SHEAR TESTS OF WOOD USING V-NOTCH BEAM AND SQUARE PLATE SPECIMENS

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ABSTRACT

Investigation of the V-notch beam specimen for shear testing as developed in Rumania showed that it is not generally applicable to the determination of shear strength of wood. The square plate twisting test performed better, and optimum results were obtained when the ratio of side length to plate thickness was on the order of 12 to 14. The plate twisting test was subject to a very substantial size factor that limits the usefulness of the test without standardization of specimen size.

Additional keywords: Douglas-fir, size factor, rolling shear, shear strength, shear parallel-to-grain, shear perpendicular to grain.

INTRODUCTION

One of the most difficult problems in materials testing is the determination of shear strength. In wood, the problem is further compounded by a high degree of anisotropy. Difficulties in the shear test arise primarily in finding practical ways of achieving a state of pure shear without excessive stress concentrations, and attempts to solve the problem have resulted in many widely differing specimen designs (Ramberg and Miller 1953; Iosipescu 1967; Kollmann and Côté 1968).

Shear stresses in wood may occur in one of three principal planes, such as the radial-longitudinal plane. In the case of pure shear, failure will then occur in the less resistant of the other two planes. With radial-longitudinal shear stress, for instance we would expect failure to occur in the tangential-longitudinal plane (shear parallel to grain) and not in the radial-tangential plane (shear perpendicular to grain). In most practical tests, however, loads are applied in such a way that they force the failure to occur in a predetermined plane. This gives rise to six principal modes of shear failure. They may be divided into three groups: shear parallel to grain, rolling shear, and shear perpendicular to grain. Table 1 shows the type of shear stress and the failure plane for each of the six modes.

Keylwerth (1945) has made tests in all six modes on several species. Shear strength perpendicular to grain was highest and rolling shear strength lowest; within each of the three groups the differences were comparatively minor. Recently, Goodman and Bodig (1971) used plate shear specimens to determine shear strength in each of the three principal planes of wood for several species. For a shear stress in the L-R plane, failure might be either in the L-T (shear parallel to grain) or T-R (shear perpendicular to grain) planes (Table 1); and since the specimen is free to fail in either plane it will fail in the plane offering the least resistance, i.e., in shear parallel to grain. A similar situation exists for shear stress in the L-T plane. For shear stress in the R-T plane, failure can occur only by rolling shear. Surprisingly the results of Goodman and Bodig (1971) indicated higher strength in rolling shear than in shear parallel to grain. Because other methods of test might have underestimated the strength of wood in rolling shear, an investigation of the plate twisting test as shear test method for wood in more detail, combined with a study of the V-notch beam test developed in Rumania by Iosipescu (1966, 1967), was decided upon.

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TABLE 1. *Principal modes of shear failure in wood*

Type of shear	Shear stress	Failure Plane
Shear parallel to grain	σ_{LR} σ_{LT}	L-T L-R
Rolling shear	σ_{TR} σ_{TR}	L-T L-R
Shear perpendicular to grain	σ_{LR} σ_{LT}	T-R T-R

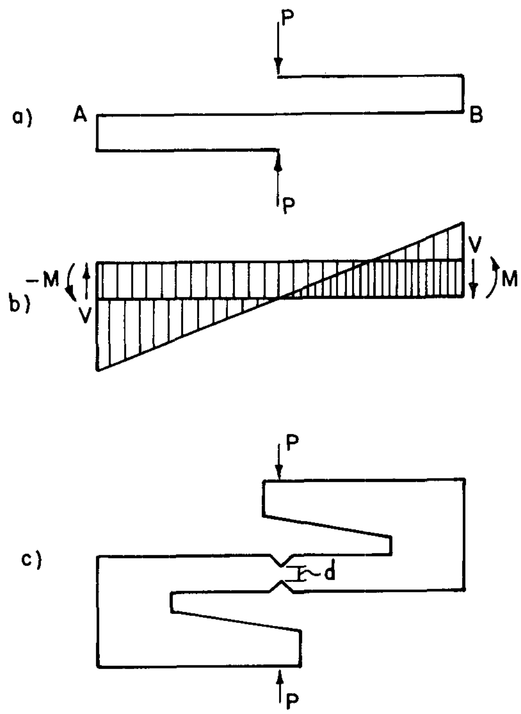


FIG. 1. S-shaped shear specimen: (a) loading scheme; (b) shear and moment diagrams for central beam portion of the specimen; and (c) specimen configuration including V-notches to localize failure at the point of zero moment.

V-NOTCH BEAM SPECIMEN

The V-notch beam specimen for shear testing (not to be confused with the notched beam specimen proposed by Radcliffe and Suddarth (1955) where the neutral plane is reduced by notching to induce horizontal shear failure) was developed by Iosipescu (1966, 1967) starting with the concept of an S-shaped specimen as shown in Fig. 1,a. With this configuration, the central portion of the specimen represents a beam with constant vertical shear and a bending moment that is positive at one end and negative at the other, and hence is equal to zero at midspan (Fig. 1,b). Notches were introduced in order to insure failure at this cross section (Fig. 1,c); and photoelastic experiments showed that the section between notch roots was subjected to uniformly distributed pure shear. The optimum depth of the notches was found to be 22.5 to 25% of the total depth (Iosipescu 1967).

In order to avoid the intricacies of the S-shaped specimen, Iosipescu (1966) introduced specimen holders to be used with a simple notched beam, as shown schematically in Fig. 2. Alternately, loads may be introduced as shown in Fig. 3 (Voiculescu 1970), which leads to the same moment and shear diagrams in each case. Furthermore, the stress distribution over the central portion of the beam is of the same type as for the S-shape specimen.

Voiculescu used the method shown in Fig. 2 to test a series of wood specimens and obtained satisfactory results in 88% of the tests. Average shear strength values of individual groups, however, ranged from 16 to 62% of the values obtained on matching material with the Rumanian standard method, a test somewhat similar to the ASTM block shear test (ASTM 1972).

The maximum shear stress and the maximum bending stress of the configuration

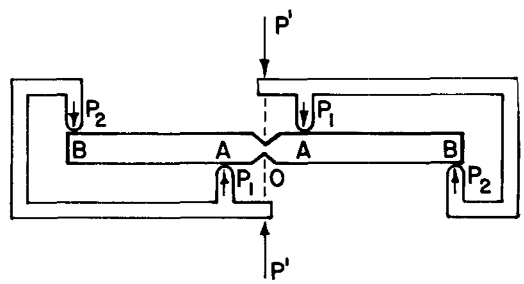


FIG. 2. Schematic of V-notch beam shear specimen with compact loading fixtures.

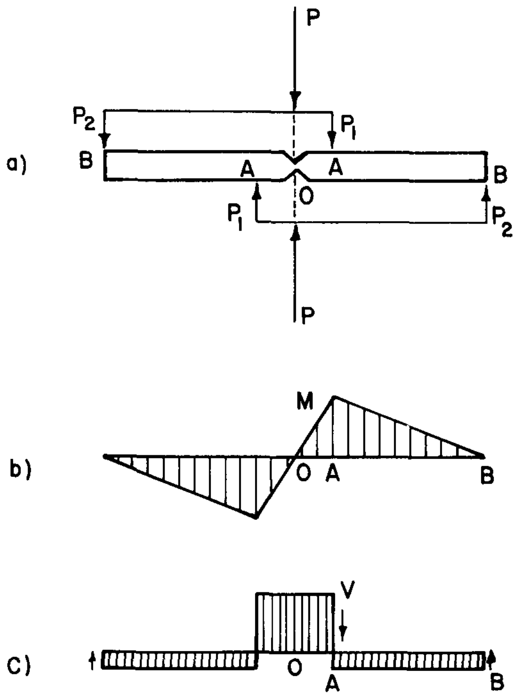


FIG. 3. Alternate loading scheme for V-notch beam shear specimen: (a) loading configuration, (b) moment diagram, and (c) shear diagram.

shown in Fig. 3 may be calculated as follows by strength of materials methods. Equilibrium requires that:

$$P = P_1 + P_2 \tag{1}$$

and

$$P_1 m - P_2 n = 0 \tag{2}$$

where P = applied load

P_1 and P_2-resulting loads at points A and B, respectively
m = distance O-A
n = distance O-B

From equations (1) and (2), the maximum bending moment, M, can be found:

$$M = \frac{m(n-m)}{(n+m)} P \tag{3}$$

and hence the maximum bending stress, σ at extreme fiber will be:

$$\sigma = \frac{Mc}{I} = \frac{m(n-m)\ 6P}{(n+m)wh^2} \tag{4}$$

where c = distance from neutral plane to extreme fiber, I = moment of inertia, w = beam width and h = beam depth outside the notch. The vertical shear, V, at midspan is given by:

$$V = P_1 - P_2 \tag{5}$$

and thus the shear stress τ is

$$\tau = \frac{V}{wd} = \frac{(n-m)}{(n+m)} \frac{P}{wd} \tag{6}$$

where d = the net (minimum) depth of the beam at the notches. Since the specimen should fail in shear and not in bending, the ratio of bending stress to shear stress is of interest, and is given by:

$$\frac{\sigma}{\tau} = \frac{6md}{h^2} \tag{7}$$

If we set d = h/2 as recommended, and note that for the recommended 90-degree notch the minimum value of m becomes m = h/4, it follows from Eq. (7) that under the most favorable conditions the maximum bending stress will amount to 75% of the shear stress. Since in testing in shear parallel to grain this will involve bending stresses perpendicular to the grain, the ratio may become a critical factor. For air-dry Douglas-fir, for instance, the published shear strength is 1160 psi (Forest Products Laboratory 1955), and we can estimate the bending strength from the tensile strength perpendicular to grain at 560 psi (Schniewind and Lyon 1973). Substituting the above values for m, d, and τ in Eq. (7), the calculated bending stress is 870 psi. This would lead us to expect failure in bending rather than in shear for the V-notch specimen.

If the loading configuration according to Fig. 2 is used, the maximum bending stress is given by:

$$\sigma = \frac{6mP'}{wh^2} \tag{8}$$

and the maximum shear stress is given by:

$$\tau = \frac{P'}{wd} \tag{9}$$

i.e., the relation to the applied load changes as compared to the configuration in Fig. 3. The ratio of bending stress to shear stress is still given by Eq. (7), since the moment and shear diagrams for the two cases are identical.

The optimum notch depth suggested by Iosipescu was based on work with isotropic materials. However, distribution of stresses in an orthotropic material will probably be different and therefore it might be worth while to consider greater notch depths, since this would tend to lower the ratio of bending to shear stress and in this respect improve the chances for a successful test. With a sufficiently deep notch, it is possible that bending stresses at intermediate points of the notch surfaces (i.e., at locations other than the point of maximum moment) might become the controlling factor. The distribution of bending stresses at the notch surfaces will now be investigated, using elementary theory. It is realized that this will give only a rough estimate since some of the assumptions are violated. For simplicity, the load configuration of Fig. 2 will be used although the result will apply equally well to the configuration of Fig. 3.

The bending stress at the extreme fiber within the notch (Fig. 4) will be given by a modified form of Eq. (8):

$$\sigma = \frac{6P'x}{w(d+2x)^2} \tag{10}$$

where $x \leq (h\text{-}d)/2$. Differentiating Eq. (10) with respect to x and setting the differential equal to zero shows that the maximum bending stress will occur when:

$$X = \frac{d}{2} \tag{11}$$

(provided that $0 < d \leq h/2$). Combining Eqs. (10) and (11), and taking the ratio of bending and shear stress as in Eq. (9) we obtain:

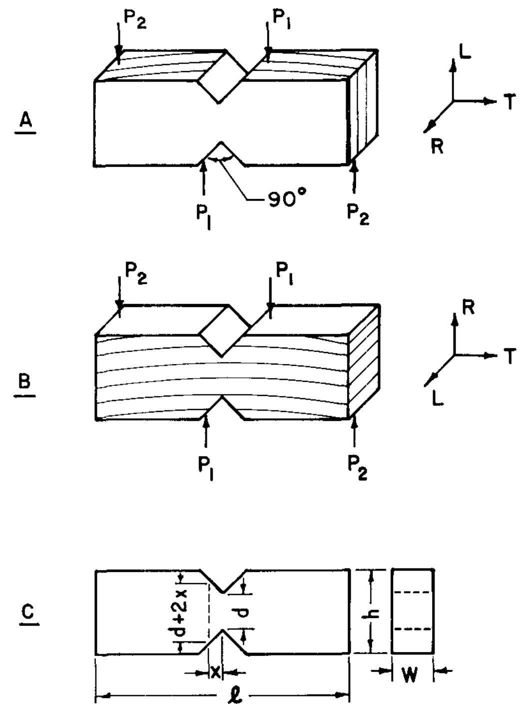


FIG. 4. V-notch beam specimens used in present study: (a) shear stress σ_{LT}, failure plane L-R (shear parallel to grain); (b) shear stress σ_{RT}, failure plane L-R (rolling shear); and (c) definition of specimen dimensions.

$$\sigma = 0.75\ \tau \tag{12}$$

In other words, there is no prospect of improving the ratio between bending and shear stresses by deepening the notches.

A series of tests were made on air-dry Douglas-fir using the load configuration of Fig. 3 and the specimen types illustrated in Fig. 4,a and b. Specimen dimensions were l = 3.125 inch, h = 1.5 inch, w = 0.75 inch, and two notch sizes corresponding to d = 0.75 and d = 0.25 inch.

When testing in shear parallel to grain (Fig. 4,a) using the recommended notch size, it proved to be impossible to attain shear failures through the notches. Instead, bending failures occurred near the point of maximum bending moment (Fig. 5,a). This agrees with the analysis according to Eq. (7) and the properties of Douglas-fir. Deepening the notch only resulted in shift-

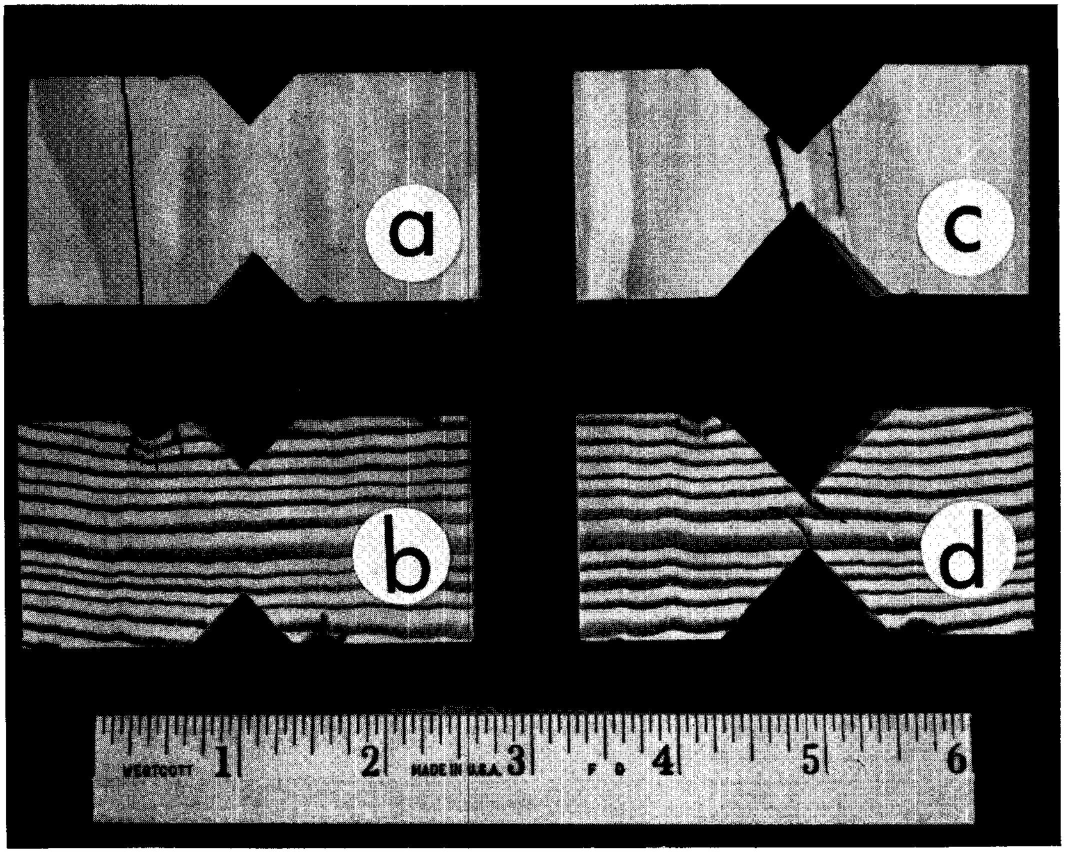


FIG. 5. Failures in V-notch beam specimens: (a) bending failure near point of maximum bending moment in specimen intended for shear parallel to grain, with recommended notch size; (b) failure by crushing under load points in rolling shear specimens; (c) bending failure within large notch in specimen intended for shear parallel to grain; and (d) rolling shear specimen with deep notches showing failure in crushing plus shear and/or tensile failures starting at the notch tip.

ing the location of the bending failure into the notch region. According to Eq. (11), the maximum bending stress is to be expected at a distance of ⅛ inch from the notch root. Specimens did indeed fail in the vicinity of this point, as illustrated in Fig. 5,c.

For rolling shear (Fig. 4,b) prospects were somewhat better, since the governing bending strength would be the same and strength in rolling shear is expected to be less. However, specimens with regular notch size failed by crushing under the load points (Fig. 5,b) and specimens with deep notches had failures that originated at the notch tips but did not propagate from tip to tip (Fig. 5,d). In this case there is also considerable crushing under the load points, and failures appear to be the result of tension rather than of shear.

The tests were intended as preliminary tests only. Because it was impossible to produce proper shear failures, and because the occurrence of bending failures was in agreement with analytical predictions, it was concluded that the V-notch beam specimen was not generally suitable for shear testing of wood, and so this method was discontinued.

This finding is in direct conflict with the results of Voiculescu (1970). Douglas-fir was not included in the species he tested,

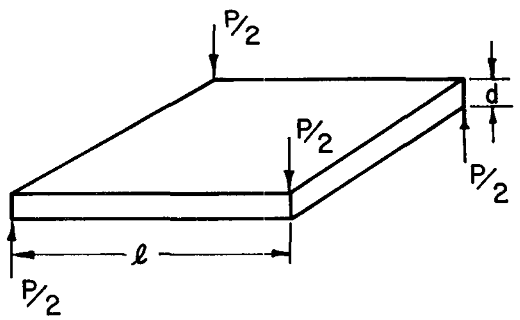


FIG. 6. Schematic of square plate twisting test.

but there is nothing unusual about either its shear strength or its tensile strength perpendicular to grain. On the other hand, the shear strength values obtained by Voiculescu were astonishingly low. It is not reasonable that a more nearly perfect state of pure shear in the specimen should result in drastic reductions in the apparent shear strength as compared to a less perfect test with stress concentrations. It is therefore likely that Voiculescu's results were influenced by some extraneous factor.

SQUARE PLATE SPECIMEN

The square plate shear test is made by twisting the plate specimen, as illustrated schematically in Fig. 6. The maximum shear stress, produced by the load, P, is given by:

$$\tau = \frac{3P}{2d^2} \tag{13}$$

where d is the plate thickness.

The plate shear test is used principally for determination of shear modulus. Recently, Goodman and Bodig (1971) used it for shear strength measurements although they pointed out that the solution used for calculating the maximum shear stress at failure is valid only within the linearly elastic region of material behavior. ASTM Standard D 3044 (ASTM 1972) specifies a ratio of side length to thickness (l/d) between 25 and 40 to 1 for shear modulus determinations of plywood, and Goodman and Bodig used a ratio of 24 to 1. Ramberg and Miller (1953) investigated the plate shear test in some detail and recommended an l/d ratio of 10 as the best compromise when tests extended beyond the elastic region. This indicated a need for experimental investigation of plate geometry in using the plate twisting test for wood. Two series of tests were therefore made: one investigating the effect of l/d ratio and the other the effect of absolute size.

Effect of l/d ratio

A series of experiments was made using five cants of air-dry Douglas-fir (nominal moisture content 12%). Plate shear specimens representing L-R, L-T, and T-R planes were cut from each cant. Plate side length was 3 inches in all cases, and plate thickness was varied to give l/d ratios of 5, 7, 10, 15, and 20. There were 10 replications of each condition, for a total of 150 specimens. In addition, block shear specimens were made from matching material of four of the five cants, and tests were made for each of the two modes of shear parallel to grain and for the two modes of rolling shear (Table 1). There were two replications of each test for a total of 32 block shear specimens. Plate shear tests were made following the applicable provisions of ASTM Standard D 3044 and all of the block shear tests (although rolling shear is not normally included) were made according to D 143 (ASTM 1972).

As might be expected, the L-R specimens failed in the L-T plane and the L-T specimens in the L-R plane (Fig. 7 shows larger specimens of another series but with similar failures). The R-T specimens would be expected to fail in rolling shear either in the L-R or L-T plane; actual failures were irregular and followed the pattern shown in Fig. 7. Similar failures occurred in all R-T specimens including one-piece specimens with perfect growth ring orientation.

Figure 8 shows the plate shear test data. There is considerable variability of the data points for the L-T and L-R specimens. The group means suggested a curvilinear relationship in both cases. Quadratic regression equations were computed, and the regression curves are shown in Fig. 8. The regres-

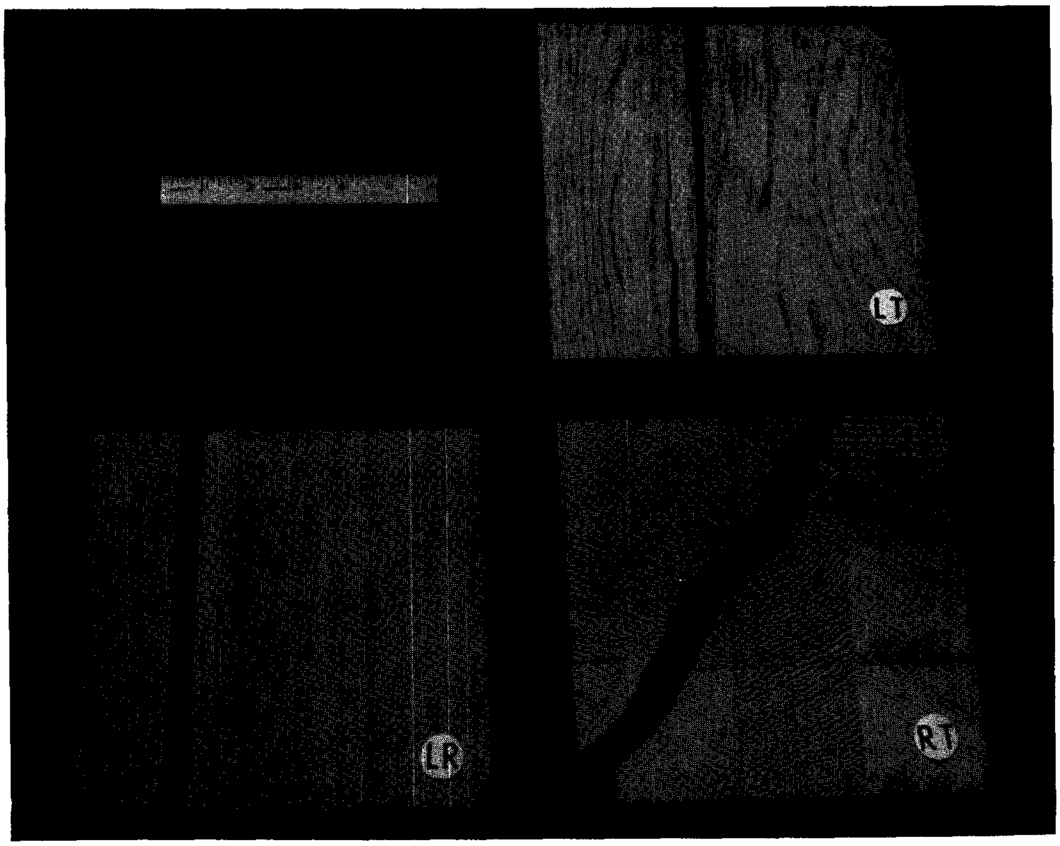


FIG. 7. Typical failures of plate shear tests; showing the three grain orientations used.

sion was not statistically significant, but the means show a definite trend of curvilinearity. The maxima in the regression curves are at l/d ratios of 12 and 14 for the L-T and L-R specimens, respectively, which is in the vicinity of the ratio of 10 suggested as optimum by Ramberg and Miller (1953). There is no consistent difference between values for L-T and L-R specimens, and the regression lines actually cross each other.

In contrast, the data from R-T specimens do not show any sign of curvilinearity. There is a linear trend of decreasing shear strength with increasing l/d ratio, but the linear regression shown in Fig. 8 was not statistically significant. The magnitude of the values representing rolling shear is well below the magnitude of data for shear parallel to grain.

The regression equations for predicting shear strength, Y, from the l/d ratio, X, are as follows:

L-R plates: $Y = 1027 + 109X - 3.89X^2$
L-T plates: $Y = 1219 + 101X - 4.08X^2$
R-T plates: $Y = 482 - 3.61X$

Table 2 shows the results of the block shear tests. The shear parallel to grain values agree closely with those published for coast-type Douglas-fir (Forest Products Laboratory 1955), and rolling shear values are considerably less by about the same factor as found by McMillin (1958) for green redwood. Munthe and Ethington (1968), using a different type of test, obtained shear strength parallel to grain 5.3 times greater than rolling shear in air-dry Sitka spruce. Table 2 also shows values from plate tests computed from the regression equations at an l/d ratio of 10. The

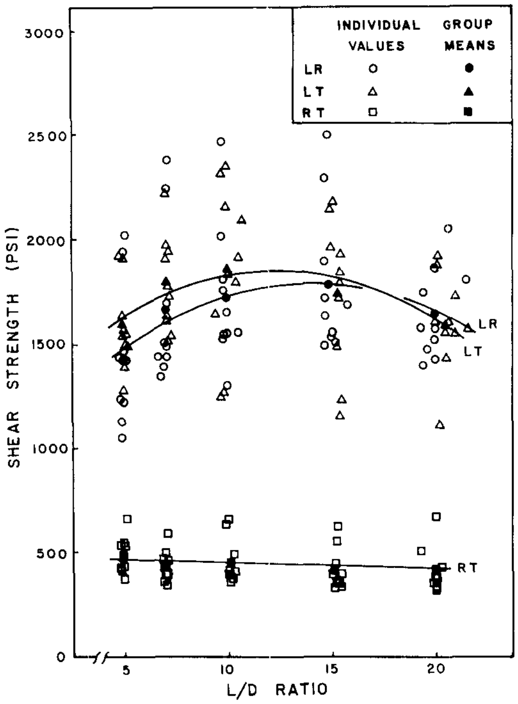


FIG. 8. Shear strength obtained from plate shear tests as related to l/d ratio, at constant side length of 3 inches.

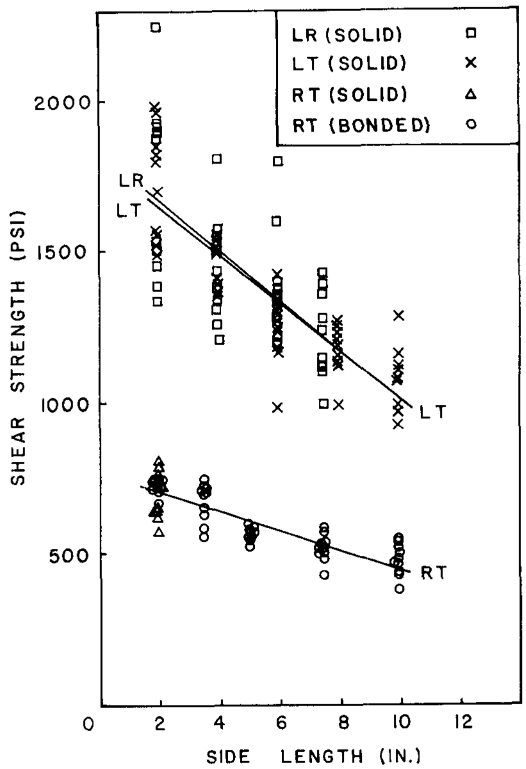


FIG. 9. Shear strength from plate shear tests as related to side length at constant l/d ratio of 10.

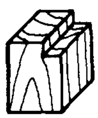
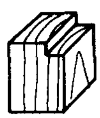
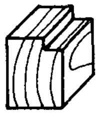
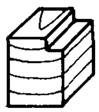
values from plate shear tests are higher for each mode of shear testing included in the table. In both tests, rolling shear values are less than one-third of the values in shear parallel to grain. Goodman and Bodig (1971) found higher values in rolling shear as compared to shear parallel to grain, which is contrary to general previous experience and the results of the present study. It therefore appears that the results of their R-T plate shear tests were subject to systematic experimental error.

Effect of plate size

Another series of tests was made with air-dry Douglas-fir to investigate the effect of specimen size. Tests were made for each of the three principal wood planes, but it was not possible to use matching material for the entire series. Hence three different sets of material were used, one each for L-T, L-R, and R-T plates. The l/d ratio in every case was fixed at 10, and plate size was varied from a side length of 2 to 10 inches. For L-T plates, side lengths of 2, 4, 6, 8, and 10 inches were used. L-R plates were represented by side lengths of 2, 4, 6, and 7.5 inches. R-T plates were glued up from 4 to 9 pieces, depending on size (Fig. 7). Side lengths of 2, 3.5, 5, 7.5, and 10 inches were tested. The 2-inch R-T plates were represented by two groups, one consisting of one-piece specimens and the other being glued up of four 1-inch squares. All tests in this series were replicated 10 times.

Figure 9 shows the results of the tests, and the most striking feature is a very strong dependence of shear strength on size. Linear regression lines were computed and are shown in the figure. L-T and L-R data, although not matched with each other, gave nearly identical regression lines. The R-T data again fall well below the others. The size effect is nearly the same for all three groups, since the shear strength for

TABLE 2. *Shear strength data from block shear tests*

Sketch	Type of shear	Shear stress	Failure plane	Block Shear Strength Mean (psi)	Block Shear Strength Standard deviation (psi)	Shear strength from comparable plate test*
	parallel to grain	σ_{LT}	L-R	1170	103	1820
	parallel to grain	σ_{LR}	L-T	1120	126	1730
	rolling	σ_{TR}	L-T	389	63	----
	rolling	σ_{TR}	L-R	351	73	445**

*Calculated from regression equations at $l/d = 10$

**Shear strength from R-T plates listed here because failure in the plate test is expected to be controlled by the weaker shear plane.

10-inch plates in any of the three planes is only about 60% of the strength of 2-inch plates.

Quadratic regression equations were also computed for the data, and the nonlinear terms were found statistically significant. However, the resulting curves were inconsistent, because of opposite curvature in one of the sets and only slight curvilinearity in the others. Hence the linear equations appear to represent the data most adequately. The equations were as follows:

$$\text{L-R plates: } Y = 1835 - 81.8X$$
$$\text{L-T plates: } Y = 1813 - 79.5X$$
$$\text{R-T plates: } Y = 765 - 31.4X$$

Specimen volume of the two extreme sizes is in the ratio of 125 to 1. Size effects in shear have apparently never been previously investigated, but comparisons might be made with other forms of loading. Size effects in bending are probably too complex to be included here. In tension, interpolation of the data of Sumiya and Sugihara (1957) indicates a reduction to 75% for the same volume ratio. In compression, the size factor depends also on absolute specimen volume and is very small in a comparable range of volume (Schneeweiss 1964).

One factor encountered in the larger sizes (side lengths of 8 and 10 inches) was a certain amount of crushing in the area of load application, although corner plates were used to achieve some load distribution. Crushing also was evident in the smaller sizes of the previous series where the l/d ratio was 5.

The mean rolling shear strength of 2-inch plates of solid wood was 690 psi compared to 720 psi for glued-up specimens. The slightly higher average for the bonded specimens, together with lack of failures in glue lines, demonstrates that shear strength is not lowered by bonding. Bonding might conceivably lead to an increase in shear strength by the disruption of natural shear planes in the composite specimen, but as indicated earlier, failure patterns were irregular and always followed the general pattern illustrated in Fig. 7. The small difference in shear strength that was observed did not prove to be statistically significant when the data were subjected to a t-test.

The large size factor explains the lack of agreement between results from block and plate shear tests as shown in Table 2. Although the material used for the block shear tests was not matched with the specimens used for the series on side length effects, appropriate block shear results were substituted in the linear regression equations to calculate the plate side length for which comparable values could be expected from both types of test. The resulting plate sizes were 8.7, 8.1, and 12.3 inches for L-R, L-T, and T-R plates, respectively. These could be considered practical specimen sizes. The pronounced size factor does raise a question regarding the potential usefulness of the plate twisting test for shear strength determinations. If the size factor in shear is indeed as large as indicated by this study, standardization of the test would be a prime requirement. There is, however, the possibility that the size factor is in part an artifact of the plate twisting test when carried to failure, and only partially related to such aspects as flaw distribution. This might be suggested as the subject of a future study.

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