MEASURING SHEAR MODULI IN WOOD WITH SMALL TENSION AND COMPRESSION SAMPLES

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ABSTRACT

Shear moduli in wood were measured on tension and compression specimens by means of rosettes of specially made bonded resistance strain gages. Angle α between the load axis and the longitudinal, L, direction for matched specimens were 10, 20, and 45 degrees. Better results were achieved with the tension specimens than with the compression specimens probably because of end restraint of the compression specimens. Although there were only small differences among shear moduli measured at angles α of 10, 20, and 45 degrees, the 20-degree specimens usually had shear moduli values that were closest to those from plate specimens. The maximum strain in each test specimen was not parallel to the load axis: for most specimens it was calculated by strain gage rosette analysis to be at an angle between 20 and 30 degrees to the load axis. Although instrumentation with strain gages is time-consuming, the specimens are easier to cut accurately from wood than are the plate specimens that are sometimes used.

Keywords: Shear modulus, modulus of rigidity, wood, tension test, compression test.

NOTATION

i = subscript L, R, or T
j = subscript L, R, or T
A = cross-sectional area of specimen
E_i = Young's modulus in the i direction
G_{ij} = shear modulus in the ij plane; $i \neq j$
L, R, T = longitudinal, radial, and tangential axes
$M_A = \epsilon_A/\sigma_1$
$M_B = \epsilon_B/\sigma_1$
$M_C = \epsilon_C/\sigma_1$
P = axial load parallel to specimen length
α = angle between longitudinal grain direction L and load P
$\epsilon_A, \epsilon_B, \epsilon_C$ = strains at 0°, 45°, and 90° to load P

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ν_{ij} = Poisson's ratio: ratio of strain in the i direction to that in the j direction for loading in the i direction; i $\neq$ j

σ_1 = P/A

ζ_P = angle between the direction of maximum principal strain and the axial load P

A way is being sought to predict the relatively undocumented shear moduli for wood as a function of its other elastic constants so that the shear deflection of wood structural members can be more accurately determined. In order to establish a pattern of relationships, a reliable method for measuring shear modulus is needed. A common way of determining shear modulus for solid wood has been the use of a plate as described in ASTM D 3044-76 (1989). This plate, which was intended for plywood, is relatively difficult to machine from solid wood because of its size and the aligning of orthotropic axes with the plate surfaces. A proven method for measuring shear modulus in synthetic composites has been through the loading of tension specimens where the fiber axis is at an angle to the load axis; i.e., an off-axis tension specimen. The object of this paper is to describe practical specimens operating on this principle that can be used with wood.

An early paper on the use of off-axis tensile specimens for measuring shear modulus of composites was written by Greszczuk (1966). He bonded three electrical resistance strain gages in a rosette pattern for his measurements: one strain gage was oriented parallel to the load axis, one was at 45 degrees to the load axis, and the third one was perpendicular to it. Shear modulus measurements were shown for tests on a fiber glass laminate where the angle between the fiber axis and the load varied form 0 to 90 degrees at 15-degree intervals on a series of specimens. Two samples each were tested at 15 degrees, 30 degrees, and 75 degrees; only one was tested at 45 degrees. Shear moduli for the pair of samples at 30 degrees differed by 9%, while differences between the other paired samples were 2% and 3%. The range of shear moduli for all angles of loading between 15 and 75 degrees was the same as the two values at the 30-degree loading, which gave the highest and lowest values. Greszczuk also presented equations for calculating E_L and E_T for the off-axis specimens.

Off-axis tension and compression specimens have been investigated for use on wood. Radcliffe (1955) suggested this method using compression specimens but did not provide any test data. Schuldt (1972) did extensive tests with tension specimens where the angle between the load direction and the wood grain was 20 degrees. Cross-sectional dimensions of his specimens were 1.125 inches by 0.75 inches; they had a length of 8 inches. Strain measurements were made at angles of 0°, 45°, and 90° to the load axis by means of steel clip gages having electrical resistance strain gages bonded to them. He noted that he had difficulty obtaining displacements that were a linear function of the applied load because of problems associated with the attaching of the clip gages to the specimens, the weight of connecting cables, and relative humidity control in the test area. All except one of his experimentally derived values for shear moduli in the LR and LT planes were larger than values obtained from plate testing. The maximum difference was 21%.

Ebrahimi and Sliker (1981) described off-axis tension tests made on wood at angles of L-axis to load direction of 20, 35, 50, and 65 degrees. Strains were measured with electrical resistance strain gages mounted at 0, 45, and 90 degrees to the load axis. The specimens used were large (32 inches by 4 inches by ½ inch) to accommodate a special strain gage designed particularly for wood. Shear moduli from the 20-degree specimens most closely matched values obtained from ASTM D 3044-76 (1978) plate tests and were within ±10% of those from plate tests. Except for one specimen, this was true for the 35-degree specimens also. Comparisons were not as good at the other two angles. According to Ebrahimi (1979), the rate of loading appeared to have little effect on shear moduli.

A key element in the off-axis specimens is the strain measuring system. Strain gages bonded directly to wood provide accurate measurements if gage types are properly selected. Commercial gages with paper or polyimide backing can reinforce low modulus substrates so that indicated strains are not the actual ones. In addition, enough heat can be generated in the compact grids of many commercial gages to cause thermal expansion of nonconducting substrates and also shrinkage of substrates such as wood, which contain water. Sliker (1967) describes how to make a free-filament type of gage that has neither of these problems, but that requires a large specimen size to accommodate its two-inch length. In a recent paper, Sliker (1989) used relatively small free-filament gages to measure Poisson's ratios. The smaller external dimensions of these gages suggested the possibility of making smaller off-axis tension and compression specimens than those made previously by Ebrahimi (1979).

PROCEDURE

Two sets of off-axis specimens were made. One set was designed to be loaded in compression and the other was for loading in tension. Specimen dimensions and strain gage placements are shown for the compression specimens in Fig. 1 and for the tension specimens in Fig. 2. Nominal angles of load to grain for both sets of specimens were 0°, 10°, 20°, and 45°. In addition, tension specimens were made for loading at 90° to the grain. Shear moduli for the compression specimens and for the sugar pine specimens loaded in tension were measured in the LT plane. Measurements of shear moduli for the remaining tension specimens were in the LR plane.

Wood for making the test specimens was material that had been stored in the test room atmosphere of 68 F and 65% relative humidity for a long time. Equilibrium moisture contents for different boards were between 7.4 and 12.5% at these conditions. However, comparisons of shear moduli were made only among specimens at the same moisture content since all the specimens for a given set were cut from a single board or plate. Scientific names for the species used are listed in Table 1. Species used for each series of tests are listed in Tables 2 and 3. Compression specimens were made from wood remaining from other projects. The tensile specimens were cut from plates tested over ten years ago by Ebrahimi (1979). The dimensions of these plates were 14 inches by 14 inches by 0.5 inches. Before making the tension specimens, the plates were tested again by the current authors according to ASTM Standard D 3044-76 (1989) in order to obtain plate shear modulus values. Because of problems with grain orientation, 45° off-axis specimens were not cut from the sugar pine plates. In addition, ν_{LT} could not be measured on the 0° specimens of sugar pine because the wider surfaces of the specimens were not true tangential surfaces.

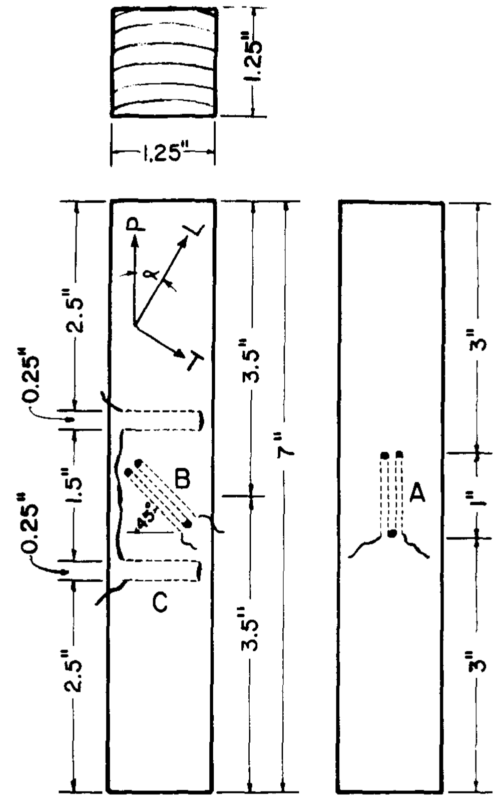

FIG. 1. Compression specimen for measuring shear modulus in the LT plane. Longitudinal direction L makes angle α with load direction P. A, B, and C are strain gages mounted at 0°, 45°, and 90°, respectively, to the load axis. One-mil strain sensitive wires are shown as dashed lines. Solid connecting wires are 12 mils in diameter.

Free-filament strain gages, which were manufactured by hand in the laboratory as described by Sliker (1967, 1989), were mounted on the test specimens in various patterns. For the specimens to be loaded at other than 0° or 90°, there were three pairs of gages per specimen. Gages were mounted at 0°, 45°, and 90° to the load axis. Specimens to be loaded at 0° to the grain had gages mounted at 0° and 90° to the grain, and specimens to be loaded at 90° to the grain had gages oriented parallel to the load axis only. For each of the above-mentioned gages, a second gage was mounted on the opposite face of the test specimen and connected in series with it. Gages oriented at 90° to the load axis were made of four parallel one-inch-long strands of one-mil diameter strain gage wire as shown in Figs. 1 and 2. Gages at 0° and 45° to the load axis consisted of 4-inch lengths of strain gage wire looped around pins to make a one-inch gage length as described by Sliker (1989). The smallest strains were recorded at 90° to the load axis, and therefore required the greatest care in their measurement. It was assumed that the strain parallel to the specimen length would average the same on the two side surfaces as it would on the front and the back containing the 0° and 90° gages.

Two different loading methods were used for the off-axis specimens. The compression specimens with a 45° angle of axis to load and all the tension specimens

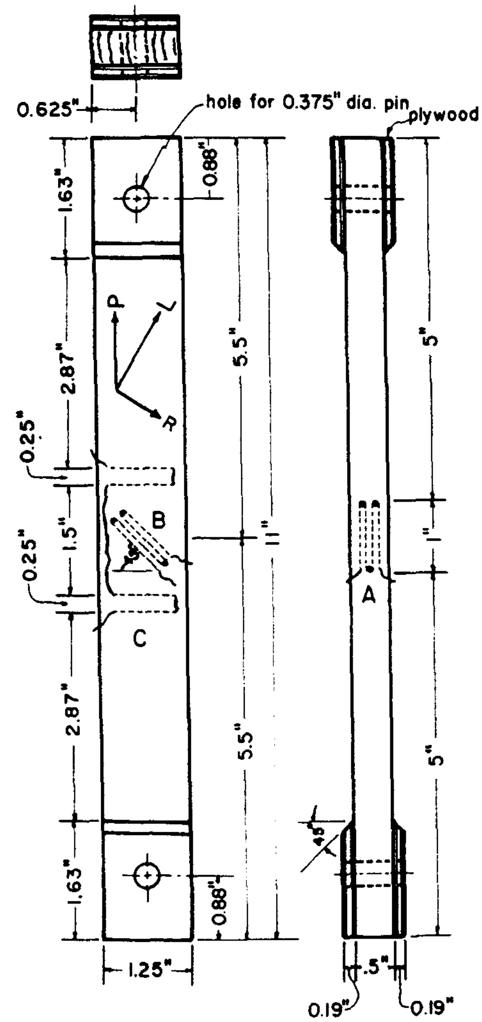

FIG. 2. Tension specimen for measuring shear modulus. Longitudinal direction L makes angle α with load direction P. A, B, and C are strain gages mounted at 0°, 45°, and 90°, respectively, to the load axis. Shear modulus was in the LR plane for all tension specimens except sugar pine where measurements were in the LT plane. One-mil diameter strain sensitive wires are shown as dashed lines. Solid connecting wires are 12 mils in diameter.

except those with a 90° angle of axis to load were loaded with a series of 10 ten-pound weights. The method of loading was essentially described in a previous publication (Sliker 1989) except that a compression cage was not needed for the tension specimens. After the application of each weight, strain readings were recorded. Time for total load application of 100 pounds was less than three minutes. The method for testing the 90° tension specimens was the same except that five-pound weights were used. All of the compression samples except the 45° off-axis specimens were tested in a compression mode in an Instron testing machine with a crosshead speed setting of 0.002 inches per minute. Figure 3 is a sketch of a compression specimen in the compression cage. Strain and load read-

TABLE 1. *Common and scientific names for species used in tests.*

Common name	Scientific name
	Softwoods
Redwood	*Sequoia sempervirens* (D. Don) Endl.
Sugar pine	*Pinus lambertiana* Dougl.
White pine	*Pinus* species (either *Pinus strobus* L. or *Pinus monticola* Dougl. ex D. Don)
	Hardwoods
Basswood	*Tilia americana* L.
Cottonwood	*Populus deltoides* Bartr. ex Marsh.
White ash	*Fraxinus* species (either *Fraxinus americana* L. or *Fraxinus pennsylvanica* Marsh.)
Yellow-poplar	*Liriodendron tulipifera* L.

ings were taken at increments of 50 microstrain as indicated by the gage oriented parallel to the specimen length until a total of 500 microstrain was reached. In some cases, this took as long as 10 minutes. The slow loading time allowed for more accurate reading of the strain meters by individuals.

Calculation of shear moduli from the off-axis specimens was accomplished with the equation presented by Greszczuk (1966, 1969):

$$G = \frac{1}{2(M_A - M_C) + (2M_B - M_A - M_C)(\cot\alpha - \tan\alpha)} \tag{1}$$

The angle between the load axis and the maximum strain was calculated according to the following formula in a book by Perry and Lissner (1962):

$$\zeta_p = \frac{1}{2}\tan^{-1}\left[\frac{2M_B - (M_A + M_C)}{M_A - M_C}\right] \tag{2}$$

RESULTS AND DISCUSSION

Elastic constants determined from the different types of loadings, moisture content of test specimens and the specific gravity of the woods at the test moisture contents are presented in Tables 2 and 3. Shear moduli calculated from the tension tests averaged 17% greater than those from the plate tests. The ratio of average shear moduli from tension and compression tests to E_L was between 0.064 and 0.089 with the exception of that for redwood which was 0.17. Ratios of G_{LR} and G_{LT} to E_L for a variety of species ranged from 0.037 to 0.115 in a Wood Handbook table (U.S. Forest Products Laboratory 1987).

The curves of strain versus stress (M_A, M_B, M_C) were better for the tension specimens than for the compression specimens. Points fell in a straight line for all the tension data except for the measurement for M_B for yellow-poplar 2 loaded at 20 degrees to the L axis. About one-third of the strain-stress curves for M_B and M_C for the compression specimens had irregularities so that the exact slopes of the curves were open to some interpretation. This was particularly true for the white pine specimens at 10 degrees loading in compression. Norris (1955) describes how shear distortion can be restrained in an off-axis compression specimen by its contact with the rigid heads of a testing machine. This was probably the

TABLE 2. *Elastic constants, moisture content and specific gravity for specimens tested as a plate and in tension with angles between longitudinal direction L and load P of 0°, 10°, 20°, and 45°.*

Species	E_L	E_R	G_{LR} from ASTM D 3044-76 plate test	G_{LR} from tension test at indicated angle to grain: 10°	20°	45°	ν_{LR}	MC (%)	Specific** gravity @ test MC	Average G_{LR} in tension/ ASTM plate G_{LR}	Average G_{LR} in tension/E_L
	(10^6 psi)										
Redwood	0.833	0.0197	0.1235	0.1618	0.1470	0.1509	0.40	9.4	0.36	1.24	0.17
Basswood 1	1.828	0.0798	0.0918	0.1073	0.0959	0.1029	0.38	10.7	0.41	1.11	0.056
Basswood 2	1.469	0.0871	0.0873	0.1176	0.0999	0.1048	0.45	10.2	0.41	1.23	0.073
Yellow-poplar 1	1.838	0.1255	0.1355	0.1624	0.1445	0.1583	0.41	11.7	0.48	1.14	0.084
Yellow-poplar 2	1.754	0.1251	0.1372	0.1428	0.0895†	0.1517	0.37	11.6	0.48	1.07	0.084
Sugar pine 1*	1.383	0.0776	0.1000	0.1267	0.1208	—	—	9.1	0.39	1.23	0.089
Sugar pine 2*	1.335	0.0818	0.0979	0.1104	0.1211	—	—	8.8	0.37	1.18	0.087
									Average	1.17	

* Tested in LT plane: values for elastic constants are for E_L, E_T, and G_{LT}.
** Based on oven-dry weight and volume at test moisture content.
† Left out of averages.

TABLE 3. *Elastic constants, moisture content, and specific gravity for specimens tested in compression with angles between longitudinal direction L and load P of 0°, 10°, 20° and 45°.*

Species	E_L	Shear modulus G_{LT} from compression at angle 10°	20°	45°	ν_{LT}	MC (%)	Specific* gravity @ test M_C	Average G_{LT} in compression/ E_L
	(10⁶ psi)							
Sugar pine	1.401	0.114	0.104	0.115	0.47	11.3	0.37	0.079
White pine	1.177	0.1340**	0.0862	0.0866	0.41	7.4	0.34	0.073
Cottonwood	1.420	0.0996	0.0931	0.0816	0.65	12.5	0.36	0.064
Yellow-poplar	1.684	0.1153	0.1010	0.1125	0.59	9.5	0.47	0.065
White ash	1.500	0.1361	0.1588	0.1486	0.50	10.7	0.62	0.099

* Based on oven-dry weight and volume at test moisture content.
** Left out of average.

case here. Our conclusion is that the tensile specimens are better than the compression specimens for measuring shear modulus because of their freedom from load-head induced shear distortion.

If Eq. (1) worked perfectly for calculating shear moduli, it would be expected that the angle of L-axis to load would not affect the value obtained: differences in shear moduli among specimens of the same material would be due only to experimental error. The experimental error for wood specimens should be greater than that for a fiberglass laminate because of the greater variability of wood structure, the alignment of strain gages, the curvature of growth rings, the orientation of rays perpendicular to the main cell axis, and the imperfect alignment of orthotropic axes with specimen axes. Discounting the values for the white pine in compression, at 10 degrees off-axis loading and yellow-poplar 2 at 20 degrees in tension, the maximum difference between wood samples in a given series was 18% or less as compared to the 9% difference Greszczuk (1966) experienced with a fiberglass laminate.

Additional observations can be made in comparing data from wood tests with those from the fiberglass laminate. One of these points is that the ratios of shear moduli to E_L and of E_T (or E_R) to E_L are much smaller for the wood than for the fiberglass laminate mentioned previously. For the fiberglass laminate, the ratio of G_{LT} to E_L was about 0.20 and the ratio of E_T to E_L was about 0.33. For the wood in this report (with the exception of the redwood), the ratios of shear moduli to E_L were between 0.056 and 0.099 or 2 to 3 times smaller than that for the fiberglass laminate and the ratios of E_T (or E_R) to E_L were between 0.024 and 0.071 or 4 to 14 times smaller than that for the fiberglass laminate.

The magnitude of differences between elastic constants for wood and fiberglass laminates may explain some differences found in measurements. In Greszczuk's paper M_A was always greater than M_B and of the same sign; M_C was smaller than M_A and M_B and of opposite sign. For the wood in this report, M_B was frequently larger than M_A; i.e., the strain at 45 degrees to the load axis was often greater than that parallel to the load axis. Occasionally for the wood, M_A, M_B, and M_C would all have the same sign. M_A, M_B, and M_C are given in Table 4 for tension specimen basswood 1; the 20-degree specimen shows positive tensile strains at all three angles of measured strain to the load axis.

The angle ζ_p at which the maximum strain occurred in each specimen was calculated using Eq. 2. Values for ζ_p are listed in Table 5. For specimens with

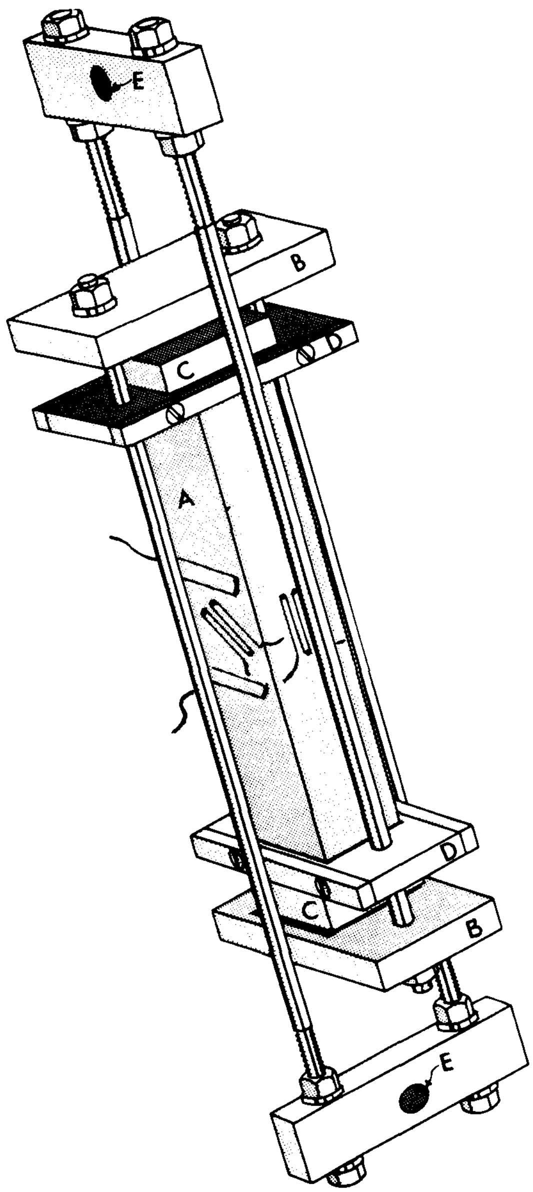

FIG. 3. Compression specimen A in compression cage. B is end block. C is end bearing block. D is centering guide. E is hole for metal dowel connection to universal joint. Ball bearing is centered between B and C at each end.

angles of 10, 20, and 45 degrees, the maximum strain was calculated to be at an angle between 14 and 35 degrees from the load axis with the great majority of the values being between 20 and 30 degrees. In this respect, there may be some significance to the fact that the 20-degree off-axis specimens gave the lowest estimate for the shear moduli and the ones closest to those obtained from plate shear tests for the first four series of tests in Table 2: the 20-degree specimens for

TABLE 4. *Slopes of strain per unit stress data for tension specimen basswood 1.*

Angle of load to grain (degrees) α	M_A	M_B (10^{-6}/psi)	M_C	G_{LR} (10^6 psi)
0	0.547			
11.25	0.857	1.119	−0.137	0.1073
21	1.861	2.504	0.0686	0.0959
45	4.591	4.743	−0.0266	0.1029
90	12.54			

these series provided shear moduli that were 3 to 18% smaller than those from the 10- and 45-degree specimens and which were 4 to 19% larger than those from the plate shear test. Since there may be some variation of shear modulus with angle α, an angle of L-axis to load axis between 20 and 30 degrees would appear to provide a minimum value for the shear modulus that most closely approaches that from the plate shear tests.

SUMMARY AND CONCLUSIONS

Off-axis tension and, less favorably at this point, compression specimens can be used for measuring shear moduli in wood. Shear moduli from tension specimens averaged 17% larger than those from plate tests with which they were matched. Careful measurements of strain and angle of load to grain have to be made to get accurate results. In this project, strain versus stress measurements on tension specimens were more accurate than those on compression specimens because of their freedom from load-head induced shear distortion. For many tension specimens, an angle of 20 degrees between the L-axis and the load axis gave a value for shear modulus that was closer to that from the plate method than did off-axis specimens tested at angles of 10 degrees or 45 degrees. Calculated maximum strain in the off-axis tension and compression specimens was at an angle ζ_p between the L-direction and the load axis of 14 to 35 degrees. For the above reasons it is suggested that best results can be obtained from off-axis tension specimens having an angle α between 20 and 30 degrees to the load axis.

The off-axis specimens will probably be used mostly for basic studies until a simpler strain measuring system is available. They would also be restricted to

TABLE 5. *Angle between load axis and direction of maximum calculated strain (ζ_p) for tension and compression specimens loaded at angles to the grain α of 10, 20, and 45 degrees. See Eq. 2 for calculation of ζ_p.*

Tension specimens				Compression specimens			
	Angle ζ_p in degrees at indicated angle α				Angle ζ_p in degrees at indicated angle α		
Species	10°	20°	45°	Species	10°	20°	45°
Redwood	14	16	14	Sugar pine	21	29	25
Basswood 1	28	30	23	White pine	21	35	30
Basswood 2	26	28	18	Cottonwood	30	34	30
Yellow-poplar 1	21	27	18	Yellow-poplar	23	32	23
Yellow-poplar 2	24	34	17	White ash	21	22	16
Sugar pine 1	20	30	—				
Sugar pine 2	24	26					

straight grained woods. An advantage over plate specimens is that they are easier to align with the orthotropic axes in wood and can be made from smaller sized pieces of wood.

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