Improved grading system for structural logs for log homes

D.W. Green*
T.M. Gorman*
J.W. Evans
J.F. Murphy

Abstract

Current grading standards for logs used in log home construction use visual criteria to sort logs into either "wall logs" or structural logs (round and sawn round timbers). The conservative nature of this grading system, and the grouping of stronger and weaker species for marketing purposes, probably results in the specification of logs with larger diameter than would be required if a more precise grading method were available. This study evaluated the relationships between log strength and stiffness as a basis for a mechanical grading system. A sample of 120 logs, 4.9-m (16-ft.) long, was obtained from a mixture of fire-killed subalpine fir and lodgepole pine trees. The logs were tested in bending and in compression parallel to grain. Flexural stiffness as determined by transverse vibration was found to be the best single predictor of static strength and modulus of elasticity (MOE). The proposed mechanical grading system uses a combination of MOE and visual characteristics to predict mechanical properties. The proposed system is predicted to yield a higher strength for a given MOE value than does the current visual system.

Logs used as structural members (sawn round timber beams such as ridge beams, floor joists, and purlins; unsawn round timber columns) in log homes are currently graded by visual examination with properties assigned by procedures given in ASTM D 3957 (Hope 1993, ASTM 2003). This standard provides procedures for grading "wall logs," which form a load-bearing, solid wood wall of a building, and "sawn round timber beams," which are shaved or sawn along one side. Allowable properties for round timber are derived using strength ratios for limiting defects as specified in grading rules and the clear wood strength value standard of ASTM D 245/D 2555 (ASTM 2003). Recent studies on both green and dry rectangular timbers have shown that nondestructive evaluation of modulus of elasticity (MOE), coupled with visual assessment of knots and other growth characteristics that affect strength, can more accurately estimate properties than can visual grading alone (Green and Kretschmann 1997, Kretschmann and Green 1999). This coupling of MOE measurement and visual assessment is the basis for the Machine Stress Rated (MSR) mechanical grading system, used commercially with softwood dimension lumber for more than 40 years (Galligan and McDonald 2000).

It is questionable whether the visual grading and property assignment system for round timbers adequately assesses the potential quality of these logs for structural use. The conservative nature of the ASTM D 3957 procedure probably results in the specification of a larger diameter log than would be required if a more precise grading system were available. The objective of this paper is to develop the technical basis for a mechanical grading system for round timbers for use by the log home manufacturing industry.

The authors are, respectively, Supervisory Research General Engineer, USDA Forest Serv., Forest Products Lab., One Gifford Pinchot Dr., Madison, WI 53705; Professor and Department Head, Dept. of Forest Products, Univ. of Idaho, Moscow, ID; Supervisory Mathematical Statistician, and General Engineer, USDA Forest Serv., Forest Products Lab. We acknowledge the interest and assistance of Rocky Mountain Log Homes (Hamilton, MT) and Timber Products Inspection (Conyers, GA) in the completion of this research. We also appreciate the cooperation of the Wood Materials and Engineering Laboratory of Washington State Univ. (Pullman, WA) in conducting the static bending tests. This study was funded by the Forest Products Lab. This paper was received for publication in March 2003. Article No. 9635.
*Forest Products Society Member.

Forest Prod. J. 54(9):52-62.

Table 1. — Allowable properties and limits on knot size and slope of grain for 229-mm- (9-in.-) diameter cut round timbers by visual grade.[a]

Species group[b]	Grade[c]	Knot size	Slope of grain	F_b[d]	MOE	F_c[e]
				(psi (MPa))	(× 10^6 psi (GPa))	(psi (MPa))
ES/AF/LP	No. 1	1/3 in. diam.	1:14	1,100 (7.6)	1.1 (7.6)	500 (3.4)
	No. 2	1/2 in. diam.	1:10	900 (6.2)	1.1 (7.6)	425 (2.9)
	No. 3	3/4 in. diam.	1:6	525 (3.6)	0.9 (6.2)	250 (1.7)
	Unsawn	1/2 in. diam	1:15	1,350 (9.3)	1.1 (7.6)	625 (4.3)

[a]TPO 1987. SI units not legally defined.
[b]Englemann spruce / alpine fir / lodgepole pine.
[c]Other limits on grade characteristics are given in TPO 1987.
[d]5th percentile MOR/2.1.
[e]5th percentile UCS/1.9.

Table 2. — Flexural and compression testing in European small-diameter round timber study.[a]

Country	Species	Bending				Compression parallel to grain			
		n	Age	Diameter	MC	*n*	Age	Diameter	MC
			(yr.)	(in.(mm))	(%)		(yr.)	(in.(mm))	(%)
Austria	Norway spruce	85	--	5.3 (135)	--	--	--	--	--
Finland	Scots pine	175	20	4.9 (124)	15.9	175	19	4.6 (117)	15.3
	Norway spruce	200	28	4.4 (112)	15.6	200	24	4.2 (107)	15.7
Holland	Japanese larch	185	41	4.8 (122)	14.8	61	43	4.6 (117)	14.5
United Kingdom	Scots pine	100	33	5.1 (130)	18.9	100	33	5.0 (127)	17.3
	Sitka spruce	100	19	5.0 (127)	18.3	100	19	4.9 (124)	17.3

[a]Ranta-Maunus 1999. Additional data are available from France, for Douglas-fir and in tension parallel to grain, but this information is not completely reported in the final report.

Background

Visual grading of round timbers

In addition to wall logs, two types of structural round timbers are used in log home construction: sawn and unsawn round timbers. The surface of a sawn round timber is flattened along one side by sawing or shaving. Sawn round timbers are 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, which limits the reduction in the cross section to less than 10 percent. Structural grading rules for sawn round timbers developed by Timber Products Inspection, Inc. (TP 1987) group logs into three grades: No. 1, No. 2, and No. 3. Logs intended for uses that do not require a flattened surface may be graded as "unsawn." 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 the four TP grades. In addition, there are limits on such potential strength-reducing factors as decay associated with knots, shake, splits, and compression wood. Examples of serviceability factors include limits on lack of "roundness," warp, and wane.

Allowable properties for sawn round timbers are derived from clear wood data, modified by strength ratios as set forth in ASTM D 3957. This "clear wood" approach is therefore very similar to ASTM D 245 and D 2555 (ASTM 2003) 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) and in compression parallel to grain (F_c) for the Engelmann spruce/ alpine fir/ lodgepole pine grouping are given in **Table 1**. Allowable properties are also established for tensile strength parallel to grain (0.55 of bending strength), strength in compression perpendicular to grain, and shear parallel to grain.

Small-diameter round logs

Several studies are in progress or have recently been completed on the grading and properties of small-diameter (≤ 254-mm, ≤10-in.) round logs. A major European study has been completed on the utilization of round timbers for construction (Ranta-Maunus 1999). As part of that study, mechanical properties were obtained on several species tested in bending and in compression parallel to grain (**Table 2**). Overall, the logs averaged a little less than 127 mm (5 in.) in diameter and were tested at a moisture content (MC) of about 16 percent. Bending tests were conducted with the logs simply supported and loaded symmetrically at the 1/3-point of the span. As is specified for lumber in Europe, the logs were tested at a span-to-depth ratio of 18:1. The MOE values were calculated using the average diameter of the log and the modulus of rupture (MOR) values calculated using the diameter near failure. Short column compression tests were conducted using an unsupported free span of six times the log diameter, with compression MOE (E_{comp}) calculated using deformation measured over a span of four times the diameter. Tests in other test modes were also conducted but are not fully reported in the final report. Information on log charac-

Table 3. — Correlation coefficients (r) of log characteristics with mechanical properties for European small-diameter round timber study.[a]

Characteristic	MOR	UCS	MOE	E_{comp}
Log diameter	-0.16	0.02	-0.02	-0.08
Knots				
Knot sum	-0.59	-0.56	-0.28	-0.46
Knot sum/diameter	-0.56	-0.56	-0.27	-0.45
Maximum knot	-0.39	-0.43	-0.22	-0.45
Specific gravity				
Age	0.64	0.70	0.28	0.52
Density	-0.41	0.61	0.40	0.59
Ring width	-0.55	-0.54	-0.25	-0.50
MC	-0.28	-0.59	0.06	-0.07
MOE	0.57	0.67	1.00	--

[a]Ranta-Maunus 1999. MOE refers to bending in this table and is based on deflections taken between the load heads.

Table 4. — Multiple regression models for relating log characteristics of larch to MOR for potential mechanical grading applications.[a]

Model	MOE	Knots	Density	Ring width	*r*
5	X	--	--	--	0.76
7	X	X	--	--	0.80
6	X	--	X	--	0.79
8	X	--	--	X	0.79
12	X	X	X	--	0.82
11	X	X	X	X	0.82

[a]Ranta-Maunus 1999.

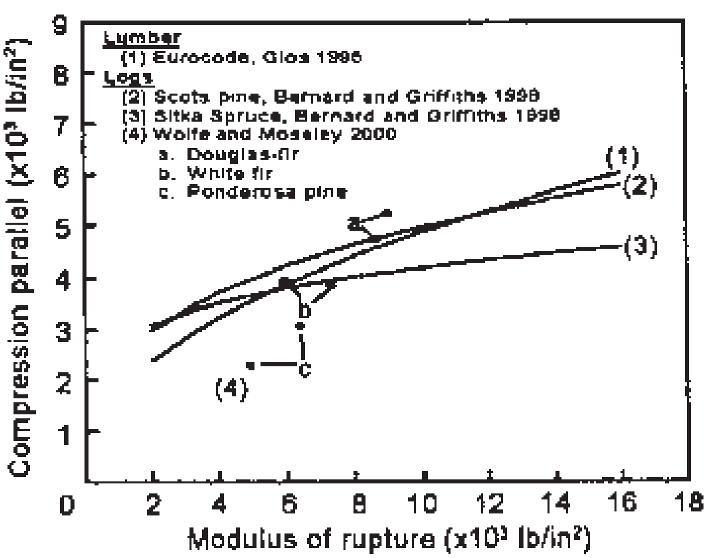

Figure 1. — Compression-bending relationship for small-diameter logs. 1 lb./in.^{2} = 6.894 kPa.

teristics, property relationships, and nondestructive testing options were also evaluated as part of the study. Initial emphasis in the material property phase of the study was on the development of visual grades geared to the European stress class system used for lumber (Glos 1995), which are not directly applicable in the United States. However, the information on factors affecting log properties and relationships between properties is applicable.

Information on the correlation coefficient (*r*) between selected log characteristics and both bending and compression strength values and MOE values (Ranta-Maunus 1999) is presented in **Table 3**. For the species listed in **Table 2**, log diameter was less important than the relationship between MOE and strength. Except for ultimate compressive strength (UCS), MC was less important than other log characteristics.

Several measures of knot properties were obtained. The largest knot in the log (max knot) had some influence on both strength and stiffness prediction, but it was less correlated with these properties than was the sum of the knots in a given cross section (knot sum). The correlation of the sum of the knots divided by the diameter of the cross section was similar to the correlation of the knot sum alone. Several different ways of looking at the overall specific gravity (SG) of the logs were evaluated, including the age of the tree, density at 12 percent MC, and ring width. One form or another of these indications of SG would appear important in a visual grading model, except, perhaps, for flexural MOE.

As noted in the previous text, visual methods were the primary grading focus in the study by Ranta-Maunus (1999). However, it was recognized that in the future there might be some interest in mechanical grading of logs. A number of multiple regression models were evaluated for larch for potential development of a mechanical grading system (Ranta-Maunus 1999). As can be seen from **Table 4**, adding some measure of knot size to MOE would appear to slightly improve the prediction of MOR (model 7 versus model 5), as does adding either density or ring width (model 6 or 8 versus model 5). The best model was that containing MOE, some measure of knots, and density (model 12). However, only slight improvement was gained by using this model than just MOE and knots (model 7). Other measures of MOE, including dynamic measures, give correlations similar to those shown in **Table 4** for static flexural MOE.

Barnard and Griffiths (1998) presented information on the relationship between bending strength and compression strength for Sitka spruce and Scots

Table 5. — Lumber property relationships for recent U.S. studies on small-diameter round logs.

Publication	Property (Y) = A+B(X)		
	Y	X	r^2
Wolfe and Moseley (2000)	MOR	MOE	0.53
		E_{sw}	0.39
	UCS	E_{comp}	0.58
	MOE	E_{sw}	0.40
Wang et al. (2001)	MOE	E_{tv}	0.86
		E_{sw}	0.53

pine from the United Kingdom (see data summary for United Kingdom in **Table 2**). The relationship obtained for small-diameter logs is given in regressions (1) and (2) of **Figure 1**. Also shown is the relationship assumed for lumber in Eurocode, regression 1 (Curry and Fewell 1977, Glos 1995). The European data on small-diameter round logs apparently show that the compression-bending relationship for logs is different from that for dimension lumber.

Two recent studies in the United States have also been looking at property relationships for small-diameter round logs. Wolfe and Moseley (2000) evaluated the bending and compression properties of Douglas-fir, white fir, and ponderosa pine. Twenty-one trees were selected for each species, with butt log diameters ranging from 102 to 330 mm (4 to 13 in.) on the large end. The average age of the Douglas-fir trees was 49 years, that of white fir 44 years, and that of ponderosa pine 24 years. Bending tests were conducted over a 2.4-m (8-ft.) span with a concentrated load at mid-span. Short column compression tests were conducted using a length of three to four times the log diameter. Both static MOE values and MOE values determined by longitudinal stress wave techniques were obtained on the logs. At the time of the test, the MC of most logs tested in bending was above the fiber saturation point, whereas the average MC of the logs tested in compression was 15 percent. For the three species combined, static MOE was found to be the best single predictor (r^2 = 0.53) of MOR (**Table 5**). The correlation between MOE in compression parallel to grain (E_{comp}) and UCS was 0.58. The MOE measured by longitudinal stress wave techniques (E_{sw}) was not well correlated with static flexural MOE, nor was it found to be as good a predictor of MOR.

Plotting the data for "tip" and "butt" logs given in Table 2 of Wolfe and Moseley (2000) suggests a species-independent relationship between MOR and UCS for small-diameter logs (**Fig. 1**). In this plot, the top two data points (a) are Douglas-fir, the next two (b) are white fir, and the last two (c) are ponderosa pine. However, the slope of the relationship shown in **Figure 1** might be different if the bending and compression samples had the same MC.

Wang et al. (2001) evaluated several nondestructive predictors of static flexural MOE for small-diameter red pine and jack pine. The trees ranged in diameter from about 127 mm to 330 mm (5 in. to 13 in.). The jack pine was 50 to 70 years old, whereas the red pine averaged 38 years. The static bending tests were conducted using 305-mm- (12-ft-.) long logs loaded at the 1/3-point of the span. Butt logs ranged in diameter from about 114 mm to 280 mm (4.5 to 11 in.); most logs were tested while green. In addition to static MOE, MOE was determined by transverse vibration (E_{tv}) and longitudinal stress wave (E_{sw}) techniques. For both red pine and jack pine combined, a very good correlation was found between MOE and E_{tv} (**Table 5**), but not between MOE and E_{sw} The authors concluded that E_{tv} values were less sensitive to geometrical imperfections of the logs than were E_{sw} values.

Materials and methods

Selection and processing

We selected 60 logs and 60 cants from the inventory of a cooperating log home manufacturer in the Bitterroot Valley of Montana. The material came from dead-standing, typically fire- and/or beetle-killed trees. The sample was a mixture of subalpine fir (*Abies lasiocarpa*) and lodgepole pine (*Pinus contorta*). Because regression relationships were to be established as part of the proposed grading procedure, we attempted to obtain a wide range of material quality in our initial selection, including some specimens that might not meet current visual grading requirements. Our selection was based on obtaining 4.9-m- (16-ft.-) long specimens using visual characteristics such as knots and spiral grain as quality indicators. Average length of rough-cut specimens was about 5 m (16.5 ft.). Only specimens with obvious decay or significant shake were rejected. The average MC of the specimens was assumed to be below the fiber saturation point based on deep checks and spot readings taken with a portable resistance moisture meter.

The specimens were divided into two groups with an approximately equal range of quality using longitudinal stress wave measurements and visual quality characteristics. First, longitudinal stress wave measurements were taken on all logs and cants. Then, pairs of logs with approximately equal stress wave transit times and visual quality characteristics were separated into 2 groups of 30 specimens. The process was repeated with the cants. Thus, each of the 2 final groups of 60 specimens was composed of 30 cants and 30 logs, and the overall range in quality was about the same for each group. One group was then arbitrarily assigned for testing in bending and the other for testing in compression parallel to grain.

After this selection process, the specimens were turned by the log home manufacturer to uniform cylinders, approximately 230 mm (9 in.) in diameter. The logs to be tested in bending were sawn on one side to create an approximately 51-mm- (2-in.-) wide flattened surface. These "sawn round timbers" represented a typical structural log profile for bending members, in which the flattened surface would be the load bearing area for a floor or roof member. We had intended to leave the members to be tested in compression as round logs but were unable to do so because 30 of these logs were also flattened on one side. The logs to be tested in bending were shipped to the University of Idaho and those to be tested in compression to the USDA Forest Products Laboratory.

Flexural testing

The processed logs were delivered to the University of Idaho for flexural testing. The logs were first graded as sawn round timbers by a TP Quality Supervisor (TP 1987). Each log was weighed and measured, and its slope of grain was recorded. The worst knot in each log and the worst knot in each quadrant of the log were recorded. The species of each log was also determined. Three nondestructive evaluation measurements were taken on each log while it was simply supported at each end.

First, center-span MOE (E_{dead}) was calculated from the deflection caused by placing a 21-kg (47-lb.) dead load at mid-span. This was done by first placing a small pre-load of 22 kg (49 lb.) on the log and then measuring the incremental deformation 60 seconds after the 64-kg (139- lb.) dead load was applied. The stiffness relationship is given by:

$$E_{dead}I = (L^3/48)(P/\Delta) \qquad [1]$$

where:

I = moment of inertia

P/Δ = slope of load/deformation relationship

L = span

Using nominal dimensions, the moment of inertia of the logs was assumed to be 1.325×10^{-4} m (318.3 in.^{4}). The value of E_{dead} served as a basic reference value between the bending and compression samples.

Second, the stress wave velocity along the length of each log was measured by attaching an accelerometer to one end of the log and impacting the other end with a 2.3-kg (5-lb.) hammer. The oscillating signal generated by the accelerometer was analyzed with a computer program written by researchers at the USDA Forest Products Laboratory to determine wave speed per unit length of logs (C). Each log was weighed for determination of density (ρ). The MOE by longitudinal stress wave techniques (E_{sw}) was then determined from:

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

Third, the transverse vibration frequency of each log was determined by striking each log with a rubber-headed hammer at mid-span to induce vibration and recording the output from a load cell located at one of the supports (Murphy 2000). The MOE by transverse vibration may then be calculated from:

$$E_{tv} = (f^2 WL^3)/(2.467\ Ig) \qquad [3]$$

where:

W = weight of beam

f = natural frequency of transversely vibrating beam

g = acceleration due to gravity

The loads were then placed in a universal testing machine and tested in 1/3-point bending with a span-to-depth ratio of 17:1 (span = 3.8 m, 12.25 ft.) according to ASTM D 198 (ASTM 2001). For this test, the beams were orientated with the round side down and the loads were applied to the flattened surface, as would typically happen in use. The rate of crosshead motion was 25.4 mm (1.0 in.) per minute, which resulted in an average time to failure of about 3 minutes. Load-deflection plots were also obtained for each specimen for calculation of static MOR and MOE.

Static MOE was determined from the slope of the load deflection curve. Load-deflection readings were taken electronically at about five readings per second over the duration of the test. A regression equation was used to fit a straight line to the linear portion of the curve, and the fit was checked both statistically and by visual observation. Coefficients of determination, r^2, for the fits were generally in excess of 0.99:

$$\text{MOE} = (23L^3/1296I)(P/\Delta) \qquad [4]$$

After testing, a 25.4-mm- (1-in.-) thick cross section was cut from near failure of each log for determining ovendry MC and SG (ASTM D 4442 and D 2395; ASTM 2001).

Compression testing

Log selection, grading, measurement of physical characteristics, and nondestructive testing of E_c, E_{tv}, and E_{sw} were conducted as described for the bending samples. Testing followed procedures given in ASTM D 198 (ASTM 2003), with lateral supports provided at 305 mm (12 in.) from the ends of the log and at 610-mm (24-in.) spacing in the middle of the log. To facilitate handling of the logs, each full-length log was cut in half; each half was tested and the lowest of the two values recorded. The average length of the logs at test was 249 cm (98 in.). The logs were loaded at a rate of crosshead movement of approximately 2.54 mm (0.1 in.), for a time to failure of 5 to 12 minutes. Longitudinal MOE in compression, E_{comp}, was obtained by measuring the deflection over the middle 152 cm (60 in.) of the span. Because a few of the members with significant spiral grain tended to twist as they were loaded, twist perpendicular to the long axis of the member was also measured. After testing, a 25.4-mm- (1-in.-) thick cross section was cut from near failure of each log for determining ovendry MC and SG (ASTM D 4442 and D 2395) (ASTM 2003).

Results and discussion

Physical and mechanical properties

Bending. — The static bending properties of the logs tested in this study are summarized in **Table 6**. Of these logs, 43 were subalpine fir and 17 were lodgepole pine. Average log diameter was about 222 mm (8-3/4 in.) and average MC was 15.5 percent, with a range from 12 to 39 percent. All but four logs had less than 20 percent MC; MC of the outer quarter of these logs averaged only 17 percent. The average branch index value ranged from 28.2 to 33.3 mm (1.11 to 1.31 in.), indicating that the logs were not particularly knotty. Branch index is the average value for the worst knots in each quadrant of the log. This characteristic has been found useful in characterizing log quality (Barbour and Parry 2001). Slope of grain was not generally a problem. For example, the average slope of grain for No. 1 logs was only 2.54 cm in 160 cm (1 in. in 62.8 in.) (**Table 6**), too small a slope to measure in the field.

Evaluating the properties of the visual grades was not a primary objective of the study, and the limited sample sizes for most visual grades precluded valid statistical analysis of the differences. The 27 No.1 logs (20 of which were subapline fir) had an average MOR of 35 MPa (5,070 psi) and a 5th percentile point estimate of 22.1 MPa (3,210 psi). Dividing the 5th percentile MOR value by the general adjustment factor of 2.1 yields an estimated F_b value of 10.7 MPa (1,550 psi), which is 35 percent higher than the allowable F_b value of 7.9 MPa (1,150 psi) shown in **Table 1**. The average MOE value of the 27 No.1 logs and the 15 No. 2 logs would both round to 8.3 GPa (1.2 million psi). Both values are slightly lower than the allowable value of 9.0 GPa (1.3 million psi) shown in **Table 1**. These values are representative of only the samples we tested, not of the population as a whole.

Compression parallel to grain. — The properties of the logs when tested in

Table 6. — Bending properties of various grades of lodgepole pine and subalpine fir 229-mm- (9-in.-) diameter cut round timbers.

Property	Grade	Sample size[a]	Average MC	Average SG	Average branch index	Average slope of grain	Mean property	COV[b]	5th percentile
			(%)		(in.(mm))	(one in *x*)	($\times 10^3$ psi (MPa))	(%)	($\times 10^3$ psi (MPa))
MOR									
	No. 1	27	15.7	0.38	1.13 (28.7)	62.8	5.07 (35.0)	23.1	3.21 (22.1)
	No. 2	15	15.8	0.39	1.31 (33.3)	27.8	5.37 (37.0)	15.8	NA
	No. 3	4	14.4	0.38	1.11 (28.2)	70.8	4.00 (22.8)	15.8	NA
	Cull	13	15.3	0.38	1.14 (29.0)	63.6	4.81 (33.2)	26.1	NA
	All	59	15.5	0.38	1.19 (30.2)	54.1	5.01 (35.0)	22.1	NA
MOE							($\times 10^6$ psi (GPa))		($\times 10^6$ psi (GPa))
	No. 1	27	15.7	0.38	1.13 (28.7)	62.8	1.19 (8.2)	13.1	0.91 (6.3)
	No. 2	15	15.8	0.39	1.31 (33.3)	27.8	1.24 (8.5)	7.5	NA
	No. 3	4	14.4	0.38	1.11 (28.2)	70.8	1.11 (7.7)	16.1	NA
	Cull	13	15.3	0.38	1.14 (29.0)	63.6	1.10 (7.6)	13.5	NA
	All	59	15.5	0.38	1.19 (30.2)	54.1	1.18 (8.1)	12.5	NA
E_{dead}							($\times 10^6$ psi (GPa))		($\times 10^6$ psi (GPa))
	No. 1	27	15.7	0.38	1.13 (28.7)	62.8	1.25 (8.6)	11.4	0.99 (6.8)
	No. 2	15	15.8	0.39	1.31 (33.3)	27.8	1.30 (9.0)	5.6	NA
	No. 3	4	14.4	0.38	1.11 (28.2)	70.8	1.18 (8.1)	14.0	NA
	Cull	13	15.3	0.38	1.14 (29.0)	63.6	1.16 (8.0)	11.2	NA
	All	58	15.5	0.38	1.19 (30.2)	54.1	1.24 (8.5)	10.8	NA
E_{tv}							($\times 10^6$ psi (GPa))		($\times 10^6$ psi (GPa))
	No. 1	27	15.7	0.38	1.13 (28.7)	62.8	1.24 (8.5)	11.5	0.98 (6.8)
	No. 2	15	15.8	0.39	1.31 (33.3)	27.8	1.28 (8.8)	7.1	NA
	No. 3	4	14.4	0.38	1.11 (28.2)	70.8	1.18 (8.1)	12.6	NA
	Cull	13	15.3	0.38	1.14 (29.0)	63.6	1.17 (8.1)	10.5	NA
	All	59	15.5	0.38	1.19 (30.2)	54.1	1.23 (8.5)	12.9	NA
E_{sw}							($\times 10^6$ psi (GPa))		($\times 10^6$ psi (GPa))
	No. 1	27	15.7	0.38	1.13 (28.7)	62.8	1.51 (10.4)	17.0	1.14 (7.9)
	No. 2	15	15.8	0.39	1.31 (33.3)	27.8	1.50 (10.3)	10.7	NA
	No. 3	4	14.4	0.38	1.11 (28.2)	70.8	1.48 (10.2)	10.8	NA
	Cull	13	15.3	0.38	1.14 (29.0)	63.6	1.38 (9.5)	15.2	NA
	All	59	15.5	0.38	1.19 (30.2)	54.1	1.48 (10.2)	14.9	NA

[a]One piece accidentally graded as a "wall log 40."
[b]COV = coefficient of variation.

short column compression are summarized in **Table 7**. Of these logs, 44 were subalpine fir and 16 were lodgepole pine. As with the bending samples, the logs averaged about 222 mm (8-3/4 in.) in diameter; MC averaged 12.3 percent, with values ranging from about 9 to 14 percent. As can be seen from the branch index, the average size of the worst knots was just 34.3 mm (1.35 in.). In general, slope of grain was not a problem. For example, the average slope of grain found for No. 1 logs was only 1 inch in 112 inches (2.54 cm in 284 cm) (**Table 7**), too small a slope to measure in the field. However, a few logs were grade limited by slope of grain.

Forty-three of the 60 logs (72%) selected for compression testing were No.1 grade as opposed to 27 of 59 logs (46%) sampled for bending tests. This imbalance in the two data sets is probably a result of having to select the specimens in the rough form, before they were machined to constant diameter. The 5th percentile UCS value of the No. 1 logs was 15.3 MPa (2,220 psi). When the 5th percentile value is divided by the general adjustment factor of 1.9, the allowable compressive strength F_c is 7.9 MPa (1,150 psi). This is almost twice as high as the allowable value of 4.1 MPa (600 psi) shown for No. 1 grade in **Table 1**.

Relationships between properties

Because determining MOE by transverse vibration or longitudinal stress wave is not standardized procedure for logs, and because both techniques require more complex analysis to obtain an MOE value, it is instructive to compare both MOE estimates with the simple case of loading with a dead load applied at mid-span (E_{dead}) (**Table 8**). Since all three measures were taken on both bending and compression samples, **Table 8** gives this comparison for the combined data set. As might be expected, MOE determined by transverse vibration is a much better predictor of E_{dead} than is MOE determined by longitudinal stress wave. The variability about the regression line, as expressed by the root mean square error (RMSE) of E_{sw} to E_{dead} (0.703 MPa, 102 psi), was more than 2.5 times larger than that between E_{tv} and E_{dead} (0.255 MPa, 37 psi).

Regression relationships determined for the bending specimens are also sum-

Table 7. — Properties of lodgepole pine and subalpine fir 229-mm- (9-in.-) diameter cut round timbers in compression parallel to grain.

Property	Grade	Sample size[a]	Average MC	Average SG	Average branch index	Average slope of grain	Mean property	COV[b]	5th percentile
			(%)		(in. (mm))		($\times 10^3$ psi (MPa))	(%)	($\times 10^3$ psi (MPa))
UCS									
	No. 1	43	12.3	0.36	1.35 (35.3)	115	3.11 (21.4)	17.0	2.22 (15.3)
	No. 2	4	13.2	0.37	1.20 (30.4)	65	2.97 (20.5)	12.1	NA
	No. 3	10	12.0	0.35	1.25 (31.8)	117	3.30 (22.8)	25.0	NA
	All	57	12.3	0.36	1.33 (33.8)	112	3.14 (21.7)	18.3	2.26 (15.6)
E_{comp}							($\times 10^6$ psi (GPa))		($\times 10^6$ psi (GPa))
	No. 1	43	12.3	0.36	1.35 (35.3)	115	1.18 (8.1)	15.6	0.94 (6.5)
	No. 2	4	13.2	0.37	1.20 (30.4)	65	1.02 (7.0)	27.1	NA
	No. 3	10	12.0	0.35	1.25 (31.8)	117	1.25 (8.6)	15.7	NA
	All	57	12.3	0.36	1.33 (33.8)	112	1.18 (8.1)	16.6	0.93 (6.4)
E_{dead}							($\times 10^6$ psi (GPa))		($\times 10^6$ psi (GPa))
	No. 1	43	12.3	0.36	1.35 (35.3)	115	1.25 (8.6)	14.9	1.00 (6.9)
	No. 2	4	13.2	0.37	1.20 (30.4)	65	1.21 (8.4)	13.5	NA
	No. 3	10	12.0	0.35	1.25 (31.8)	117	1.26 (8.7)	21.7	NA
	All	57	12.3	0.36	1.33 (33.8)	112	1.25 (8.6)	15.9	0.98 (6.4)
E_{tv}							($\times 10^6$ psi (GPa))		($\times 10^6$ psi (GPa))
	No. 1	43	12.3	0.36	1.35 (35.3)	115	1.12 (8.5)	13.9	0.98 (6.7)
	No. 2	4	13.2	0.37	1.20 (30.4)	65	1.16 (8.0)	16.8	NA
	No. 3	10	12.0	0.35	1.25 (31.8)	117	1.24 (8.5)	20.6	NA
	All	57	12.3	0.36	1.33 (33.8)	112	1.22 (8.4)	15.2	0.96 (6.6)
E_{sw}							($\times 10^6$ psi (GPa))		($\times 10^6$ psi (GPa))
	No. 1	43	12.3	0.36	1.35 (35.3)	115	1.43 (9.9)	13.2	1.15 (7.9)
	No. 2	4	13.2	0.37	1.20 (30.4)	65	1.30 (9.0)	22.9	NA
	No. 3	10	12.0	0.35	1.25 (31.8)	117	1.51 (10.4)	22.6	NA
	All	57	12.3	0.36	1.33 (33.8)	112	1.43 (9.9)	16.0	1.14 (7.9)

[a]One piece accidentally graded as a "wall log 40."
[b]COV = coefficient of variation.

marized in **Table 8**. As expected, the correlation between static MOE determined by 1/3-point load and the center-point dead load is excellent, with a RMSE of 0.241 MPa (35 psi). The correlation between E_{tv} and MOE is also excellent, with an RMSE of 0.351 MPa (51 psi). A good, but more variable correlation, with a RMSE of 0.483 MPa (70 psi), was found between E_{sw} and MOE. As can be determined from the equation given in **Table 8**, E_{tv} readings would be close to those of MOE over most of the expected range of MOE, with E_{tv} values being slightly higher at low values of MOE. The E_{sw} and E_{tv} relationship has a much different slope, and numerical values of E_{sw} are higher than those of MOE for E_{sw} readings above 5.9 GPa (0.86 million psi). The higher E_{sw} values over much of the range of MOE are consistent with the observations of Wang et al. (2001).

The correlation between MOR and various nondestructive measures of MOE is also given in **Table 8**. Coefficients of determination, r^2, are highest for static MOE by 1/3-point load (**Fig. 2**) and are typical of those found for dimension lumber (Doyle and Markwardt 1966). As might be expected, the axial modulus, E_{sw}, is less well correlated with flexural strength than are the flexural methods of estimating MOE.

For MOE in compression parallel to grain (E_{comp}), all three measures of MOE correlate equally well with E_{comp}. Thus E_{sw} is just as good a predictor of E_{comp} as are the two bending MOE measurements. Surprisingly, E_{comp} is not the best predictor of UCS. With an RMSE of 2.5 MPa (368 psi), E_{tv} is the best predictor of MOE, E_{dead} is virtually identical (RMSE = 2.6 MPa (378 psi)), and E_{sw} is almost as good (RMSE = 2.8 MPa [408 psi]). Since the difference in RMSE between the predictions of UCS using E_{comp} and E_{tv} is only 0.503 MPa (73 psi), perhaps this is just an anomalous result. In any case, current practice for MSR lumber is to predict UCS from its relationship with MOR, not its relationship with MOE (ASTM D 6570).

Development of mechanical grading criteria

Predicting log strength. — The relationship between MOR and MOE forms the basis for the MSR grading system, used commercially in the United States since the 1960s for grading dimension lumber (Smulski 1997, Galligan and McDonald 2000). For the MSR grading systems, a lower 95 percent confidence interval (CI) on the predicted MOR values provides the equivalent of the 5th percentile used to determine allowable strength values for visual grades. A true 95 percent CI is nonlinear, being wider at the upper and lower ends of the MOE distribution than it is near the mean. Such a nonlinear trend is not convenient for estimating allowable properties.

We first obtained a true 95 percent lower CI to the data. We then obtained a

Table 8. — Regression relationships for 229-mm- (9-in.-) diameter sawn round timbers.[a]

Property (*Y*)	X	*n*	Property (Y) = $A + B(X)$ A	B	r^2	RMSE
Combined data						
E_{dead}	E_{tv}	118	-0.039	1.045	0.95	0.037
	E_{sw}	118	0.350	0.611	0.63	0.102
Bending data						
MOE	E_{tv}	60	-0.138	1.071	0.88	0.051
	E_{sw}	56[b]	0.393	0.543	0.67	0.070
	E_{dead}	58[c]	-0.134	1.063	0.94	0.035
MOR	MOE	60	-1.930	5.902	0.61	0.696
	E_{dead}	58[c]	-2.848	6.357	0.56	0.746
	E_{tv}	60	-2.566	6.174	0.51	0.778
	E_{sw}	60	1.210	2.576	0.25	0.962
Compression data						
E_{comp}	E_{tv}	57	0.081	0.903	0.72	0.104
	E_{sw}	57	0.084	0.799	0.76	0.096
	E_{dead}	57	0.148	0.829	0.70	0.107
UCS	E_{comp}	57	0.663	2.090	0.49	0.441
	E_{tv}	57	0.187	2.416	0.60	0.368
	E_{sw}	57	0.493	1.921	0.50	0.408
	E_{dead}	57	0.373	2.212	0.57	0.378

[a]For MOR and UCS, values in thousand psi; MOE values in million psi; RMSE in same units as property values; 1 psi = 6.895 MPa.
[b]Four "outlying" pieces dropped (see text).
[c]Readings lost as a result of LVDT error.

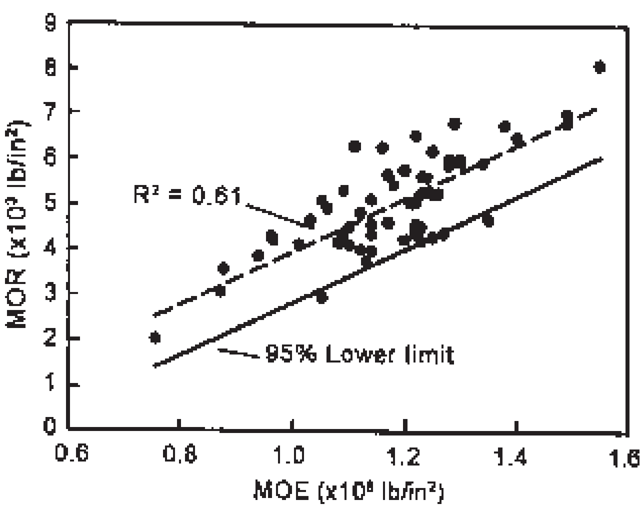

Figure 2. — Bending-stiffness relationship for 229-mm- (9-in.-) diameter logs.

linear model relating MOR and MOE having the same slope as the mean trend of the MOR-MOE regression line but with an intercept displaced downward by the difference between the mean trend line and the true CI at its narrowest point (**Fig. 2**). The equation for the 95 percent lower CI is:

$$MOR_{.95LCI} = 5.902MOE - 3.084 \quad [5]$$

If MOE were the only grading criterion, the near minimum MOE for a grade having an allowable E value of 13.8 GPa (2.0 million psi) would be 0.82 times the grade average value, or 11.3 GPa (1.64 million psi). The allowable MOR value, F_b, would be obtained by determining the MOR value predicted from Equation [**5**] with an MOE of 11.3 GPa (1.64 million psi) and then dividing that MOR value by the general adjustment factor of 2.1 (ASTM D 245). For example, for an allowable MOE of 9.0 GPa (1.3 million psi), the F_b value would be 22.1 MPa (3,208 psi). Dividing this value by 2.1 yields 10.5 MPa (1,528 psi) and would round to 10.7 MPa (1,550 psi) (ASTM D 245).

Table 9 presents some potential F_b-E combinations developed from Equation [**5**] and compares them to allowable MOE values for current grades of visually graded sawn round timbers (TP 1987). Note that for a given MOE value, mechanical grading would give a higher F_b value than does the current visual system, especially for the No. 3 visual grade. In many cases, however, the value of the proposed system may not be the ability to get a higher MOR value for a given value of MOE, but the possibility to obtain a higher grade yield for a given set of properties than would be possible through visual grading (Kretschmann and Green 1999).

In an effort to find other variables that might be useful in developing grading criteria, a stepwise regression was run to see what other variables might have predictive capability for MOR. In addition to MOE, the variables included in the regression were the average of the largest knots on each face of the log, largest knot anywhere on log, minimum of largest knots on each side, slope of grain, density, SG, and log grade. MOE was by far the most important variable, explaining 61 percent of the variability and being a significant predictor of MOR with a significance level of 0.0001. Next in importance was any of the knot measures. All knot measures were essentially the same in importance. Maximum knot size was used because of its simplicity as a grading criterion. This variable was also significant at the -0.0001 level, and with MOE it increased the r^2 value from 61 to 67 percent. The inclusion of maximum knot size also reduced the variability of a predicted MOR value. The RMSE used in such a prediction decreased from 4.8 MPa (696 psi) based on MOE alone to 4.5 MPa (647 psi) using both MOE and knot size. The following predictive equation allows us to get predictive equations for MOR of logs with different maximum size knots.

$$MOR = 5.576\,MOE - 0.314\,Knot_{max} - 1.036 \quad [6]$$

Table 9. — *Predicted allowable flexural properties for mechanically graded sawn round timbers of subalpine fir/lodgepole pine using only MOE.*

MOE		$MOR_{.95LCI}$	F_b-E	
Average	0.82E	(Eq. [**5**])	Predicted[a]	Current[b]
1.4	1.148	3.691	1750F_b-1.4E	--
1.3	1.066	3.208	1550F_b-1.3E	1450F_b-1.3E
1.2	0.984	2.724	1300F_b-1.2E	--
1.1	0.902	2.240	1100F_b-1.1E	550F_b-1.1E
1.0	0.820	1.756	850F_b-1.0E	--

[a]Equation [**5**] of text, divided by 2.1, and rounded by ASTM D 245.
[b]Alpine (subalpine) fir values for Unsawn (1.3E) and No. 3 Sawn (1.1E) grades.

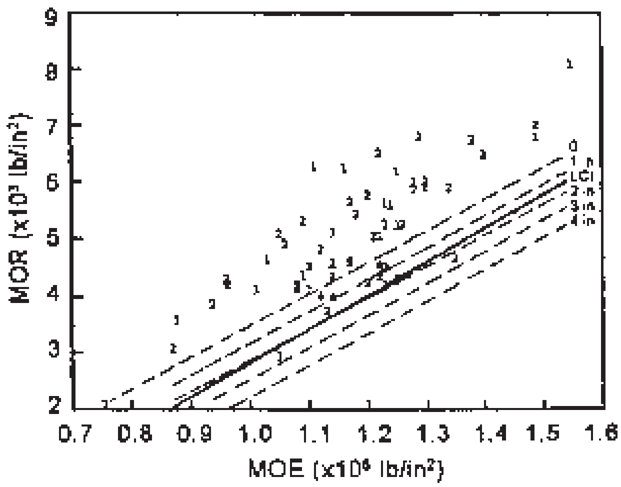

Figure 3. — Comparison of 95 percent lower confidence intervals for models with and without knots. Maximum knot size, in inches, is shown for each data point. (1 in. = 25.4 mm).

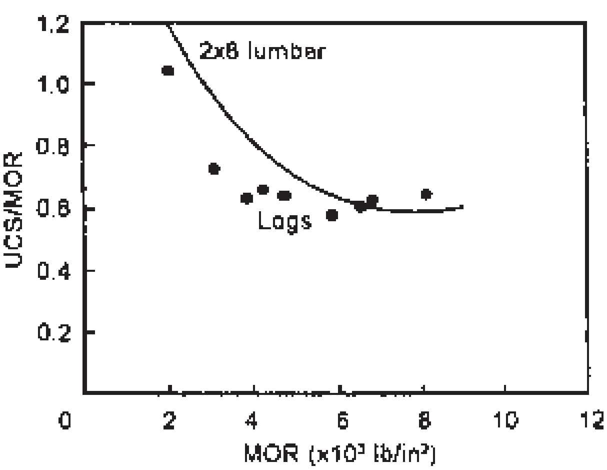

Figure 4. — Compression-bending relationship for 229-mm- (9-in.-) diameter round logs. Ratios plotted are at 1st, 5th, 10th, 25th, 50th, 75th, 90th, 95th, and 99th percentiles of MOR and UCS strength distributions.

Figure 3 shows an approximate 95 percent lower confidence limit of predicted MOR values for Equation [**6**] for maximum knots ranging from 0 to 102 mm (0 to 4 in.). The figure shows that the limit for the 51-mm (2-in.) knot is very close to the 95 percent confidence limit for the original MOR-MOE curve, Equation [**5**] (indicated as LCI on **Fig. 3**). This is due in part to the limited number of knots larger than 51 mm (2 in.), as may be seen from the data points on **Figure 3**. With more samples of larger knots, the confidence limit for the MOR-MOE curve would be expected to be lower than the confidence limit for this sample. The next phase of this project will more than double the number of available samples, which should help clarify the regression relationships.

Predicting compression strength. — In current practice, the compression strength of MSR lumber is estimated from the bending strength. A plot of the ratio of UCS to MOR, plotted versus MOR using the 1st through 99th percentiles of each property, shows a relationship similar in form to that seen for dimension lumber (Green and Kretschmann 1991) (**Fig. 4**). Although the relationship for round members would yield different UCS/MOR ratios than would the relationship for dimension lumber, it would appear possible to estimate properties by the same process used for dimension lumber. Further, the initial results of Wolfe and Moseley (2000) for 102-mm- (4-in.-) diameter tapered logs suggest that the relationship might be a function of log size, as it is with dimension lumber (Green and Kretschmann 1991), but perhaps independent of species (**Fig. 5**).

As previously noted, there was a much higher percentage of No. 1 visual grade logs in the compression data set than in the bending data set. This difference raised concerns that the quality of the logs in the lower end of the compression data might not be equivalent to that for the bending data. This is further demonstrated in **Figure 6**, where it would appear that the lower tail of the UCS distribution has been truncated. To correct this problem, we plan to sample some additional ungraded pieces with low predicted compression strengths during phase II of our study. Also, the lower end of the MOR data appears somewhat jagged, perhaps not unexpected given the small sample size of the data set. Some additional pieces with lower estimated MOR values will also be sampled in phase II. These additional samples should help to smooth out the UCS-MOR relationship (**Fig. 4**).

Conclusions and recommendations

From the results of our study on dry, 229-mm- (9-in.-) diameter, round timbers we conclude the following:

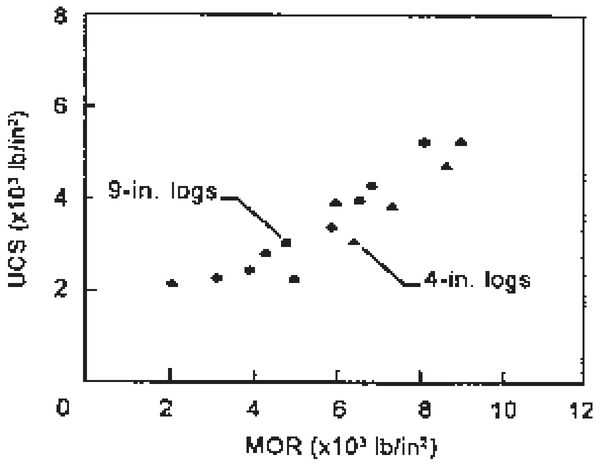

Figure 5. — Compression-bending relationship for logs of two diameters. Data for 229-mm- (9-in.-) diameter logs are at 1st, 5th, 10th, 25th, 50th, 75th, 90th, 95th, and 99th percentiles of MOR and UCS strength distributions. Data for 102-mm- (4-in.-) diameter logs are mean values from Wolfe and Moseley (2000).

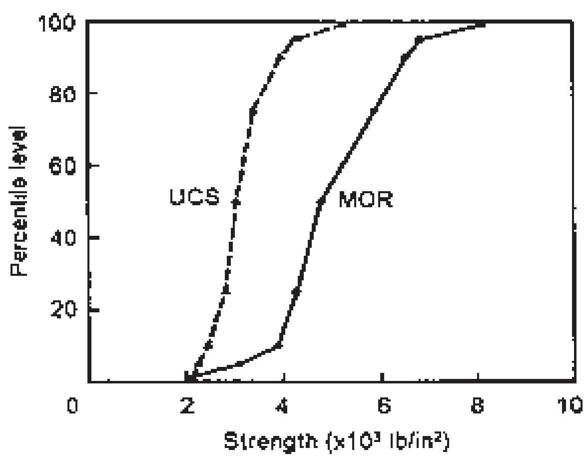

Figure 6. — Strength distribution of 229-mm- (9-in.-) diameter logs.

• A prototype machine developed to determine log stiffness by transverse vibration provides an excellent correlation with MOE determined by applying a dead load in the center of an untapered round timber.

• Good correlations exist between static MOE in 1/3-point bending and MOE determined by transverse vibration or longitudinal stress wave. For estimating flexural MOE, presorting logs using transverse vibration is preferred because it yields a better correlation and requires less judgment on the part of the operator.

• Both MOE by transverse vibration and MOE by longitudinal stress wave appear to be equally well correlated to static MOE by axial compression.

• For logs, there appears to be a correlation between UCS parallel to grain and MOR that is similar in form to that established for dimension lumber. The relationship may be species independent.

• A good correlation exists between flexural strength (MOR) and MOE. Thus, there would appear to be no technical barrier to developing a mechanical grading system for round timbers.

The initial results of our study are favorable. However, it is necessary to verify that the proposed procedures can be used to successfully sort mechanical grades of round timbers. A follow-up study is needed in which logs of at least two proposed grades are sorted and then tested to confirm flexural properties. At least one of these grades should have properties comparable to those of an existing visual grade so that grade yield comparisons may be made. This study would also provide additional data to clarify the contribution of knots to the predictive relationship for MOR (Eq. [**6**]).

Additional information is needed on the flexural and compressive strength of lower quality logs to help quantify the UCS-MOR relationship. Information is needed on the effect of MC on log MOE and MOR as an aid in setting grade boundaries in the field. Finally, it is important that research be continued on the factors that affect log strength, such as the complementary studies of Wolfe, to help provide insight into the variation in log properties over a wide geographic range and the relationship between material and log properties.

Literature cited

American Society for Testing and Materials (ASTM). 2003. Standard methods of static tests of lumber in structural sizes, D 198-02.; Standard practices for establishing structural grades and related allowable properties for visually graded lumber, D 245-00; Standard test methods for specific gravity of wood and wood-based materials, D 2395-02; Standard test methods for establishing clear wood strength values, D 2555-98; Standard practice for establishing design stresses for round timber piles, D 2899-99; Standard practice for establishing stress grades for structural members used in log homes, D 3957-90; Standard test methods for direct moisture content measurement of wood and wood-based materials, D 4442-92; Standard practice for assigning allowable properties for mechanically graded lumber, D 6570-00. *In*: Annual Book of Standards, Volume 04.10. Wood. ASTM, West Conshohocken, PA.

Barbour, R.J. and D.L. Parry. 2001. Log and lumber grades as indicators of wood quality in 20- to 100-year-old Douglas-fir trees from thinned and unthinned stands. Gen. Tech. Rept. PNW-GTR-510. USDA Forest Serv., Pacific Northwest Res. Sta., Portland, OR.

Barnard, G. and R. Griffiths. 1998. Strength characteristics of small roundwood in bending and compression from a UK resource. *In*: Proc. World Conference of Timber Engineering. Vol. 1. pp. 602-609.

Curry, W.T. and A.R. Fewell. 1977. The relationships between the ultimate tension and ultimate compression strength of timber and its modulus of elasticity. Current Paper 22/77. Building Res. Establishment, Garston, Watford, UK.

Doyle, D.V. and L.J. Markwardt. 1966. Properties of southern pine in relation to strength grading of dimension lumber. Res. Paper FPL-RP-64. USDA Forest Serv., Forest Prod. Lab., Madison, WI. 62 pp.

Galligan, W. and K.A. McDonald. 2000. Machine grading: Practical concerns for lumber producers. Gen. Tech. Rept. FPL-GTR-7 (rev.). USDA Forest Serv., Forest Prod. Lab., Madison, WI. 39 pp.

Glos, P. 1995. Timber Engineering STEP 1. STEP lecture A5. Centrum Hout, The Netherlands.

Green, D.W. and D.E. Kretschmann. 1991. Lumber property relationships for engineering design codes. Wood Fiber Sci. 23(3):436- 456.

__________ and __________. 1997. Properties and grading of southern pine timbers. Forest Prod. J. 47(9):78-85.

Hope, M. 1993. Log grading: Development and practical applications. *In*: Proc. Log Home Design, Engineering, and Marketing Conference. WUD Pub. No. 93-1. T. Gorman, ed. College of Forestry, Wildlife and Range Sci., Univ. of Idaho, Moscow, ID.

Kretschmann, D.E. and D.W. Green. 1999. Mechanical grading of oak timbers. J. Mat. Civil Engineering 11(2):91-97.

Murphy, J.F. 2000. Transverse vibration of a simply supported frustum of a right circular cone. J. Test. Eval. 28(5):415-419.

Ranta-Maunus, A. (ed). 1999. Round small-diameter timber for construction. Final report. Project FAIR CT 95-0091. VTT publication 383. Tech. Res. Center of Finland, Espoo, Finland. 210 pp.

Smulski, S.G, ed. 1997. Issue on machine-graded-lumber. Wood Design Focus 8(2):1- 24.

Timber Products Inspection, Inc. (TP). 1987. Log home grading rules, including supplements 1-5. TP, Conyers, GA.

Wang, X., R.J. Ross, J.A. Mattson, J.R. Erickson, J.W. Forsman, E.A. Geske, and M.A. Wehr. 2001. Several nondestructive evaluation techniques for assessing stiffness and MOE of small-diameter logs. Res. Paper FPL-RP-600. USDA Forest Serv., Forest Prod. Lab., Madison, WI. 12 pp.

Wolfe, R and C. Moseley. 2000. Small-diameter log evaluation for value-added structural applications. Forest Prod. J. 50(10):48-58.