven-dry weight and oven-dry volume.

^bCOV is coefficient of variation (percent).

Table 6. - Regression relationships for 3- to 6-inch diameter round timbers at about 14 percent moisture content.

Property = A + B × X						
Property	X	N	A	B	r ²	RMSE
Douglas-fir						
E _{iv}	E _{dead}	93	0.637	0.632	0.42	0.264
MOE	E _{iv}	93	0.770	0.722	0.54	0.229
	SpGr	93	−0.124	5.047	0.47	0.246
MOR	MOE	92	1.961	4.513	0.58	1.299
	E _{iv}	92	4.507	3.683	0.39	1.561
Ponderosa pine						
E _{tv}	E _{dead}	97	0.287	0.724	0.55	0.157
MOE	E _{iv}	97	0.135	0.877	0.66	0.146
	SpGr	97	0.289	2.123	0.10	0.238
MOR	MOE	97	0.853	4.125	0.55	0.942
	E _{iv}	97	1.159	3.838	0.41	1.077

r² = coefficient of determination, RMSE = root mean square error

E_{tv} = modulus of elasticity in transverse vibration

MOE = flexural modulus of elasticity by static test

MOR = modulus of rupture

SpGr = specific gravity based on oven-dry weight and volume

2004). For our small diameter, tapered logs, the r² value between E_{tv} and E_{dead} is 0.42 for Douglas-fir and 0.55 for ponderosa pine (Table 6). Thus the accuracy of the assumptions used in deriving the formula for the natural frequency of round members that was used to calculate E_{tv} (Murphy 2000) is confirmed by experimental evidence.

There is a good relationship between E_{tv} and MOE, with r² values of 0.54 and 0.66 for the individual species (Table 6). Plots of the two regression lines showed them to be basically parallel, but with slightly different intercepts. The correlations found in the current study are very similar to those reported by Wang et al. (2001) for 4- to 10-inch diameter green red pine logs and 5- to 11-inch diameter green jack pine logs. These results demonstrate that E_{tv} provides a good method for quickly estimating the MOE of logs at a mill.

MOE versus MOR. — The precision with which a mechanical grading system can sort lumber into strength classes (grades) is dependent upon the degree of correlation between bending strength and bending stiffness. For the two species

tested in this program the r² value between static MOE and MOR are quite similar at about 0.56 (Table 6). This is about the expected value for softwood dimension lumber (Green and McDonald 1993). The regressions equations are statistically different at the 95 percent confidence level, with the slopes being equal but the intercepts different at the 95 percent confidence level (Fig. 1). From the results shown in Figure 1, and some preliminary results on lodgepole pine (Green et al. 2005b), we hypothesize that it may be possible to assign properties to small-diameter logs on a species independent basis. A future study similar in scope to this study is in progress for

lodgepole pine. When the results are available for a third species we will be better able to judge the limitations of our hypothesis.

Compression versus bending strength. — For lumber, the relationship between UCS and MOR is established on a conservative basis that is independent of species and grade (ASTM D6570, 2006). Because the relationship for lumber decreases with decreasing beam depth (Green and Kretschmann 1991), the standard assumes a relationship based on 2 by 4's and applies this relationship to wider widths. It is anticipated that a similar consensus could be applied to developing the compression versus bending strength relationship for logs. Figure 2 shows the UCS/MOR ratio plotted versus MOR for both species of small-diameter logs tested in this study. The form of the relationship for the two species appears to follow a consistent pattern. The average trend in the relationship is given by Eq. [1].

$$\text{UCS/MOR} = 0.00704(\text{MOR})^2 - 0.1130(\text{MOR}) + 0.853$$

$$\text{for MOR} \leq 8.018 \text{ by } 10^3 \text{ lb/in}^2, \text{ and}$$

$$\text{UCS/MOR} = 0.40 \quad [1]$$

$$\text{for MOR} > 8.018 \text{ by } 10^3 \text{ lb/in}^2$$

UCS/MOR relationships of this form have also been observed for hardwood dimension lumber (Green and McDonald 1993, Green and Rosales 2006) and 6 in. by 6 in. southern pine and 7 in. by 9 in. oak timbers (Green and Kretschmann 1997, Kretschmann and Green 1999). The relationship appears to be primarily a function of the MOE of the material (Green and Kretschmann 1991). The relationship for small-diameter logs yields a lower UCS/MOR ratio than the relationship previously found (Green et al. 2006) for 9-inch diameter logs, Figure 2. This is consistent with observations for dimension lumber.

Plotting the data for small-diameter logs by diameter class also indicates a size effect, with the logs in the 3- to 4-inch diameter class tending to have a lower UCS/MOR ratio than do the logs in the 4- to 5-inch and 5- to 6-inch classes, Figure 3. Inspection of Figure 3 indicates that the UCS/MOR equation for all sizes (Eq. [1]) could provide non-conservative estimates for logs less than 4 inches in diameter. Because the logs tested in bending and compression were not "matched" by log diameter class, and because the sample sizes get quite

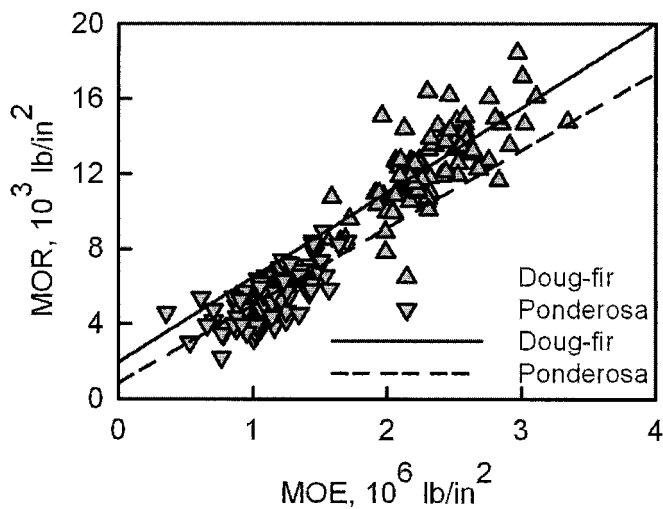


Figure 1. - Modulus of rupture (MOR) versus modulus of elasticity (MOE) for small-diameter tapered logs at 14 percent moisture content.

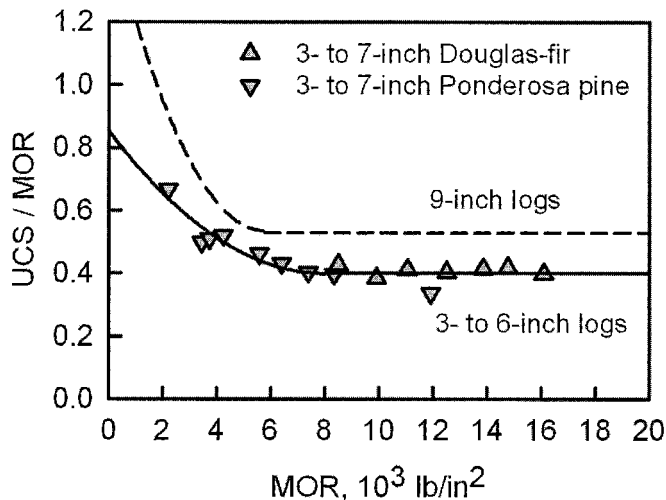


Figure 2. - Relationship between UCS and MOR for 3- to 7-inch diameter logs at approximately 14 percent moisture content (solid line = predicted values from this study, dotted line = predicted values for 9-inch diameter logs from Green et al. 2006).

small when considered by diameter class, it is not appropriate to fit a UCS/MOR vs. MOR curve to the data for the 3-inch diameter class. However, the relationship given in Eq. [1] could be adjusted to fit the lower boundary of the data by individual size.

$$\begin{aligned} \text{UCS/MOR} &= 0.00704(\text{MOR})^2 - 0.1130(\text{MOR}) + 0.750 \\ &\text{for MOR} \leq 8.018 \text{ by } 10^3 \text{ lb/in}^2, \text{ and} \\ \text{UCS/MOR} &= 0.30 \\ &\text{for MOR} > 8.018 \text{ by } 10^3 \text{ lb/in}^2 \end{aligned} \quad [2]$$

Equation [2] is plotted in Figure 3.

Potential mechanical grading criteria

Six allowable properties are commonly assigned to solid wood products. In mechanical grading MOE would be measured directly or estimated using dynamic methods such as by

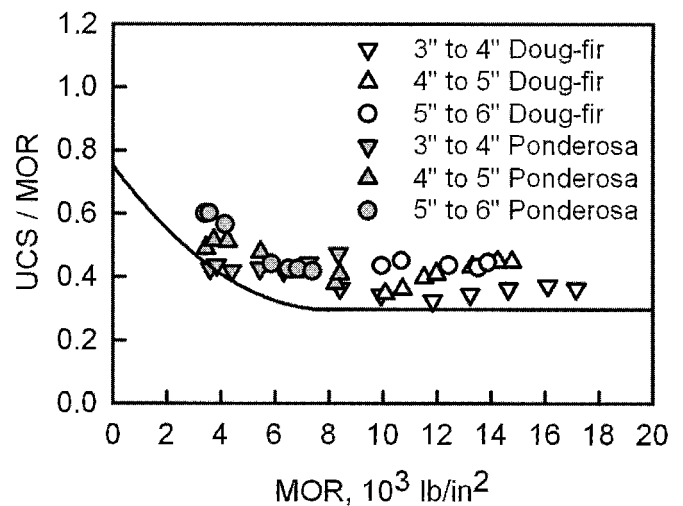


Figure 3. - Effect of log diameter class on UCS-MOR relationship for small-diameter logs at approximately 14 percent moisture content (solid line is reduced relationship given in Eq. [2]).

measuring Etv (Table 5). The strength in compression perpendicular to the grain, $F_{c\text{perp}}$, and in shear, F_v , are estimated from the clear wood procedures of ASTM D245. Currently allowable tensile strength parallel to the grain is estimated as 0.55 times the F_b value. Further discussion of the tensile strength-bending strength relationship for small-diameter logs machined to a constant diameter is given in Gorman, et al.(in progress). Procedures for estimating allowable bending strength, F_b , and allowable strength in compression parallel to the grain, F_c , are given below.

Allowable bending strength.

As previously discussed, the MOR-MOE relationship for Douglas-fir and ponderosa pine have the same slopes, but different intercepts, Figure 1. If mechanically grading either of these two species the most accurate procedure would be to base the grade on the species specific equations. The equation for the 90 percent lower confidence interval for Douglas-fir is:

$$\text{MOR}_{\text{LCL}} = -0.187 + 4.513 \text{ MOE} \quad [3]$$

and for ponderosa pine, the equation is:

$$\text{MOR}_{\text{LCL}} = -0.704 + 4.125 \text{ MOE} \quad [4]$$

If converted to an allowable bending strength (F_b) by dividing MOR_{LCL} by 2.1, for softwood species (ASTM D6570), the resulting equation, based on the average MOE of the desired grade, becomes:

$$F_b = -0.089 + 2.150 \text{ MOE} \quad [5]$$

for Douglas-fir and

$$F_b = -0.335 + 1.964 \text{ MOE} \quad [6]$$

for ponderosa pine.

Allowable compressive strength parallel to the grain

The estimation of allowable compressive strength ($F_{c\text{parallel}}$) is defined, for softwood species, as $\text{UCS}/1.9$ (ASTM D6570). Here a consensus decision would be needed on the

apparent effect of log diameter on the UCS/MOR ratio. Machine stress rated (MSR) lumber uses the relationship for 2 by 4's as the basis for property assignment. This gives a more conservative estimate of F_c -parallel for wider width lumber. Currently small-diameter logs used in roundwood engineered structures are usually 6 or 7 inches in diameter, and almost none are less than 4 inches. Thus the relationships of Eq. [1] might be appropriate for all logs greater than 4 inches in diameter, and the resulting F_c value could be estimated from Eq. [7].

$$F_{c\text{-parallel}} = (\text{MOR} \times \text{Eq. [1]})/1.9 \quad [7]$$

For logs 3 to 4 inches in diameter, $\text{MOR} \times \text{Eq. [2]}$ divided by 1.9 would provide a safer estimate of F_c .

Conclusions

This paper has presented the technical data necessary to establish a mechanical grading system for small-diameter logs with taper. At present, comprehensive data is only available for two U.S. species, and virtually all the data are on dry logs. The commercial production of mechanically graded logs requires many other decisions by the certifying grading agency, the producer of the logs, and the responsible engineering firm. An example of the use of such a system is given in Green et al. (2005b). Preliminary information on the effect of moisture content on log properties is given in Green et al. (2007). From the information presented on 2- to 7-inch diameter ponderosa pine and Douglas-fir logs that have been mechanically debarked and equilibrated to a moisture content of 13 to 14 percent, we conclude:

1. Test data, primarily for Unawn grade, indicate that the allowable flexural properties assigned by visual grading are conservative, especially for the suppressed growth Douglas-fir.
2. Compression data for Unawn grade indicates that the assigned strength value is conservative for Douglas-fir. For ponderosa pine the experimental data would yield an allowable property that is the same as the assigned value.
3. Although the test data indicated the flexural properties of small-diameter plantation grown ponderosa pine were higher than the assigned allowable properties, the tendency of these logs to fail suddenly in a brash manner is of concern, and might limit their use in critical applications where there is minimal structural redundancy.
4. For logs 3- to 7- inches in diameter flexural MOR and MOE do not vary significantly by size. There is a weak relationship between UCS and log diameter with UCS tending to increase with increasing log size.
5. There is a good correlation between modulus of rupture and modulus of elasticity in static bending and between MOE by static bending and MOE by transverse vibration for both Douglas-fir and ponderosa pine.
6. For small-diameter Douglas-fir Eq. [5] might be an appropriate basis for establishing mechanical grading and for ponderosa pine it would be Eq. [6].
7. Based on the results of this, and previous, studies it is recommended that the maximum strength reducing characteristics such as knot size and slope of grain be limited to the maximum characteristic allowed for No. 3 visual grade. Other characteristics that effect serviceability such as warp, roundness, and shake should also

be limited to the characteristics given for No. 3 visual grade.

7. There is a good relationship between compression strength parallel to the grain and bending strength. The ratio of compression to bending strength is lower for small-diameter logs than it is for larger diameter logs. For logs 4 to 7 inches in diameter, the relationships given in Eq. [7] may be used to establish allowable compression strength. Because of the potential for brash failures, we do not recommend the use of this relationship for logs less than 4 inches in diameter.

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