Shear Strength of Wood Beams

Douglas R. Rammer, Forest Products Laboratory, USDA Forest Service
David I. McLean, Washington State University

Abstract

Experimental shear strength research conducted cooperatively with the USDA Forest Service, Forest Products Laboratory; Washington State University; and the Federal Highway Administration on solid-sawn beams is summarized in this paper. Douglas Fir, Engelmann Spruce, and Southern Pine specimens were tested in a green condition to determine shear strength in members without checks and splits. Sizes tested ranged from nominal 51 by 102 mm to 102 by 256 mm. Additional tests were conducted on air-dried solid-sawn Douglas Fir and Southern Pine specimens. A three-point loading setup investigated the effect of splits and checks on shear strength and a five-point loading setup investigated drying effect on beam shear. Based on the experimental tests, the following are concluded: (1) shear strength of green solid-sawn without splits varies with size and may be characterized using a shear area or volume parameter (2) air-dried Southern Pine shear strength free of splits is equivalent to that for Southern Pine glued-laminated timber; (3) tests on seasoned Douglas Fir and Southern Pine gave mixed results on the effect of splits and checks; and (4) fracture mechanics predictions of the shear strength of artificially split Southern Pine were conservative.

Keywords: Shear strength, beams, design, size effect, Engelmann Spruce, Douglas Fir, Southern Pine, fracture mechanics, splits, checks.

Introduction

Shear design values for solid-sawn structural members are currently derived from small clear, straight-grain specimens (ASTM 1995a). Under typical conditions, wooden beams and columns sometimes develop splits and checks (Fig. 1). These splits and checks are a result of drying as the member equilibrates to the surrounding moisture condition or from repeated wet/dry moisture cycling that may be encountered in exposed timber bridge stringers. Because of the placement of the member within a structure and the local climate, the occurrence and degree of splitting are varied and unpredictable. Published shear design values (AFPA 1991b) account for this uncertainty by assuming a worst case scenario-a beam that has a lengthwise split at the neutral axis. If the design engineer is confident that a member will not split lengthwise, then the design shear value may be doubled.

This approach may lead to an inefficiently designed beam. To increase design accuracy for shear strength, typical beams, rather than small, clear specimens, must be studied. Structural members may or may not contain splits or checks; therefore, an understanding of the shear strength of both unsplit/unchecked and split/checked beams is critical to the design process.

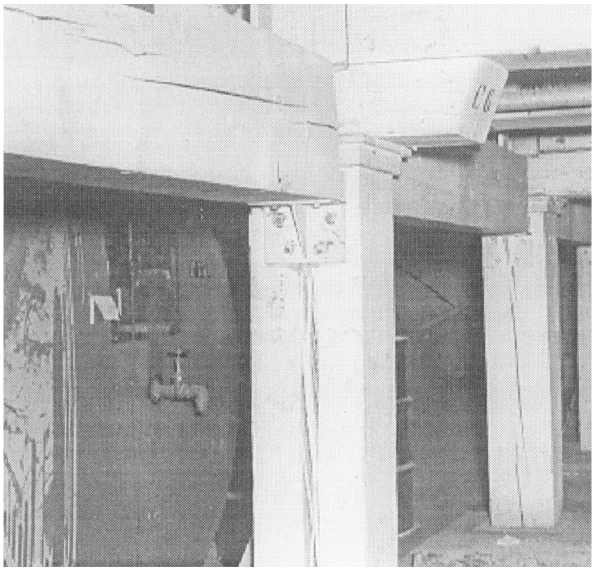

Figure 1—Deeply checked structural timber beams and columns.

The overall purpose of this research was to improve the shear design criteria as it applies to wooden beams. Specific objectives were to

- Develop a beam shear strength database for different solid-sawn wood species;
- Determine the unsplit, unchecked shear strength for wood beams of different sizes and if strength varies with size;
- Determine if the solid-sawn shear strength for unchecked, unsplit beams is similar to that for glued-laminated timber; and
- Determine the effect of checks and splits on beam shear strength.

These objectives were met through an experimental testing program and analysis of the experimental results.

Background

Two approaches based on different failure criteria have historically been used for studying the shear strength of wood beams: (1) a classical approach based on the strength of an unsplit member and (2) a fracture mechanics approach based on the strength of a split or checked member.

Unsplit Wood Shear Strength

In the past, most shear research focused on the small, clear strength for various species using the standard ASTM shear block test (ASTM 1995a). Alternative shear test procedures have been proposed (Radcliffe and Suddarth 1955), 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 and others (1964) found that beam shear strength and ASTM D143 shear strength were different and 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 (Longworth 1977, Quaile and Keenan 1978). Foschi and Barrett (1976, 1977) 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 size effect relationship in the Canadian building code.

For the past 10 years, the Forest Products Laboratory has increased its research focus on beam shear. Soltis and Gerhardt (1988) summarized and reviewed existing literature on shear research. Rammer and Soltis (1994) investigated shear strength with a five-point loading setup for glued-laminated members. Leicester and Breitinger (1992) investigated beam shear test configurations. All this activity focused on determining the unsplit, unchecked beam shear strength. Research currently underway is addressing the effects of splits and checks after seasoning on shear strength.

Shear Failures In Actual Structures

Practitioners and scientists have long been interested in the effect of splits and checks on residual shear strength. A bulk of the early research on the effects of splits and checks in timber members came from the evaluation of stringers removed from railroad bridges. Railroad engineers are concerned with the proper time to replace the member because of strength loss as a result of checking, splitting, and deterioration.

The Santa Fe railroad system investigated the condition of timbers removed from a 35-year-old bridge in Arkansas and two 20-year-old bridges in Oklahoma and Arizona. Strength of these timbers was compared with the strength of four virgin timbers to determine strength loss. At the time of testing, all in-service timbers had moisture content levels less than 12% and the virgin timbers had a moisture content level of approximately 17%. Testing consisted of third-point loading on a span-to-depth ratio between 10 and 11. All members showed signs of checking or splitting and some had signs of deterioration. Of the 25 beams tested, 20 experienced shear failures that were influenced by checks. Maximum shear strength loss was 72% for the timbers from Arizona and approximately 40% to 50% for the timbers from Oklahoma and Arkansas (Santa Fe System 1921).

McAlister (1930) reported on the strength tests of 12 untreated 203- by 305-mm Douglas Fir timbers removed from a bridge with 53 years of service life. His experiments included bending and compression tests on timbers and small, clear specimens. Of the 12 specimens tested in three-point bending, five failed in horizontal shear at a span to depth ratio of 10 and a 14% moisture content. McAlister attributed the shear failures to the degree of checking in the timbers.

Newlin and Heck (1934) tested the residual strength often 203- by 457-mm Douglas Fir stringers removed from a bridge that had been in service for 23 years. Two end-matched specimens were fabricated whenever possible from the original specimens, which were greater than 9.14 m long. One specimen was tested on a 5.79-m span and the other on a 4.57-m span. Seven of the ten 5.79-m specimens failed in horizontal shear, and all the 4.57-m specimens failed in shear. They noted that all shear failures occurred at checks, splits, or bolt holes. Small, clear specimens taken from the material showed no effects of service life, unlike the large timbers.

Wood (1954) investigated the residual strength of two 101-year-old Eastern White Pine floor beams. Each beam was approximately 254 by 254 mm and was tested on a 3.96-m span in three-point loading. One beam failed in bending, and the other failed in horizontal shear along a plane containing deep checks.

In all these cases, the failure mode in the existing timber members tended to be governed by shear if a deep check or split was present. Checking and splitting were a result of drying or cyclic environmental changes over the life of the member.

Experimental Shear Failures

Documented shear failures were noted in experimental programs as early as 1912. Cline and Heim (1912) summarized a large experimental testing program to determine the mechanical properties of 11 wood species. Third-point bending specimens ranged in size from nominal 51 mm by 51 mm by 0.46 m to 203 mm by 406 mm by 4.6 m in a wet and air-dried condition. Shear failures were noticed in both the green and air-dried specimens. As the specimen size decreased, so did the percentage of shear failures. In general, the air-dried members had a higher percentage of shear failures at each size when compared with their green counterparts.

In a study to determine the mechanical properties of Alaskan wood, Markwardt (1931) tested Sitka Spruce and Western Hemlock timbers in a green and air-dried condition. Members were tested in third-point loading at a span-to-depth ratio of 11.25. Of the green material tested, 30% of the Sitka Spruce and 24% of the Western Hemlock timbers failed in shear. For the air-dried specimens, 50% of the Sitka Spruce and 66% of the Western Hemlock timbers failed in shear. Markwardt observed that the Sitka Spruce material was of a higher grade than the Western Hemlock, because the Sitka Spruce members were cut from larger diameter trees with few defects. Western Hemlock members were cut from small-diameter trees that contained heart rot, shakes, and decayed knots and might have contributed to the increased occurrence of shear failures.

To evaluate the effects of checks, Newlin and others (1934) conducted bending tests using a built-up beam made of Sitka Spruce. Additionally, they proposed a theory to explain the effect of checks or splits, which is incorporated into current design standards (AREA 1991, AFPA 1991a), by the following, for a concentrated load

$$V = \frac{P(\ell_c - x)\left(\frac{x}{d}\right)^2}{\ell_c\left[2 + \left(\frac{x}{d}\right)^2\right]} \qquad (1)$$

In this theory, known as the two-beam theory, the length and depth of checks are not considered, only the position x of the load, P from the support, beam depth d and the clear span ℓ_c are relevant. Researchers have since shown that the underlying assumptions of this theory are incorrect (Keenan 1974, Soltis and Gerhardt 1988).

Norris and Erickson (1951) conducted a pilot study on the effect of splits on shear strength. They developed a theory based on the assumption that the stress concentration at the tip of the split is approximated by an unknown function that relies on the split length to beam depth ratio. This function can only be determined empirically from test data. Fifteen tests with two different loading patterns were conducted using Sitka Spruce. Based on these tests, the equation developed by Norris and Erickson to explain the effects of splits is

$$\frac{\tau_c}{\tau_m} = 0.674\frac{d}{a}\sqrt{\frac{a-c}{c}} - 0.053 \qquad (2)$$

where τ_c is the shear stress at the neutral axis; τ_m is the maximum shear stress; a is the position of the concentrated load; d is the beam depth; and c is the length of the split.

Based on a survey of glued-laminated timber bridges, Huggins and others (1964) conducted a study on the effect of delamination on the static and repeated load strength for glued-laminated beams. After testing 175 small glued-laminated beams, of which 115 had simulated splits or delamination, they concluded that shear span influences strength and delamination reduces ultimate strength. Additionally, they stated that shear strength is less under repeated loading than static loading, based on the 48 beams tested.

Fracture Mechanics

One method to evaluate the strength of a split, checked, or cracked beam is fracture mechanics. Fracture mechanics evaluates the state of stress at the end of a crack for three load cases. Mode I is an opening displacement; mode II is a sliding displacement; and mode III is a tearing displacement (Fig. 2).

Wood fracture was first investigated by Porter (1964). Since Porter's first study, wood fracture investigations have generally focused on mode I fracture with some limited studies on modes II and III fracture. A problem with mode II and III investigations is the lack of a standard test procedure to determine fracture properties. Recently, efforts have been made to standardize a test procedure for mode II fracture. General details of the use of fracture mechanics in wood research is summarized by Valentin and others (1991).

Barrett and Foschi (1977) numerically analyzed the influence of beam splits under concentrated and uniform loading. Based on their analysis, the following were developed to express the mode II stress intensity factor K_{II}:

$$K_{II} = \tau\sqrt{\pi a}H \qquad (3)$$

where τ is the shear stress in MPa; a is the split length; and H is a nondimensional factor that characterizes the loading and beam geometry. For concentrated loading, H takes the following form:

$$H = \frac{A + B\left(a/s\right)}{\sqrt{a/s}} \qquad (4)$$

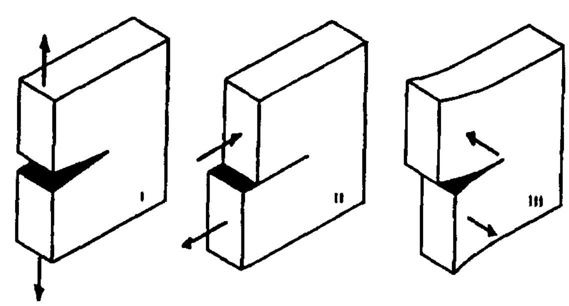

Figure 2—Three modes of loading.

where A and B are functions depending on a/s and s/d, with s being distance from the load to the support and d the beam depth. Using Equation (3), Barrett and Foschi determined the critical stress intensity factor K_{IIc} value for select structural, No. 1, and No. 2 Western Hemlock.

Murphy (1979) used a boundary collocation method to develop a simplified equation to evaluate the effects of beam splits under concentrated and uniform loading. His equation for concentrated loading is

$$K_{II} = \left[-2.785\left(\frac{a}{d}\right) - 0.731\right]\frac{R}{b\sqrt{d}} \qquad (5)$$

where R is the support reaction nearest the split; a is the split length; d is beam depth; and b is the width of beam. Murphy used the work of Norris and Erickson (1951) to validate Equation (5) for Sitka Spruce beams.

Equations (5) developed by Murphy and (3) by Barrett and Foschi are approximately equivalent for all sized beams.

The previous two studies focused on end-split beams; however, a majority of actual defects are checks that are classified as a mode III fracture problem. Murphy (1980) applied mode III fracture mechanics to predict the effect of checks on beam strength. Correcting Sih's (1964) mode III solution, Murphy developed an isotropic two-dimensional expression for mode III fracture and validated it with Newlin and others (1934) data. Murphy stated that this expression could not explain the effects of shear span. Therefore, he developed an empirical expression to address this deficiency.

In the fracture research previously discussed, the focus was to determine the applicability of fracture mechanics to explain wood failure for simulated splits. In actual structural members, the geometry of the crock front is highly irregular. Sometimes the beam is completely split but more often the beam is checked on one or both sides. Further investigation into the application of fracture mechanics is needed to explain the effect of splits and checks.

Test Program

An investigation of shear strength is currently underway through a cooperative study with the USDA Forest Service, Forest Products Laboratory; Washington State University; and the Federal Highway Administration. This research was undertaken to investigate the green, unchecked shear strength, and the seasoned (checked or split) shear strength of solid-sawn beams. Brief descriptions of the procedures are discussed.

Table 1—Nominal size and number of beam shear specimens used in this investigation.

Specimen (mm)	Green unchecked material			Dry seasoned material			
				Southern Pine			
	Douglas Fir	Southern Pine	Engelmann Spruce	5-point bending	3-point bending	3-point bending[a]	Douglas Fir
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 a 0.5*d*, *d*, and 1.5*d*.

Green Shear Strength

Douglas Fir, Southern Pine, and Engelmann Spruce specimens with nominal sizes ranging from 51 by 102 mm to 102 by 356 mm were tested to determine unchecked beam shear strength (Table 1). All specimens had moisture content levels of 20% or more. A total of 160 Douglas Fir, 183 Southern Pine, and 187 Engelmann Spruce beams were tested.

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. This test setup had been successfully used to create shear failures by Langley Research Center (Jegly and Williams 1988), Purdue University (Bateman and others 1990), and the Forest Products Laboratory (Rammer and Soltis 1994). 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 and others (1996) and the Southern Pine and Engelmann Spruce testing are published by Asselin (1995).

Dry or Seasoned Shear Strength

Only Douglas Fir and Southern Pine specimens were studied in a dry or seasoned condition at an average moisture content of 12%. Nominal specimen size ranged from 102 to 102 mm to 102 by 356 mm for both species (Table 1). All Douglas Fir specimens contained natural splits and checks after 1½ 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. A 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 (Table 1). First, a five-point loading setup was used to determine dry shear strength. Maximum shear force occurs between the load points; therefore, only checks will influence the results as splits are predominantly located at the ends of the beam. 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 with saw kerfs at lengths of 0.5 *d*, *d*, and 1.5 *d* was conducted to examine the effects of manufactured defects of known size on shear failures.

Details of the Southern Pine experiments are given by Peterson (1995), and Douglas Fir details will be published in a USDA Forest Service research paper by Rammer.

Shear Block Tests

Small, clear ASTM D143 shear block specimens were cut in all the studies from each specimen after failure to benchmark the results to published shear strength values. Two shear block specimens were tested from the green, unchecked beam specimens. One specimen was tested at the moisture condition of the beam and one at 12% moisture content. Only one shear block specimen at 12% moisture content was tested from the air-dried, seasoned beam specimens.

Results

Green Shear Strength

Not all of the five-point loading specimens failed in a shear mode; a significant number failed in tension or from local instability. Therefore, true shear strength is best estimated by application of censored statistics. Censored statistics techniques were discussed and applied by Rammer and others (1996) to adjust the green Douglas Fir results. This same technique was applied to 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 2.

Table 2—Estimated mean and coefficient of variation (COV) green data considering censored data.

Size (mm)	Engelmann Spruce Shear strength (MPa)	Engelmann Spruce COV (%)	Southern Pine Shear strength (MPa)	Southern Pine 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

The size effect for the different species is compared by plotting the ratio of estimated mean beam shear strength to mean ASTM shear block strength versus either shear area or volume (Fig. 3). In these plots, the beam and ASTM shear block strength values are not adjusted for moisture content or specific gravity. In addition, the mean beam shear strength and the 80% mean confidence limits are indicated to show the potential variability in the mean results. In Figure 3, the relative shear strength ratio increases with a decrease in the shear area or volume parameter. These trends are similar to glued-laminated beam shear results (Rammer and Soltis 1994, Longworth 1977). Plotted lines represent empirical relationships that relate beam shear strength to shear area (Rammer and Soltis 1994) and volume (Asselin 1995). In both cases, the curve predicts the means of the large members well, but underestimates the estimated average values for the small beams. This under estimation is a consequence of performing a regression analysis of data that only failed in shear and not considering the censored nature of the data. In almost every case, the empirical curves are conservative.

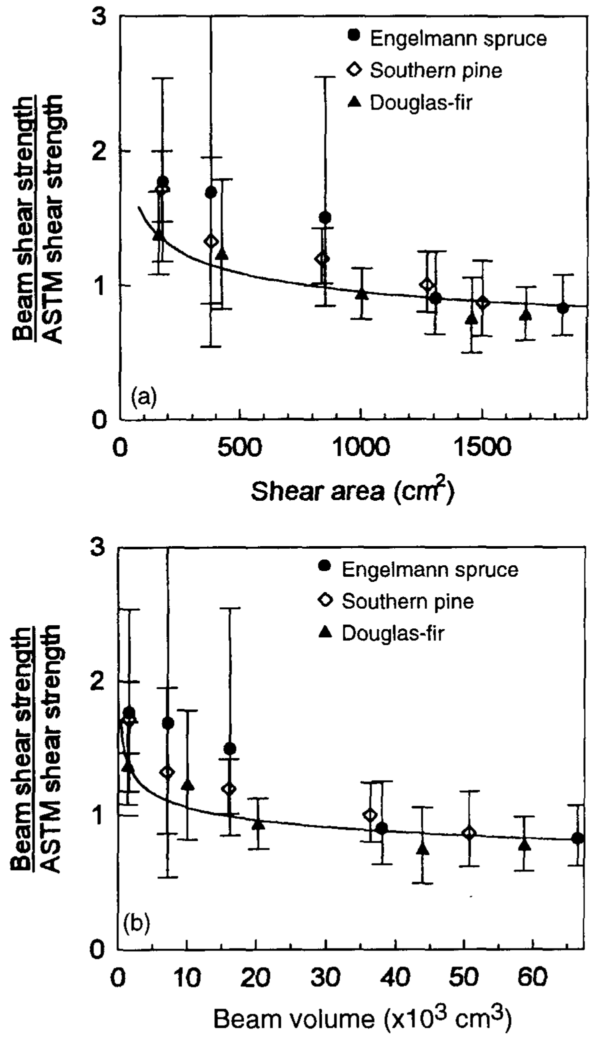

Figure 3—Five-point beam shear to ASTM shear block ratio versus beam size: (top) shear area, (bottom) beam volume.

Seasoned Five-Point Beam Test

Air-dried Southern Pine was tested in a five-point loading setup to determine the dry shear strength. Drying effects are most noticeable at the end of a beam; therefore, the five-point configuration results are influenced only 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 and coeffecient of variation of the air-dried Southern Pine (Table 3). Mean values for solid-sawn and glued-laminated (Rammer and Soltis 1994) Southern Pine beams and the 80% mean confidence levels are plotted in Figure 4. Comparison of the air-dried solid-sawn results with previously tested glued-laminated Southern Pine results indicates similar trends, but the solid-sawn material is slightly lower and more variable as a result of checking effects.

Table 3—Estimated mean and coefficient of variation (COV) 12% moisture content Southern Pine considering censored data.

Size (mm)	Shear strength (MPa)	COV (%)	Beam D/G[a] ratio	ASTM D/G[b] ratio
51 by 102	12.76	13.1	1.25	1.30
51 by 203	10.71	15.6	1.36	1.35
102 by 203	11.27	20.9	1.59	1.58
102 by 305	8.33	20.0	1.40	1.69
102 by 356	7.39	8.5	1.44	1.86

[a]Beam dry/green ratio based on Peterson (1995).
[b]Shear block dry/green ratio based on Asselin (1995).

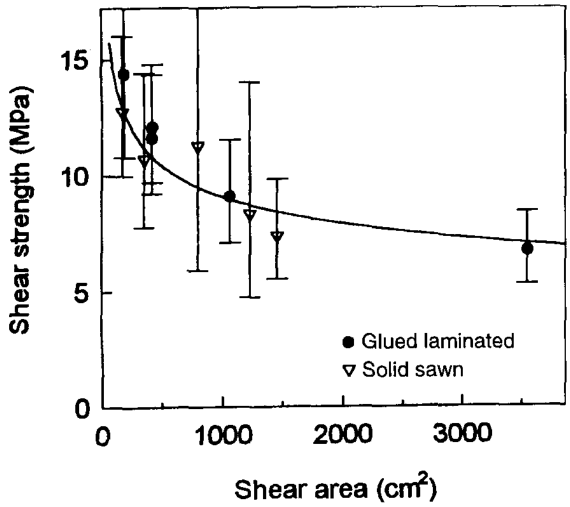

Figure 4—Comparison of seasoned solid-sawn and glued-laminated Southern Pine by five-point beam test.

Typically the dry/green shear strength ratios for the individual Southern Pine species range between 1.45 and 1.75 (ASTM 1995b), and Kretschmann and Green (1994) recently found a 1.47 increase for the general Southern Pine classification. An estimated dry/green ratio based on the estimated means for the Southern Pine five-point specimen at each size was calculated with the shear block dry/green ratio found by Asselin, as shown in Table 3. Beam shear dry/green ratios tended to be smaller than values published in ASTM (1995b), but similar to dry/green ratios found by Asselin in shear blocks cut from smaller beam sizes. In the 102- by 305-mm and 102- by 356-mm sizes, the beam dry/green ratios are at the upper bound of the acceptable ASTM values and 20% lower than values develop from tested shear blocks.

Seasoned Three-Point Beam Test

Both Southern Pine and Douglas Fir beams with natural defects (splits and checks) were tested in three-point loading to determine the effects of both splits and checks on member strength. Of the 209 Southern Pine beams tested, 73 failed in shear; of the 160 Douglas Fir beams tested, 76 failed in shear. It was difficult in both studies to predict which split or check was critical prior to 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 strength versus lost area are plotted in Figure 5. Southern Pine beams showed little decrease in strength

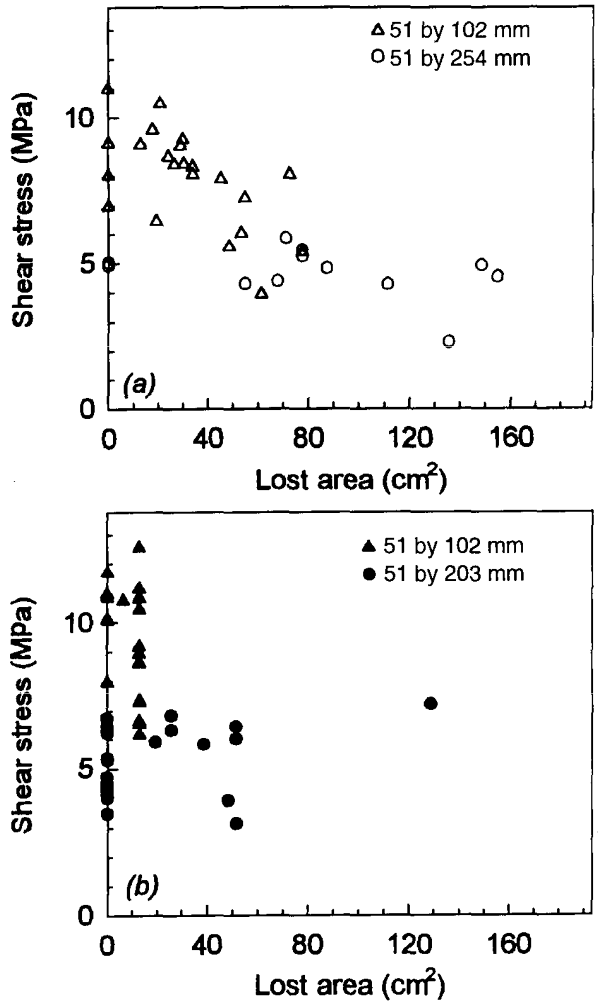

Figure 5—Three-point shear strength results for beams failing in shear of seasoned (a) Douglas Fir and (b) Southern Pine.

as a result of splitting or checking. Douglas Fir beams, on the other hand, visually showed a stronger decreasing tend with increasing lost area. It also appears that the Douglas Fir members had a higher degree of splitting and checking.

Based on research to be published later in a Forest Products Laboratory report, Douglas Fir material checks dominated the 102-mm specimens; in contrast, splits dominated the shear failures in the 51-mm specimens. As indicated by Murphy (1980), the influence of checks on beam shear strength, characterized by mode III fracture, occurs when checks have depths greater than 15% of the cross sectional width.

Three-Point Beam Test With Saw Kerfs

Peterson's (1995) third testing series evaluated the effects of saw kerfs on shear strength. Application of a

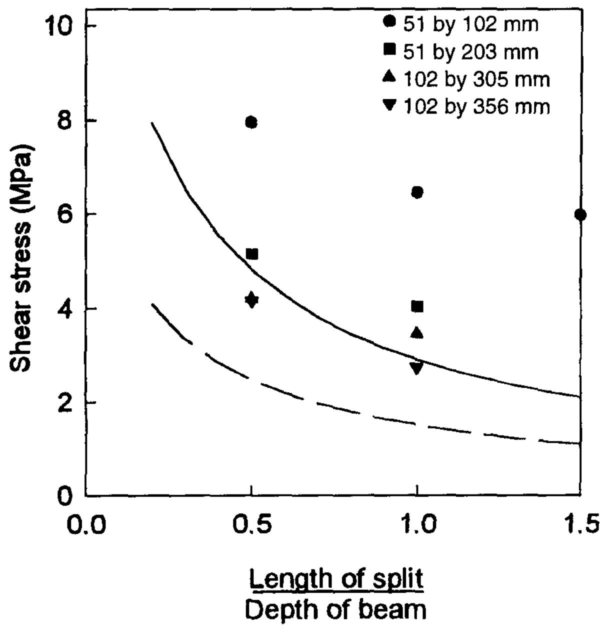

Figure 6—Comparison of saw kerf Southern Pine beam with Equation (5). Solid line represents 51- by 102-mm strength prediction. Dashed line represents 102- by 356-mm strength prediction.

saw kerf increased the percentage of shear failures from 35% in the seasoned material to 68% in the cut specimens. To compare fracture mechanics approaches, a critical mode II (K_{IIc}) stress intensity property is needed. Kretschmann and Green (1992) determined the K_{IIc} for Southern Pine at several moisture levels using a center-split beam. At 12% moisture content, the K_{IIc} value is 2060 kN•m$^{-3/2}$. Using this value of K_{IIc} in Murphy's Equation (5), mode II fracture yields a prediction for the shear strength of the beams. For this test configuration, Murphy's Equation (5), and Barrett and Foschi's Equation (3), yield similar results. Figure 6 compares the experimental and predicted shear strength to the split length to beam depth ratio.

The predicted values for the split beam shear strength were conservative at all sizes. This conservatism was probably because the derived solutions assume traction forces were not applied over the crack surfaces. Peterson (1995) 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.

Concluding Remarks

Several studies were conducted to determine the shear strength of wood beams. These studies were conducted on various member sizes of Douglas Fir, Engelmann Spruce, and Southern Pine beams. As a result of this research, the following are concluded.

- Unsplit, unchecked shear strength for all species varied with beam size and had similar trends after estimated beam strength was divided by ASTM shear block values to normalize material effects. An empirical expression based on both shear area and volume gave conservative results at smaller beam sizes after censored statistics techniques were applied.

- Air-dried Southern Pine material tested in a five-point loading configuration gave similar results to Southern Pine glued-laminated shear strength data. This is likely due to the lower incident of splits and checks as a result of drying in the region of maximum shear in a five-point configuration. The application of dry/green ratios for shear strength design should be further investigated. For larger-sized members, dry/green ratios developed from the beam shear tests were at least 20% less than ASTM dry/green ratios.

- 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 these tends are based on limited sample sizes. Further testing is needed to better conclude the effect of natural defects.

- Finally, a comparison of shear strength obtained on artificially split Southern Pine beams with predicted strength based on existing mode II fracture theories revealed the predictions are conservative.

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