IN-PLACE SHEAR STRENGTH OF WOOD BEAMS

Douglas R. Rammer, David I. McLean and William F. Cofer

This paper presents a summary of results from 3 series of experimental and analytical studies of the shear strength of solid-sawn wood beams. Beams in both green and dried conditions, three softwood species, and six sizes were investigated. Different loading configurations were used to study the influence of test setup on shear failures. Finite element and fracture mechanics analyses were performed to better understand the observed behavior. Beam shear strength was found to decrease with beam size. Equations were developed to characterize beam shear strength as a function of beam area or volume. The effects of beam splitting and checking on measured shear strength were found to be smaller than is predicted by current code procedures or by fracture mechanics. Measured shear strength was found to be influenced by test setup, possibly due to difficulty in obtaining shear failures with some loading configurations.

1. INTRODUCTION

In the US, shear design values for solid-sawn structural members are currently derived from small dear, straight grain specimens [1]. The values obtained from the clear specimens are reduced by a factor of safety, but unlike the design values for bending, no modification factors to account for member size effects are applied to shear strength values. Recent experimental studies, however, have indicated a strong relationship between a beam's shear strength and its size [2-6].

Wood beams will often develop splits and checks arising from drying as the member equilibrates to the surrounding moisture conditions or from repeated wet/dry moisture cycling. Because of the placement of the member within a structure and the local climate, the occurrence and degree of splitting are varied and difficult to quantify. Published shear design values [7] account for this uncertainty by assuming a worst case scenario, i.e, a beam that has a lengthwise split at the neutral axis. If the designer is confident that a member will not split, then the design shear value may be doubled. This approach may lead to inefficiently designed beams.

This paper presents results obtained from experimental and analytical investigations of the sheer strength of wood beams conducted cooperatively by Washington State University, the USDA Forest Products Laboratory and the US Federal Highway administration. Tests were conducted on both unsplit and split/checked beam specimens of five different sizes. Three softwood species were investigated: Douglas Fir, Engelmann Spruce and Southern Pine. Different loading configurations were used to study the influence of test setup on shear behavior. Finite element and fracture analyses were performed to gain insight into the observed behavior. The focus of the research is to obtain an improved understanding of the in-place shear strength of glued-laminated and solid-sawn wood beams for application to timber bridges.

2. BACKGROUND

Two approaches based on different failure criteria have historically been used to characterize the shear strength of wood beams: (1) a classical approach based on the strength of an unsplit member, with approximate adjustments made to account for *checks* and splits, and (2) a fracture mechanics approach based on the strength of a split or checked member.

2.1 Classical Approach for Wood Shear Strength

Design shear strength values are based upon strengths obtained using the standard ASTM shear block test [1] Alternative shear test procedures have been proposed [8], but the shear block test Is still the accepted method for determining wood shear strength values. However, researchers have questioned the applicability of shear block information to predict the actual strength of wood beams.

Huggins et al [9] found that beam shear strength depends on the shear span, defined as the distance from the support to the nearest concentrated load A series of Canadian studies investigated the effects of member size on shear strength. Several of these studies experimentally investigated shear strength using simply-supported beams [10]. Foschi and Barrett [11] approached shear strength with Weibull's weak link theory. They showed that shear strength varies with beam geometry and loading. Their work is the basis for the shear size effect relationship in the Canadian building code.

To account for splits and checks, design values may be adjusted by the "two-beam theory,' which was developed by Newlin et al [12] based on tests of built-up beams. This theory considers the position of the load, beam depth and span. The length and depth of checks are not considered. Researchers have since shown that the underlying assumptions of the two-beam theory are incorrect [13,14].

2.2 Fracture Mechanics Approaches

Barrett and Foschi [11] numerically analyzed the influence of splits in a beam under concentrated and uniform loading. Based on their analysis, they developed the following expression to express the mode II stress intensity factor, K_{II}:

$$K_{II} = \tau\sqrt{\pi a}H \tag{1}$$

where τ is the shear stress in MPa, *a* is the crack length, and *H* is a nondimensional factor that characterizes the loading and beam geometry.

Murphy [15] used a boundary collocation method to develop a simpler expression to evaluate the effects of beam splits under concentrated and uniform loading. His expression for concentrated loading is:

$$K_{II} = \left[-2.785\left(\frac{a}{d}\right) - 0.731\right]\frac{R}{b\sqrt{d}} \tag{2}$$

where *R* is the support reaction nearest the split, *a* is the split length, *d* is the beam depth, and *b* is the beam width. Equations (1) and (2) are approximately equivalent for all sizes of beams.

The previous two studies focused on determining the applicability of fracture mechanics to explain wood failure for simulated end-splits. In actual structural members, the geometry of the crack front is highly irregular. Sometimes the beam is completely split but more often the beam is checked on one or both sides. Further research into the application of fracture mechanics is needed to explain the effects of splits and checks.

3. TESTING PROGRAM

3.1 Initial Tests on Green Specimens

Douglas Fir, Southern Pine end Engelmann Spruce specimens with nominal sizes ranging from 51 mm by 102mm to 102mm by 356mm were tested to determine unchecked beam shear strength (see table 1). All specimens had moisture content levels of 20% or more.

Specimen Size (mm by mm)	Green unchecked material			Dry seasoned material			
	Douglas-Fir	Southern Pine	Engelmann Spruce	Southern Pine			Douglas-fir
				5-point	3-point	3-point[a]	
51 by 102	40	56	57	60	60	80	40
51 by 203	–	42	40	30	30	30	–
51 by 254	40	–	–	–	–	–	40
102 by 203	40	30	30	59	59	–	40
102 by 305	20	25	30	29	30	32	20
102 by 356	20	30	30	30	30	30	20

[a] simulated splits of 0.5*d. d, and* 1.5*d*.

Table 1 Size and number of initial beam sheaf specimens.

A two-span, five-point loading test, with each span length equal to five times the member depth, was selected to produce a significant percentage of beam shear failures. information recorded included maximum load, type and location of failures, material properties, beam geometry, moisture content and specific gravity. Further details of the Douglas Fir testing are published by Rammer et al [3] and for the Southern Pine and Engelmann Spruce testing by Asselin [4].

3.2 Initial Tests on Seasoned Specimens

Douglas Fir and Southern Pine specimens were tested in a seasoned condition at an average moisture content of 12%. Nominal specimen size ranged from 102mm to 102mm to 102 by 356mm for both species (see table 1). All Douglas Fir specimens contained natural splits and checks after 1-1/2 years of air-drying and were tested in a single-span, three-point loading setup with a center-to-center span length of five times the member depth. The three-point Configuration was used to locate the split in the high shear force region.

Three different tests were conducted on the Southern Pine specimens that were air-dried for 1 year before conditioning to 12% moisture content. First, a five-point loading setup was used to determine dry shear strength. Second, a three-point loading setup, with a center-to-center span length of five times the member depth, investigated the influence of natural checks and splits on shear strength. Finally, a three-point loading setup was used on specimens with saw kerfs cut into both ends of the beam et mid-depth in order to examine the effects of manufactured defects of known size on shear failures. Details of these experiments are given by Peterson [5].

3.3 Shear Block Tests

Small clear ASTM D143 shear block specimens were cut from each of the specimens. Two shear block specimens were tested from the green, specimens: one at the moisture condition of the beam and one at 12% moisture content. Only one shear block at 12% moisture content was tested from the seasoned specimens.

3.4 Tests to Investigate Effects of Test Setup

After completing the initial series of tests on green and seasoned specimens, an additional series of tests was conducted by Sanders [6] on three different sizes of

Douglas Fir beams, as shown in table 2. For each moisture condition, specimens were tested under the five-point loading setup and the three-point loading setup in order to evaluate differences in measured shear strengths resulting from the two testing configurations.

Specimen Size	Green unchecked material		Dry seasoned material	
(mm by mm)	5-point	3-point	5-point	3 point
51 by 102	60	60	60	60
51 by 203	60	60	43	37
63 by 115	50	60	36	36

Table 2 Size and number of beam shear specimens investigating test setup.

4. TEST RESULTS

4.1 Green Shear Strengths

Not all the five-point loading specimens failed in a shear mode; a significant number failed in tension or by local instability. Therefore, true shear strength is best estimated by application of censored statistics. Censored statistics techniques were discussed and applied by Rammer et al [3] to adjust the green Douglas Fir results. This same technique was applied lo the green Southern Pine and Engelmann Spruce data. Estimated true shear strength values and coefficients of variation for these two species are listed in table 3.

Specimen Size (mm by mm)	Engelmann Spruce		Southern Pine	
	Shear Strength (MPa)	COV (%)	Shear Strength (MPa)	COV (%)
51 by 102	8.52	20.9	10.17	8.2
51 by 203	8.13	29.1	7.86	22.0
102 by 203	7.20	19.7	7.10	9.1
102 by 305	4.34	17.0	5.94	11.6
102 by 356	3.96	13.4	5.12	18.7

Table 3 Estimated mean and coefficient of variation green data considering censored data.

The effects of beam size on shear strength for the different species can be observed by plotting the ratio of estimated mean beam shear strength to mean ASTM shear block strength versus either shear area or volume, as shown in fig. 1. In these plots, the beam and ASTM shear block strength are not adjusted for moisture content or specific gravity. In addition, the mean beam shear strength and the 80% mean confidence limits are indicated on the graph to show the potential variability in the mean results. In fig. 1, the relative shear strength ratio increases with a decrease in the shear area or volume parameter. Plotted lines represent empirical relationships developed to relate beam shear strength to shear area [2] and volume [4] as:

$$\tau = \frac{1.3\, C_I\, \tau_{ASTM}}{A^{0.2}} \qquad (3)$$

$$\tau = \frac{1.3\, C_I\, \tau_{ASTM}}{V^{0.14}} \qquad (4)$$

where τ_{ASTM} published shear block strength, C_I = stress concentration factor to account for notch effects in the shear block and is taken as 2.0, 1.3 = factor to account for shear block size, A = area of beam under shear, and V = volume of beam under shear. In both cases the curve predicts the means of the large members well but underestimates the estimated average values for the small beams. This underestimation is a consequence of performing a regression analysis of data that only failed in shear and not considering the censored nature of the data.

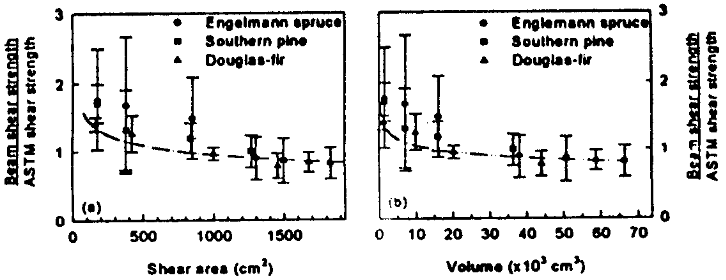


Figure 1 Beam shear/ASTM shear block ratio versus beam (a) area and (b) volume.

SpecimenSize (mm by mm)	Shear strength(MPa)	COV (%)	Beam D/G Ratio	ASTM D/G Ratio
51 by 102	1850	13.1	1.25	1.30
51 by 203	1553	15.6	1.36	1.35
102 by 203	1634	20.9	1.59	1.58
102 by 305	1208	20.0	1.40	1.69
102 by 356	1072	8.5	1.44	1.86

Table 4 Estimated mean and coefficient of variation 12% MC considering censored data.

4.3 Seasoned Five-Point Beam Shear Strengths

Air-dried Southern Pine specimens were tested in a five-point loading setup lo determine the dry shear strength. Since drying effect are most noticeable at the end of a beam, the five-point configuration results are only influenced by checks in the middle portion of the beam and should give a good approximation of the dry shear strength. Censored statistical techniques were again used to estimate the mean strengths and coefficients of variation of the air-dried Southern Pine specimens (see table 4). Mean shear strength values for solid-sawn and glued-laminated Southem Pine [2] were compared. Results indicated similar trends, but the solid-sawn material was found to be slightly weaker and more variable possibly due to checking effects.

4.4 Seasoned Three-Point Beam Shear Strengths

Both Southern Pine and Douglas Fir beams with natural defects (splits and checks) were tested in three-point loading to determine the effects of defects on member strength. It was difficult in both studies to predict which defect was critical prior lo testing so that critical pre-test information could be gathered. After testing, beams were split open and the amount of lost area was calculated after testing. Lost area was determined by observing the transition zone between the glossy weathered to newly formed dull surfaces.

To show the effect of splits and checks on strength, shear strengths versus lost area are plotted in fig. 2. Southern Pine beams showed little decrease in strength due to splitting or checking. Douglas Fir beams, on the other hand, showed visually a stronger decreasing tend with increasing lost area. It also appears that the Douglas Fir members had a higher degree of splitting and checking. Douglas Fir material checks dominated the 102mm-by sizes; in contrast splits dominated the shear failures in the 51mm-by specimens.

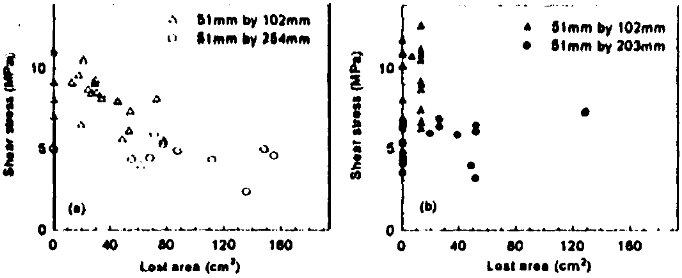


Figure 2 Shear strengths for seasoned (a) Douglas Fir and (b) Southern Pine.

4.6 Three-Point Beam Tests With Saw Kerfs

Peterson's [5] testing series evaluated the effects of saw kerfs on shear strength. Application of a saw kerf increased the percentage of shear failures from 35% in the seasoned material to 68% in the cut specimens. Shear strengths obtained using this test configuration were predicted using the fracture mechanics equations (1) and (2). The predicted values for the split beam shear strength were found to be conservative for all sizes. This conservatism likely arises because the derived solutions assume traction forces are not applied over the crack surfaces, Peterson observed crack closure and contact as the load was applied. This action could develop surface traction and frictional forces along the crack. To correctly model this type of fracture, crack closure should be considered.

4.6 Comparison of Five-Point and Three-Point Results

Sander's [6] results from the tests on green and seasoned Douglas Fir specimens using the five-point and three-point testing configurations are summarized in table 5. While similar trends of decreasing shear strength with increasing beam size exist for both configurations, it can be seen that different measured shear strengths resulted with the two setups for both the green and seasoned specimens. The average ratio of the five-point to three-point results is approximately 1.35.

Specimen Size (mm by mm)	Green unchecked material				Dry seasoned material			
	5-point		3-point		5-point		3-point	
	Shear Strength (MPa)	COV (%)	Shear Strength (MPa)	COV (%)	Shear Strength (MPa)	COV (%)	Shear Strength (MPa)	COV (%)
51 by 102	8.76	17	6.89	25	10.91	24	8.38	26
51 by 203	6.34	14	4.63	17	8.56	15	6.19	18
63 by 115	8.47	11	5.89	15	9.92	12	7.15	14

Table 5 Five-point and three-point test results.

6. FINITE ELEMENT ANALYSES

To better understand the effects of test setup on measured shear strength, a series of two-dimensional, plane stress finite element analyses were performed of the test specimens [16]. A Tsai-Hill failue criterion was applied in the analyses to predict beam failure. The finite element results yielded similar relative stress values for the beams of the various sizes. However, the finite element predictions compared reasonably well with measured strengths for small member sizes, for both the five-point and three-point test results, but did not show a reduction in strength with increased size. Since the computer models do not account for any beam defects, such as checks, splits, knots, or grain orientation, these findings support the conclusion that beam size effects are likely the cause of shear strength variations in the beams of different sizes.

The finite element results indicated different stress states in the beams in the five-point and three-point setups. However, the resulting differences in predicted strengths were much smaller than those observed experimentally. By comparing the Tsai-Hill coefficients for the shear and tension zones of beams within the two test setups, it was found that beams loaded with the three-point loading configuration are much more likely to fail in tension rather than shear. Thus, those beams that do fail in shear in the three-point setup may be at the tower end of the shear strength distribution, thereby producing lower apparent shear strengths. Thus, the five-point setup not only is a more efficient method of determining beam shear strengths; it may also provide a better estimation of the true shear strength distributions.

8. CONCLUSIONS

Measured beam shear strength was found to decrease with beam size for the Douglas Fir, Engelmann Spruce and Southern Pine specimens. Empirical expressions based on beam shear area and volume were developed which gave conservative predictions of observed shear strengths.

Tests on naturally split and checked beams showed mixed results for Southern Pine and Douglas Fir specimens. Southern Pine specimens showed little change with increasing lost area. In contrast, Douglas Fir specimens indicated a decreasing trend with an increase in defected area. In both materials, shear failures were difficult to replicate and the above tends are based on limited sample sizes. Further testing is needed to better conclude the effect of natural defects. A comparison of shear strengths obtained on the artificially split Southern Pine beams with predicted strengths based on current code procedures and on existing mode II fracture theories revealed the predictions to be conservative.

Measured shear strength was found to be influenced by the particular testing configuration used.[1] However, finite element analyses indicated that the different stress states resulting with each configuration are not suffcient to explain the differences in measured shear strengths. The analyses suggest that the different strengths are possibly due to difficulty in obtaining shear failures and the resulting truncation of the shear failure distributions.

REFERENCES

[1] ASTM, *Standard Methods Of Testing Small Clear Specimens Of Timber*, ASTM Desig. D143-94. American Society of Testing Materials, Philadelphia, PA, 1995.

[2] Rammer, D. R. and Soltis, L. A., *Experimental Shear Strength Of Glued-Laminated Beams,* Res. Pap. FPL-RP-527. Madison, WI: U.S. Department of Agriculture, Forest Products Laboratory, 1994.

[3] Rammer, D. R.; Soltis, L. A. and Lebow, P.K., *Experimental Shear Strength Of Solid-Sawn Douglas Fir Beams,* Res. Pap. FPL-RP-5__. Madison, WI: U.S. Department of Agriculture, Forest Products Laboratory, 1996.

[4] Asselin, S.S., *Effects Of Member Size On The Shear Strength Of Sawn Lumber Beams,* MS thesis, Washington State University. Pullman, WA, 1995.

[5] Peterson, J.N., *Shear Strength Of Checked And Split Southern Pine Lumber,* MS thesis, Washington State University. Pullman, WA, 1995.

[6] Sanders, C.L., *The Effects of Testing Conditions on the Measured Shear Strength of Wood Beams,* MS special project, Washington State University, Pullman, WA, 1996.

[7] AFPA, ANSI/NFPA NDS® *National Design Specification of Wood Construction,* and supplement. American Forest and Paper, Washington, DC, 1991.

[8] Radcliff, B. M. and Suddarth, S. K., "The Notched Beam Shear Test For Wood," *Forest Products Journal,* 5(2):131-135, 1955.

[9] Huggins, M.W.; Palmer, J.H.L.; and Aplin, E.N., Evaluation Of The Effect Of Delamination, *Engineering J.*, Feb., pp 32-41, 1966.

[10] Longworth, J., "Longitudinal Shear Strength Of Timber Beams," *Forest Products Journal,* 27(8). pp. 19-23, 1977.

[11] Foschi, R.O. and Barrett, J.D. "Longitudinal Shear In Wood Beams: A Design Method," *Canadian Journal of Civil Engineering,* 4: 363-370, 1977.

[12] Newlin, J.W; Heck, G.E.; and March, H.W., "New Method Of Calculating Longitudinal Shear In Checked Wooden Beams" *Transactions ASME,* 739-744, 1934.

[13] Keenan, F.J., "Shear Strength Of Wood Beams," *Forest Products Journal,* 24(9), pp. 63-70, 1974.

[14] Soltis, L.A. and Geerhard, T.D., *Shear Design of Wood Beams: State of the Art,* Gen. Tech. Rep. FPL-GTR-56, Madison, WI: U.S. Department of Agriculture, Forest Products Laboratory, 1988.

[15] Murphy, J.F., *Strength Of Wood Beams With End Splits,* Res. Report FPL-RP-347. Madison, WI: U. S. Department of Agriculture, Forest Products Laboratory, 1979.

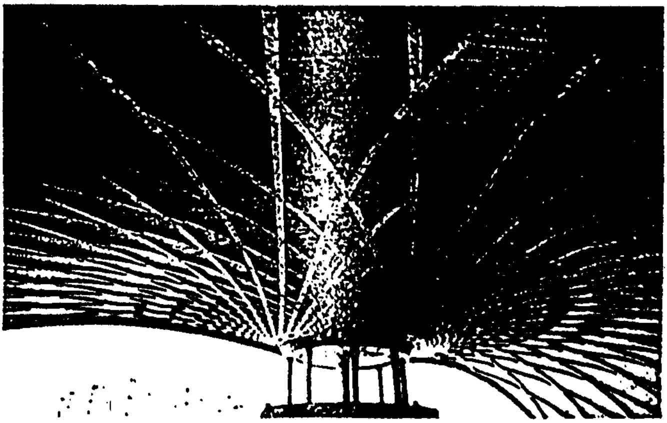
[16] Cofer, W.F., Proctor, F.D. and McLean, D.I., "Prediction of Shear Strength of Wood Beams Using Finite Element Analysis," *Proceedings of the ASME Symposium on Mechanics of Cellulosic Materials,* Chicago, IL, 1997.

W C T E '98

SWISS FEDERAL
INSTITUTE OF TECHNOLOGY
LAUSANNE - SWITZERLAND

5th WORLD CONFERENCE ON TIMBER ENGINEERING

August 17-20, 1998
Montreux, Switzerland



PROCEEDINGS

Volume 1

Edited by J. Natterer and J.-L. Sandoz

Presses polytechniques et universitaires romandes