

## Recent Research on the Shear Strength of Wood Beams

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### 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.

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### Introduction

Shear design values for solid-sawn structural members are currently derived from small clear, straight-grain specimens (ASTM 1995a). Wood beams often develop splits and checks from drying as the member equilibrates to the surrounding moisture condition or from repeated 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 difficult to quantify. 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 obtain a better representation of actual shear strength, full-sized beams, not small, clear wood specimens, need to be studied. Because structural members may or may not contain splits or checks, an understanding of the shear strength of unsplit/unchecked and split/checked beams is critical to the design process.

### 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, Quaille 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 Breitingner (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.

### Effects of Splits and Checks

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

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

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  $\ell_c$  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

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

where  $\tau_c$  is the shear stress at the neutral axis;  $\tau_m$  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.

### Fracture Mechanics Approaches

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  $K_{II}$ :

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

where  $\tau$  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:

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

Specimen (mm)	Dry seasoned material						
	Green unchecked material			Southern Pine			
	Douglas Fir	Southern Pine	Engelmann Spruce	5-point bending	3-point bending	3-point bending <sup>a</sup>	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

<sup>a</sup>Simulated splits at 0.5*d*, *d*, and 1.5*d*.

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

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<sub>IIc</sub>* 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

$$K_{II} = \left[ -2.8\left(\frac{a}{d}\right) - 0.73 \right] \frac{R}{b\sqrt{d}} \quad (5)$$

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 crack 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.

### 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 of specimens 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.

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. 1). 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 1, 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.

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

Size (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

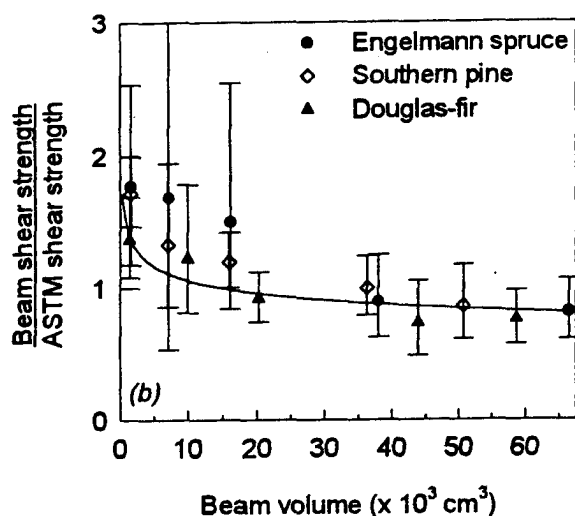
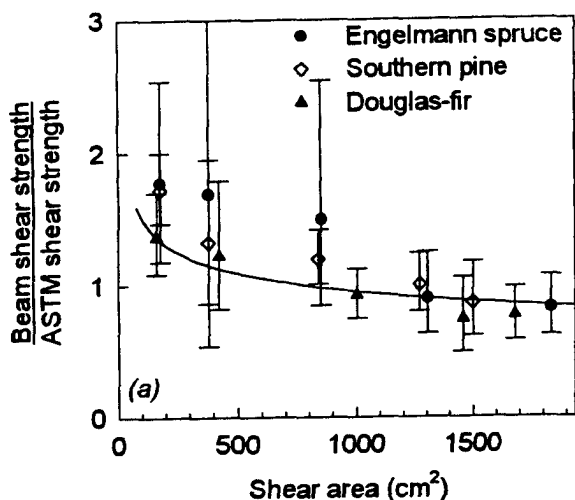


Figure 1—Beam shear -to-ASTM shear block ratio plotted versus beam size (a) shear area (b) beam volume.

In almost every case, the empirical curves are conservative.

#### 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 coefficient of variation of the air-dried Southern Pine (Table 3). Mean values for solid-sawn and glued-laminated

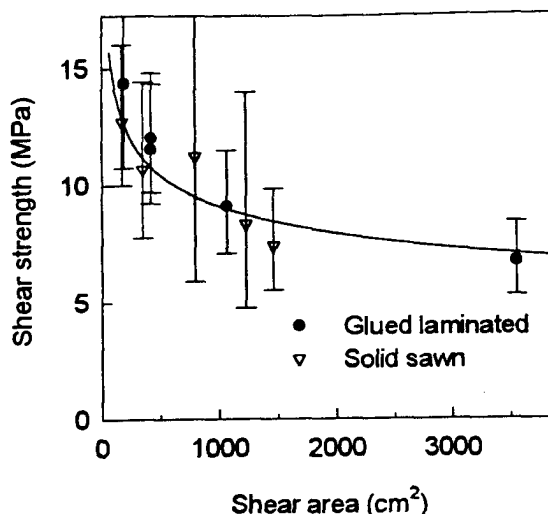


Figure 2—Comparison of solid-sawn and glued-laminated Southern Pine.

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

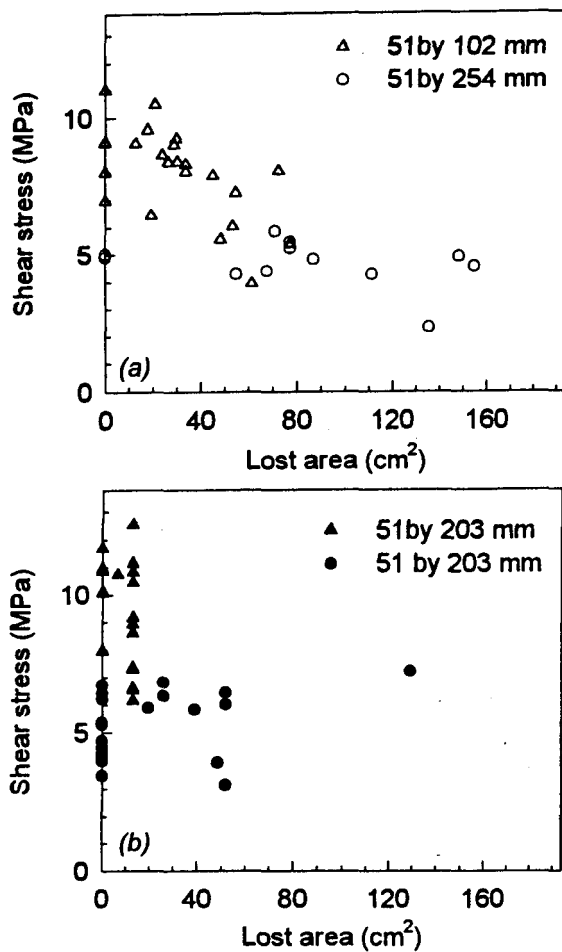
Size (mm)	Shear strength (MPa)	COV (%)	Beam D/G <sup>a</sup> ratio	ASTM D/G <sup>b</sup> ratio
51 by 102	12.76	13.1	1.25	1.30
51 by 203	10.71	15.6	1.36	1.35
102 by 203	11.27	20.9	1.59	1.58
102 by 305	8.33	20.0	1.40	1.69
102 by 356	7.39	8.5	1.44	1.86

<sup>a</sup>Beam dry/green ratio based on Peterson (1995).

<sup>b</sup>Shear block dry/green ratio based on Asselin (1995).

(Rammer and Soltis 1994) Southern Pine beams and the 80% mean confidence levels are plotted in Figure 2. 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.

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



**Figure 3—Shear strength of beams failing in shear of seasoned (a) Douglas Fir and (b) Southern Pine.**

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 developed 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

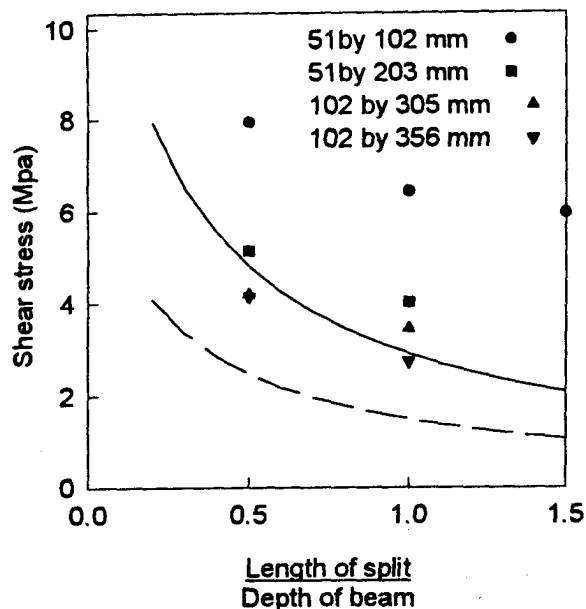
160 Douglas Fir beams tested, 76 failed in shear. It was difficult in both studies to predict which split or check was critical prior to testing so that critical pre-test information could be gathered. After testing, beams were split open and the amount of lost area was calculated after testing. Lost 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 3. Southern Pine beams showed little decrease in strength as a result of splitting or checking. Douglas Fir beams, in contrast, visually showed a stronger decreasing trend 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 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 ( $K_{Ic}$ ) stress intensity property is needed. Kretschmann and Green (1992) determined the  $K_{Ic}$  for Southern Pine at several moisture levels using a center-split beam. At 12% moisture content, the  $K_{Ic}$  value is  $2060 \text{ kN}\cdot\text{m}^{-3/2}$ . Using this value of  $K_{Ic}$  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 4 compares the experimental and predicted shear strength with 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



**Figure 4—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.**

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 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 trends 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 that the predictions are conservative.

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