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# FULL-SCALE EDGEWISE SHEAR TESTS FOR LAMINATED VENEER LUMBER

B Yeh
T G Williamson

APA - The Engineered Wood Association

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# *Full-Scale Edgewise Shear Tests for Laminated Veneer Lumber*

Borjen Yeh, Ph.D., P.E.
Thomas G. Williamson, P.E.
*APA - The Engineered Wood Association, U.S.A.*

## Abstract

The shear strength of laminated veneer lumber (LVL) has traditionally been determined based on the results of small block shear tests conducted in accordance with ASTM D 143 [1]. In recent years, there has been a significant interest in determining the shear strength of engineered wood products using full-scale bending test methods [2,3,4,5,6] in lieu of small block shear tests. However, due primarily to different shear-to-bending strength ratios among a variety of engineered wood products, the use of a prismatic cross section and test setup similar to those adopted for full-scale shear tests of glulam [6] does not normally produce an acceptable shear failure rate in the edgewise or joist orientation (loads are applied parallel to gluelines), as required for LVL. Therefore, special considerations should be given to the test setup and specimen configuration for LVL edgewise shear tests.

This paper describes the development of shear test methods for both LVL edgewise full-scale and small-scale tests. The full-scale test method can be used for product qualification of the LVL shear strength and the small-scale test method can be used as an in-plant quality assurance tool to monitor the LVL shear strength on an on-going basis. A noticeable size effect is discussed. The moisture effect on the full-scale LVL edgewise shear specimens is also presented.

## 1. Introduction

Laminated veneer lumber (LVL) has been used in North American for more than 30 years as both flanges for I-joists and as beams and headers. With improved technology in veneer grading, adhesives, and machining, LVL is known for its excellent load-carrying capacities and consistent quality. Since the grade and quality of each individual layer of veneers can be closely controlled in the LVL manufacturing processes, the variability in product properties is typically much lower than that of sawn lumber. Due to its manufacturing processes, LVL can be customized to a wide variety of widths, thickness, and lengths. Most importantly, the end (scarf or lap) joints between adjacent veneer layers can be staggered to minimize the strength reducing effect of those joints on the bending and tensile strengths of LVL.

In North America, the design stress for LVL is traditionally determined based on the procedures set forth in ASTM D 5456 [7] using ASTM D 143 [1] small block shear specimens with a shear area of only 2581 mm$^2$ (4 in.$^2$). In recent years, there have been significant interests in determining the shear strength of engineered wood products using full-scale bending test methods [2,3,4,5,6]. A review of various full-scale shear test methods for engineered wood products has been provided by Lam and Craig [4]. However, due primarily to different shear-to-bending strength ratios among a variety of engineered wood products, the use of a prismatic cross section and test setup similar to those adopted for the full-scale shear tests of glulam [6] does not normally produce an acceptable shear failure rate in the edgewise or joist orientation (see Figure 1), as required for LVL. Therefore, special considerations should be given to the test setup and specimen configuration for full-scale LVL edgewise shear tests.

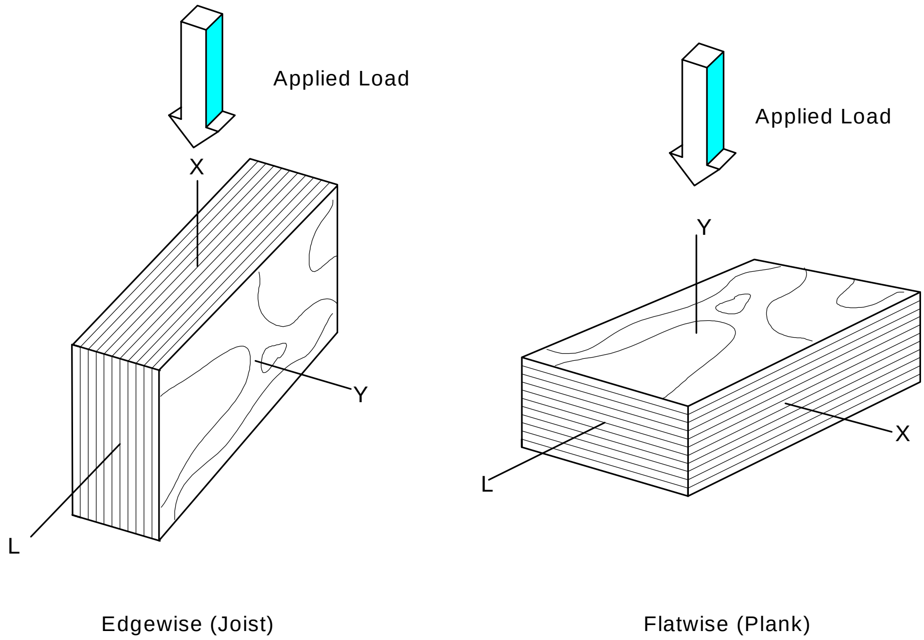


Figure 1. Orientations for LVL

## 2. Objective

This paper describes the special considerations given to the development of LVL edgewise shear test methods for both full-scale qualification and small-scale quality assurance tests. The size and moisture effects on the full-scale LVL edgewise shear specimens are also presented.

## 3. Development of Test Methods

It has been reported that it is very difficult to fail LVL in edgewise shear using a prismatic cross section due to the high shear-to-bending strength ratio of the LVL, as compared to other engineered wood products such as glulam [3,4]. One solution to increase the edgewise shear failure rate in full-scale shear tests is to decrease the shear-to-bending strength ratio by either reinforcing the edgewise bending capacity of the LVL or using an I-section. The reinforcement approach, such as by using fiber-reinforced plastics, is considered unfeasible due to the requirement of determining the transformed section and the need for sophisticated specimen preparation processes.

Lam and Craig [4] tested edgewise shear of Douglas-fir LVL, southern pine Parallel Strand Lumber (PSL), and Douglas-fir PSL using I-shaped specimens, as shown in Figure 2. The I-sections were 44 x 184 mm (1-3/4 x 7-1/4 in.) and 44 x 305 mm (1-3/4 x 12 in.), and were prepared by using a router. The specimens were tested using the center-point load as well as five-point load methods. The on-center span was 6 times the specimen depth (6d) for the center-point load method and 5d for the five-point load method. However, as the shear stress induced by the five-point load method at the intermediate reaction can be interfered by the cross-grain stresses, the wood industry in the United States has not considered the five-point load method an appropriate test method for evaluating the edgewise shear strength of glulam and LVL. Therefore, for the purpose of this study, only the LVL test results using the center-point load method are reviewed below.

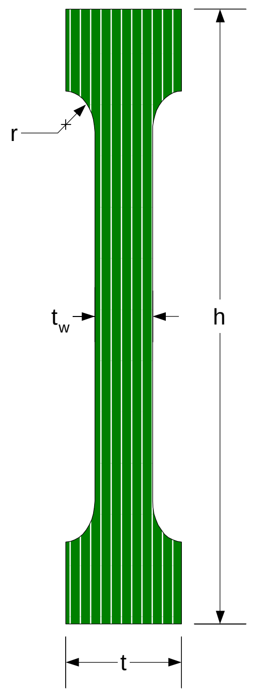


Figure 2. The I-shaped specimen used by Lam and Craig [4] (t = LVL thickness)

The shear failure rate reported by Lam and Craig [4] using the center-point load method was excellent (89 out of 96 specimens or 93%). When compared to the ASTM D 143 block shear test results, the center-point load method yielded a shear strength of 83% on average for the 44 x 184 mm (1-3/4 x 7-1/4 in.) and 73% on average for the 44 x 305 mm (1-3/4 x 12 in.) specimens, indicating a likely size effect.

While the center-point load method has been demonstrated as appropriate for edgewise shear tests, some concerns may be raised on the specimen preparation technique. Among them, the most significant one is that the high-quality face veneers that are normally densified are required to be removed for making the I-section. Therefore, the shear strength obtained from this type of specimens is likely to be conservative. In addition, the router used to prepare the specimens requires multiple passes for deeper specimens, which could be quite time-consuming.

In 1996, APA -The Engineered Wood Association initiated a full-scale LVL edgewise shear test program based on prior experience on full-scale glulam shear tests [6]. In developing the specimen configuration, it was decided through a preliminary study that an I-section, as shown in Figure 3, should be used to ensure a high percentage of shear failure. The flanges of the I-section were cut from materials adjacent to the web and face-glued to the web so that the gluelines for both flanges and web were parallel to each other, resulting in a net flange width of 3 times the web thickness.

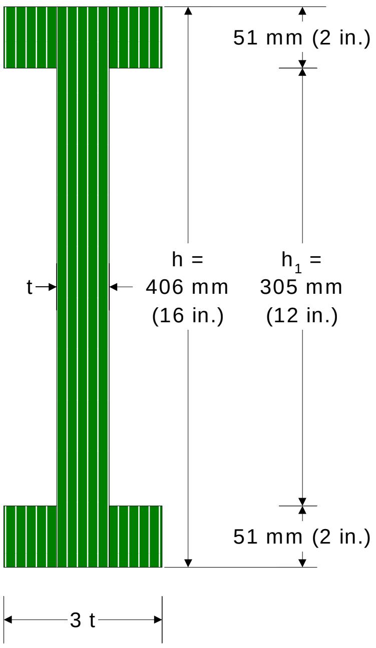


Figure 3. Specimen dimension used in APA full-scale edgewise shear tests (t = LVL thickness)

By selecting the matched flanges and web materials, and orientating the web and flange materials, the moduli of elasticity for the entire I-section could be assumed as the same in the edgewise orientation. As a result, a calculation of the transformed section is not required. Furthermore, this specimen configuration does not require the removal of face veneers and therefore, the shear strength obtained from this specimen configuration reflects the best estimate of the LVL edgewise shear strength.

The specimen size is an important consideration for evaluating the edgewise shear strength of LVL due to the consideration of size effect. Since most LVL products used in light-frame construction in North America are generally limited to 406 mm (16 in.) in depth, this was selected as the specimen depth. The length of the specimen was determined based on prior experience from glulam tests [6]. Specifically, it was considered desirable to use a 4-point load method so that the applied load could be spread over 2 load heads, which were set 152 mm (6 in.) apart, to reduce the likely crushing under the load. In this loading configuration, each load head applied the same load carried by each reaction (bearing plate). In addition, the clear distance between the bearing plate and the nearest load head was maintained at least 2 times the specimen depth to avoid the interference of cross-grain stresses to the shear strength. Figure 4 shows the resulting test setup. It is expected that bending or deflection criteria will govern the design when the span-to depth ratio of the LVL increases. Therefore, the shear strength derived from this specimen configuration represents the near maximum size of the LVL governed by the shear strength in design. This is the same concept used to develop the glulam shear test setup given in Annex A5 of ASTM D 3737 [8].

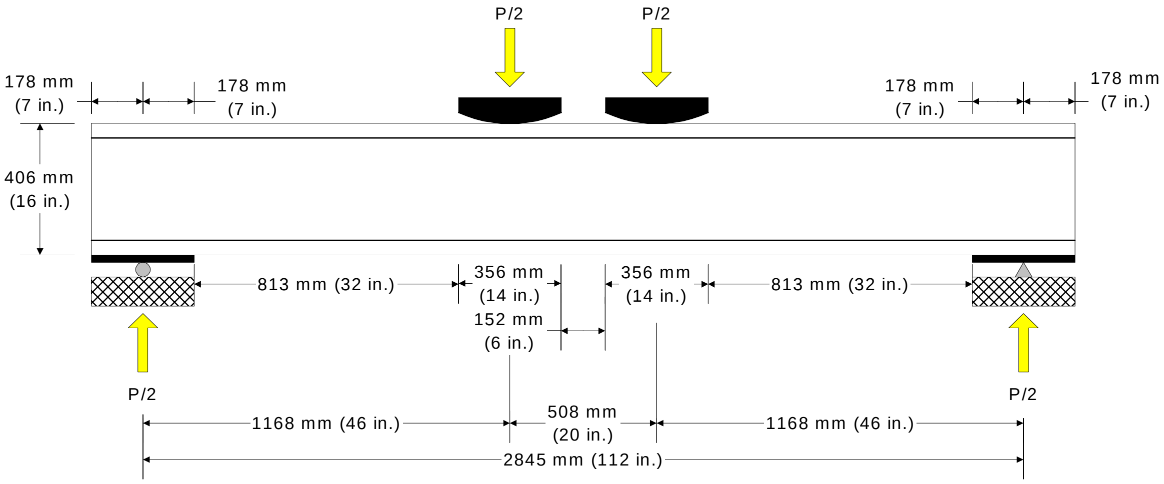


Figure 4. Test setup for LVL edgewise shear tests

The likelihood of shear failure could be estimated using the loading configuration given in Figure 4 if the bending and shear strengths of the LVL can be estimated. For example, if the characteristic bending strength of LVL is 43.4 MPa (6,300 psi) with a COV of 0.15 based on the depth of 305 mm (12 in.) and a volume effect factor of $(h/305)^{(1/8)}$, where h is the LVL depth (mm), the 5$^{th}$ percentile ultimate load required for bending failure using the test setup given in Figure 4 can be estimated as 200 kN (45,000 lbf). If the same LVL has a characteristic shear strength of 1/10 of the characteristic bending strength, but with a COV of 0.10, the 99$^{th}$ percentile ultimate load required for shear failure can be estimated as 177 kN (39,900 lbf). Since the 99$^{th}$ percentile of shear capacity is lower than the 5$^{th}$ percentile of bending capacity, the shear failure rate based on the test setup given in Figure 4 is expected to be 94% or higher. The probability of shear failure will increase with a decreasing shear-to-bending strength ratio. For example, when the shear-to-bending strength ratio is reduced to 1/12 for the example given above, the 99.9$^{th}$ percentile of shear capacity is approximately the same as the 0.4$^{th}$ percentile of the bending capacity, which ensures a near perfect shear failure rate.

To assemble the I-section, a white glue readily available from retail stores was applied to both web and flange faces (double applications). Soon after the application of the white glue, 24 - 8d ring-shank screws (64-mm or 2-1/2-inch long) were applied at 76 mm (3 in.) on center for the outer 457 mm (18 in.) from both ends and both faces. The first screw were located 76 mm (3 in.) from each end. The screws were staggered vertically on both faces to avoid splitting. Additional 28 - 8d ring-shank screws were applied at 152 mm (6 in.) on center for the remaining length on both faces. It should be noted that the main purpose of using those screws was to provide pressures for the white glue to cure. If the glue can be cured by other mechanical or chemical means, the use of those screws is not necessary. Through a preliminary study, it was determined that smooth-shank nails do not provide adequate pressures for the white glue to cure due likely to the effect of stress relaxation.

# 4. Materials and Methods

Forty-two pieces of 44 mm x 406 mm x 8,230 mm (1-3/4 in. x 16 in. x 27 ft) LVL were sampled by an APA auditor at a commercial LVL plant and shipped to the APA Research Center in Tacoma, Washington for testing. These materials were manufactured with 8 plies of 3.2-mm (1/8-inch) thick Douglas fir Grade 1 veneers and 7 plies of 3.2-mm (1/8-inch) thick Western Hemlock Grade 2 veneers. APA staff witnessed the veneer peeling, sorting, and drying processes, and the LVL manufacturing.

Upon the receipt of those materials, each LVL was cut in half in the lengthwise direction. All materials were then conditioned at the APA Research Center at 65 ± 5% relative humidity and 68 ± 11°F until reaching an equilibrium moisture content. Fifty-four I-shaped specimens were then manufactured at the APA Research Center using matched materials as web and flange sections, as shown in Figure 3. As previously noted, the flange sections were attached to the web sections using a commercially available white glue and 8d ring-shank screws. All I-shaped specimens were kept in the conditioning chamber until the full-scale shear tests were conducted.

The remainder of the LVL materials was manufactured into an additional 15 I-shaped specimens for testing without moisture conditioning. Results from these tests were compared with those obtained from conditioned specimens to evaluate the effect of moisture conditioning, if any, on full-scale shear tests. In the meantime, some LVL materials randomly selected from the same production lot were tested using the small block shear test setup in accordance with ASTM D 143.

The 4-point load method shown in Figure 4 was used to test all 69 I-shaped specimens. The test apparatus, including rocker-type reaction supports, reaction bearing plates and rollers, load bearing blocks, and load bearing rollers were set up following ASTM D 198 [9]. The curved load bearing blocks had a chord length of 356 mm (14 in.) and a radius of curvature of 711 mm (28 in.). The clear distance between the edge of the reaction bearing plate to the edge of the nearest load bearing block was 2 times the specimen depth or 813 mm (32 in.) for all specimens. A load button was installed between a 890-kN (200,000-lbf) capacity load cell and load bearing block/rollers to function as a load-alignment device. Lateral supports were provided at 610-mm (2-ft) intervals along the test span to prevent lateral buckling. All specimens were cut to the exact length of 3,200 mm (126 in.) and no end overhangs were allowed.

Before testing, the web thickness for each specimen was measured at both reaction points. The mean of the readings was used to calculate the sectional properties of the specimen. Load was applied by a hydraulic cylinder at a constant rate so as to reach the ultimate load in about 10 minutes. The load readings were continuously recorded by a computerized data acquisition system up to the ultimate load. As verification of LVL stiffness was not part of this study, no deflection readings were recorded.

After testing, a 152 x 152 mm (6 in. x 6 in.) section was cut from the web of each tested specimen at about 305 mm (12 in.) away from each specimen end for determining the moisture content and specific gravity of each specimen in accordance with the oven-drying method of ASTM D 4442 [10] and D 2395 [11], respectively.

Based on the theory of elasticity, the maximum applied shear stress ($f_v$) can be calculated using the following equations:

$$f_v = \frac{VQ}{It} = \frac{3V[b(h^2 - h_1^2) + t h_1^2]}{2t(bh^3 - bh_1^3 + th_1^3)} \qquad [1]$$

where $f_v$ = calculated shear strength (MPa)
$V$ = applied ultimate shear force (N) = 1/2 of the ultimate load
$Q$ = first moment ($mm^3$)
$I$ = moment of inertia ($mm^4$)
$t$ = measured web thickness (mm)
$b$ = measured flange width (mm)
$h$ = measured height of the I-section (mm)
$h_1$ = net height of the web between flanges (mm)

As previously mentioned, the materials used for the flanges were intentionally matched with those used for the web. Therefore, the first moment (Q) for each specimen can be determined without calculating the transformed section.

## 5. Results and Discussions

All 54 specimens that were conditioned and 15 specimens that were not conditioned (as-received) failed in shear. The typical failure mode was shear through the web at one of the supports near the neutral axis of the I-section, as shown in Figure 5. Table 1 summarizes the test results.

Data distributions for both conditioned and as-received specimens are shown in Figure 6 with an empirical normal distribution overlaid. As seen from Figure 6, the normal distribution fits the test data well. Based on the Kolmogorov-Smirnov statistical test, the assumed normality for the distribution function cannot be rejected at the 20% statistical significance level (the higher the significance level, the easier to reject the null hypothesis assuming the test data have the same distribution as the underlying empirical function).

Table 1. Summary statistics for all shear specimens

| | Moisture-Conditioned | | | Without Moisture Conditioned | | |
|---|---|---|---|---|---|---|
| | MC, % | SG[a] | $f_v$[b], MPa | MC, % | SG[a] | $f_v$[b], MPa |
| N | 50[c] | 50[c] | 54 | 15 | 15 | 15 |
| Mean | 9.0 | 0.51 | 5.10 | 6.8 | 0.52 | 5.04 |
| COV | 0.030 | 0.028 | 0.060 | 0.057 | 0.035 | 0.045 |
| Range | 8.3 - 9.8 | 0.48 - 0.55 | 4.29 - 5.87 | 6.3 - 7.6 | 0.47 - 0.55 | 4.61 - 5.51 |

[a] Based on the oven-dry weight and as-received volume of the web.
[b] Shear stress calculated based on Equation 1.
[c] Data for 4 specimens were unavailable.

Figure 5. Typical shear failure from full-scale LVL shear tests

Characteristic values (the 5th percentile with 75% confidence) for the conditioned and as-received specimens are given in Table 2, which shows that the characteristic values are practically identical between the specimens with and without the moisture conditioning. The standard error on the characteristic value is approximately 1.5% for the conditioned specimens and 2.0% for the as-received specimens, which are within the typically acceptable range of 5% for the mechanical properties of engineered wood products.

Table 2 and Figure 6 also show the small block shear test results in the edgewise orientation. As shown, the ratio of the mean shear strength between the small block shear and moisture-conditioned full-scale shear is 1.52. However, due to the higher COV in the block shear test results, the ratio of the characteristic shear strength between the small block shear and full-scale shear tests is only 1.42. It should be noted that the mean block

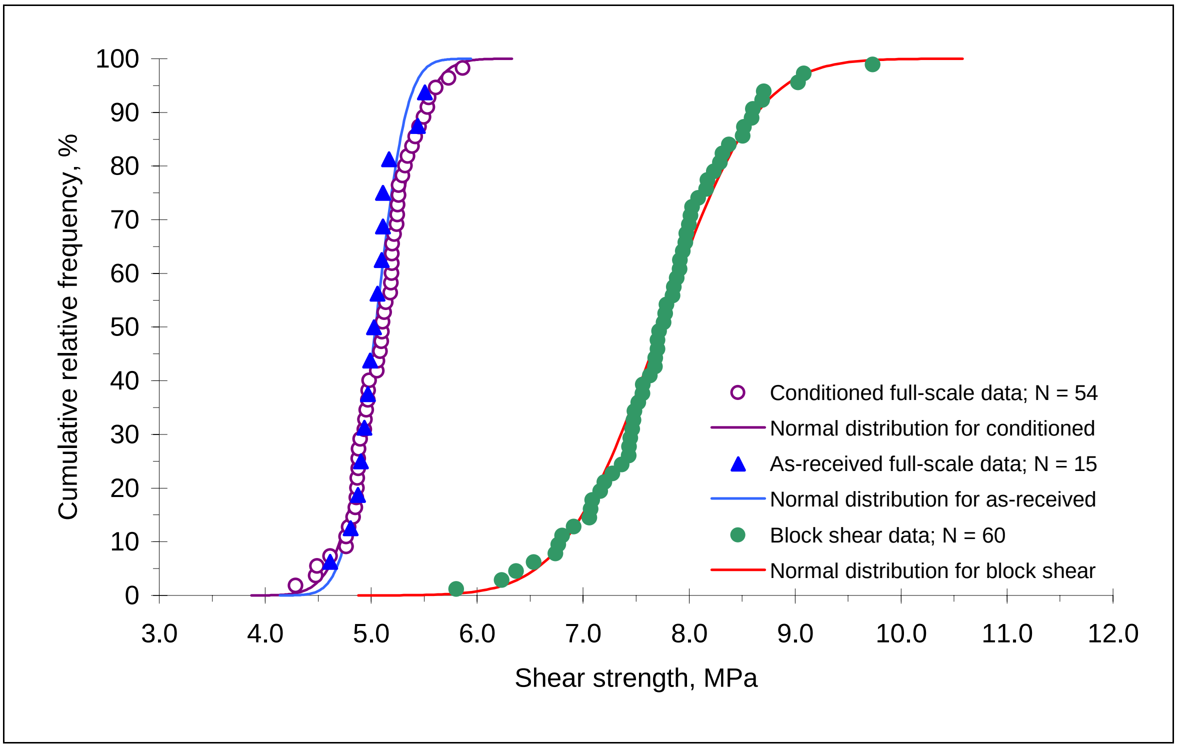


Figure 6. Data distribution for full-scale (conditioned & as-received) and block shear tests

shear value of 7.73 MPa is comparable to the value of 7.52 MPa, as published by Lam and Craig [4]. However, the mean full-scale shear value obtained from this study (5.10 MPa) is much lower than the value of 6.83 MPa (44 x 184 mm specimens) or 6.39 MPa (44 x 302 mm specimens) reported by Lam and Craig [4].

Table 2. Characteristic shear strengths

| | Small block shear | Full-scale shear | |
|---|---|---|---|
| | Moisture conditioned | | As-received |
| N | 60 | 54 | 15 |
| Mean, MPa | 7.73 | 5.10 | 5.04 |
| COV | 0.092 | 0.060 | 0.045 |
| K[(a)] | 1.795 | 1.804 | 1.991 |
| LTL[(b)], MPa | 6.45 | 4.54 | 4.59 |
| SE[(c)], % | 2.3 | 1.5 | 2.2 |

(a) Obtained from Table 3 of ASTM D 2915 [12] at the 5th percentile with 75% confidence
(b) Lower tolerance limit = Mean x (1 - K x COV) based on an assumed normal distribution
(c) Standard error on the lower tolerance limit estimate determined in accordance with ASTM D 2915 [11]

A significance difference between these 2 reports is the specimen size (44 mm x 302 mm x 1812 mm used by Lam and Craig [4], and 44 mm x 406 mm x 2845 mm used in this study). It is recognized that the specimens used between these 2 studies were not manufactured by the same producer, and the layup and species were not the same. Nonetheless, the specimen configuration and test setup used between these 2 studies were similar. Therefore, if the small block shear strength is an indication of the similarity in the LVL materials tested between these 2 studies, the difference in the test results seems to suggest a notable size effect. As a result, for the development of a design shear value, it is imperative that the size effect on the LVL shear strength be addressed by selecting an appropriate specimen size for full-scale shear tests. As previously mentioned, since most LVL products used in light-frame construction in North America are generally limited to 406 mm (16 in.) in depth, the specimen size selected for this study seems to be reasonable and practical. Alternatively, a minimum of 4 sizes should be tested so that the appropriate size effect can be quantified in a similar manner as the volume effect required in ASTM D 5456 [7].

# 6. Additional Data

In a separate study undertaken soon after the completion of this study, another set of 29 pieces of 44 mm (1-3/4 in.) specimens made with 6 plies of 3.2-mm (1/8-inch) thick Western Hemlock Grade 1 and 7 plies of 4.2 mm (1/6-inch) thick Western Hemlock Grade 2 veneers was tested in the same manner as those reported above. All 29 specimens failed in shear. The mean value obtained from the full-scale shear tests was 4.55 MPa (660 psi) with a COV of 0.07. The matched small block shear tests gave a mean of 6.83 MPa (990 psi) with a COV of 0.16. Figure 7 shows the data distribution.

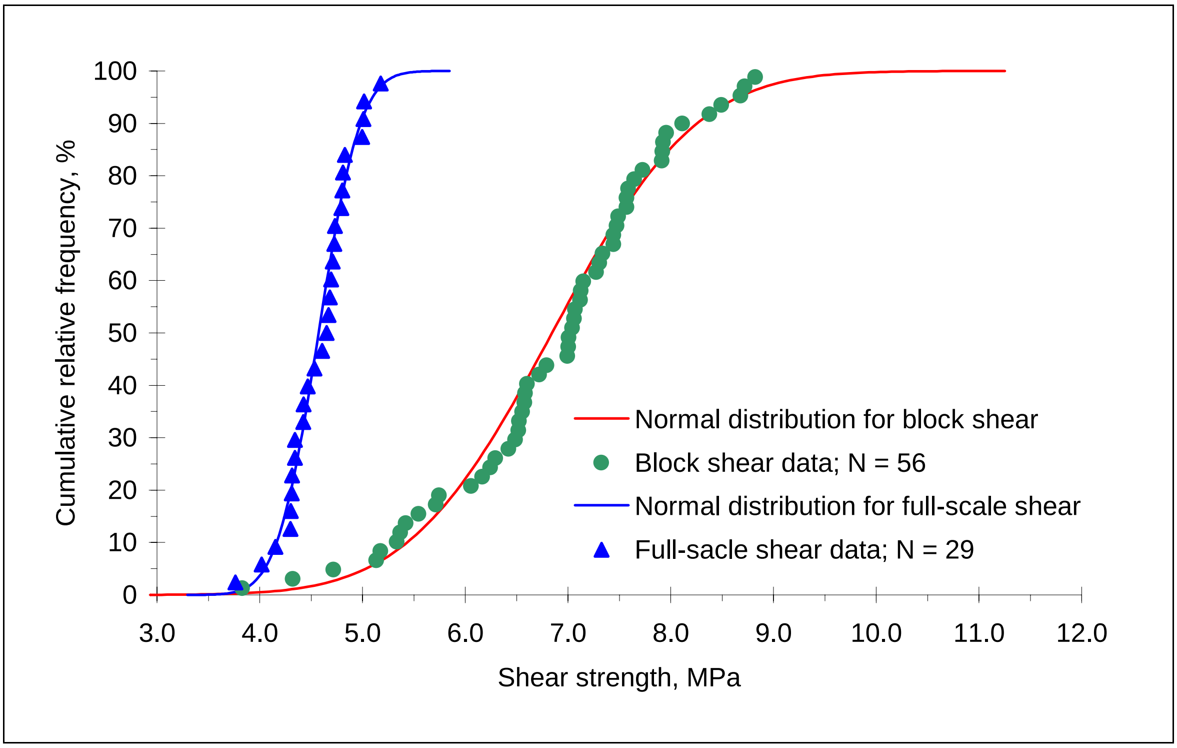


Figure 7. Data distribution for full-scale and block shear tests of Western Hemlock LVL

As shown in Figure 7, the difference in the COV between the block shear and full-scale shear test results is substantial, suggesting that the full-scale shear test method is a more reliable test method for evaluating the LVL edgewise shear strength. Incidentally, the ratio of the mean shear strength between the small block shear and full-scale shear tests is also 1.5. However, due to the higher COV for the small block shear test results, the ratio of the characteristic shear strength between the small block shear and full-scale shear tests is only 1.22.

## 7. Small-Scale QA Shear Test Method

It is impractical to use full-scale shear specimens for in-plant quality assurance (QA) tests. For monitoring the LVL edgewise shear strength on an on-going basis, a small-scale QA shear test method is needed, as shown in Figure 8.

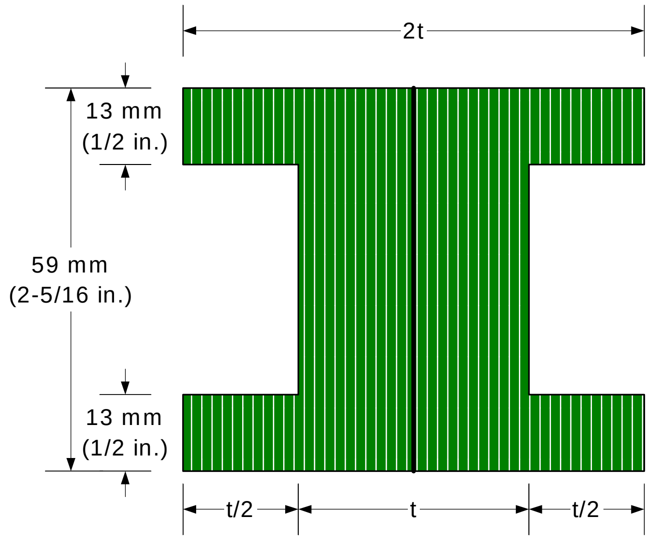

Figure 8. Specimen dimension for small-scale QA shear tests (t = LVL thickness)

The small-scale QA specimen is manufactured by gluing 2 matched LVL's back-to-back using a white glue. The web of the I-section is then created by using a router. As the specimen is small, the web can be readily produced in one single router run. Most importantly, since the web is composed of 1/2 of LVL thickness from each half specimen, the net web thickness is exactly the same as the LVL thickness, thereby preserving the high-grade and densified face veneers in the shear-resistive cross-sectional area.

Due to the small specimen depth (59 mm or 2-5/16 in.), a center-point load method with a span-to-depth ratio of approximately 6 was employed, as shown in Figure 9, for the edgewise QA shear tests. The adoption of the center-point load method, instead of four-point load method, was intended to simplify the test setup for a typical lab at a manufacturing plant. The length of the bearing plates was 51 mm (2 in.) and the loading plate had a length of 76 mm (3 in.). The testing procedures followed ASTM D 4761 [13] with a targeted time to failure of approximately 1 minute. The shear strength was calculated using Equation 1.

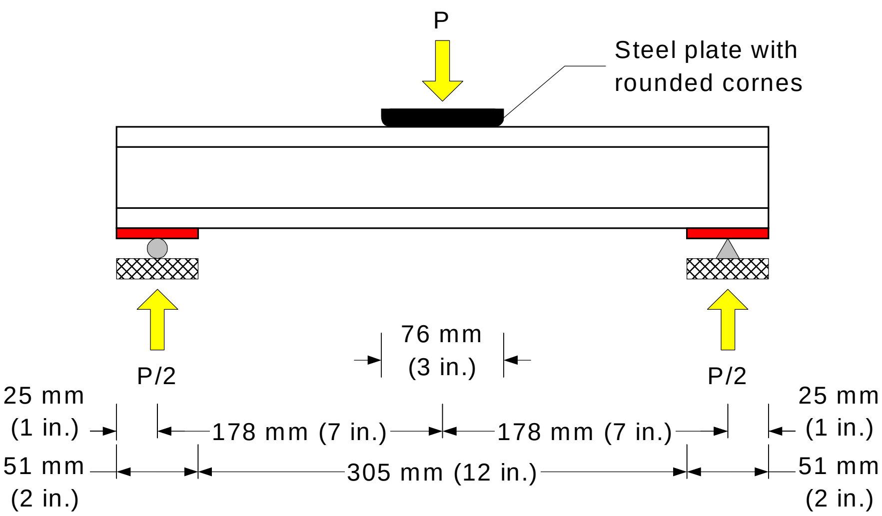

Figure 9. Test setup for edgewise QA shear tests.

The likelihood of shear failure could be estimated using the loading configuration given in Figure 9 if the bending and shear strengths of the LVL can be estimated. For example, if the characteristic bending strength of LVL is 43.4 MPa (6,300 psi) with a COV of 0.15 based on the depth of 305 mm (12 in.) and a volume effect factor of $(h/305)^{(1/8)}$, where h is the LVL depth (mm), the 5th percentile ultimate load required for bending failure using the test setup given in Figure 9 can be estimated as 25.6 kN (5,750 lbf). If the same LVL has a characteristic shear strength of 1/9 of the characteristic bending strength, but with a COV of 0.12, the 99th percentile ultimate load required for shear failure can be estimated as 24.9 kN (5,590 lbf). Since the 99th percentile of shear capacity is lower than the 5th percentile of bending capacity, the shear failure rate based on the test setup given in Figure 9 is expected to be 94% or higher. When compared to the example given for the full-scale shear tests, this example uses a higher shear-to-bending strength ratio (1/9 vs. 1/10) and a higher COV (0.12 vs. 0.10) for the shear strength.

In order to demonstrate the feasibility of using the small-scale edgewise QA shear test method, a total of 35 pieces of 38-mm (1-3/4-in.) thick Douglas fir and southern pine LVL were sampled by an APA auditor at a commercial LVL plant and shipped to the APA Research Center for testing. Eighteen of these specimens were Douglas-fir LVL's made with 2 plies of 3.2-mm (1/8-in.) thick G1, 8 plies of 3.2-mm (1/8-in.) thick G2, and 3 plies of 2.5-mm (1/10-in.) thick G1 veneers. The remaining 17 specimens were southern-pine LVL made with 14 plies of 3.2-mm (1/8-in.) thick G1 veneers. APA staff witnessed the veneer peeling, sorting, and drying processes, and the LVL manufacturing.

Table 3 shows the summary of the test results. All 18 Douglas-fir specimens and 14 out of 17 southern pine specimens failed in shear through the web. Figure 10 shows the typical failure mode, which is similar to the full-scale shear tests. Overall, the shear failure rate was 32/35 or 91%, indicating that the test method can be used for edgewise QA shear tests. The relatively low shear failure rate for the southern pine LVL reflects the higher shear-to-bending strength ratio. A change in the specimen configuration, such as an increase in the flange depth from 13 mm (1/2 in.) to 16 mm (5/8 in.) would increase the probability of shear failure for southern pine LVL.

Table 3. Summary of small-scale edgewise QA shear tests

| Species | Douglas-fir LVL | Southern Pine LVL |
|---|---|---|
| Sample size | 18 | 14[a] |
| Mean MC, % | 7.1 | 9.9 |
| Mean shear strength, MPa | 6.13 | 8.26 |
| COV | 0.079 | 0.097 |

[a] Shear failure only.

The appropriate QA shear value using the small-scale edgewise QA shear test method should be established in accordance with the correlation between the test results obtained from the small-scale edgewise QA shear (Figure 9) and the full-scale edgewise shear qualification tests (Figure 4). As a result of the size effect, the QA value is expected to be higher than the published characteristic shear strength. Unfortunately, due to the proprietary nature of most LVL products and the lack of a broad database available to the public today, the correlation between the small-scale edgewise QA shear and the published characteristic shear strength should be established from qualification tests of individual species or layup combinations unless the most critical species or layup is pre-determined and tested.

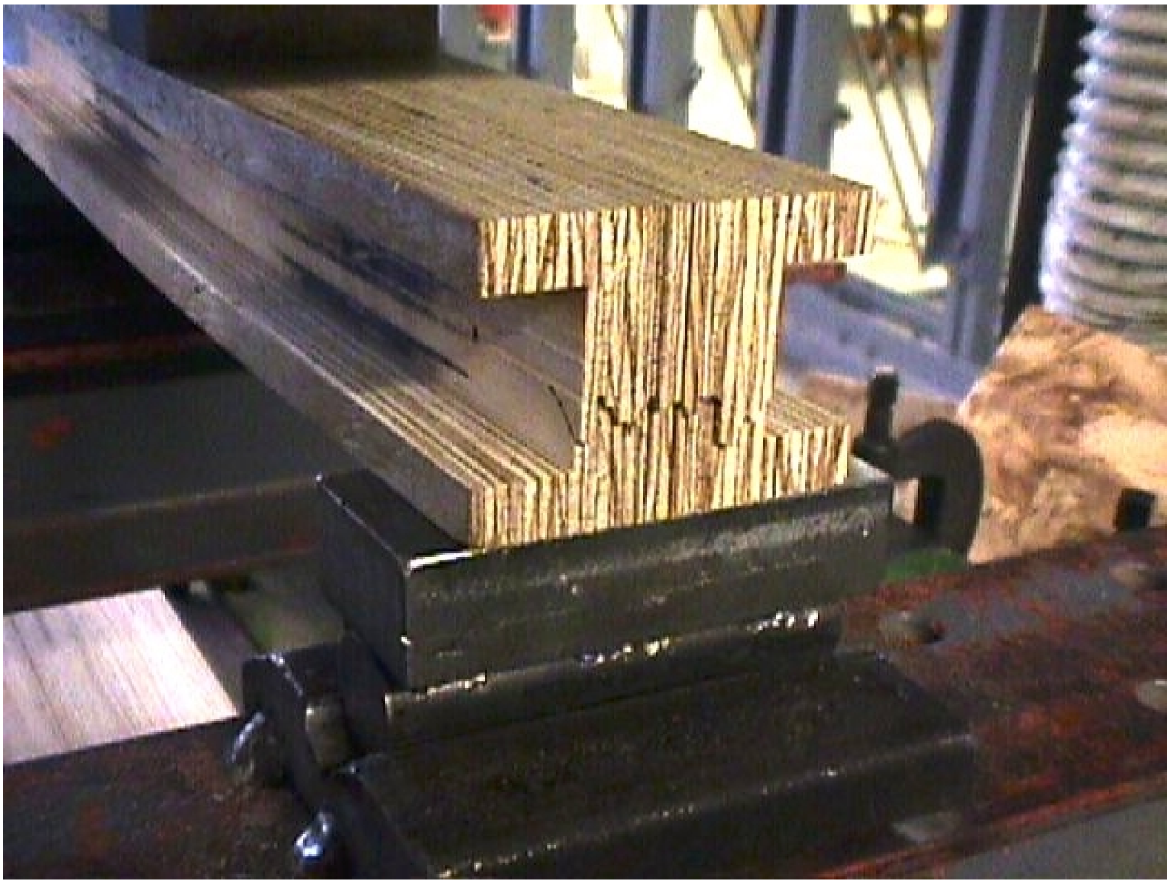

Figure 10. Typical shear failure from small-scale LVL QA shear tests

# 8. Conclusions

The following conclusions can be substantiated by the test results presented above:

- The full-scale test method used in this study is adequate for qualification of the edgewise shear strength of LVL.

- The difference in the characteristic shear stresses between the specimens tested at the standard environmental conditions (9.0% moisture content in this study) and as-received conditions (6.8% moisture content in this study) are negligible.

- The mean shear strength derived from the ASTM D 143 small block shear tests is approximately 50% higher than the mean shear strength determined from full-scale shear tests, suggesting the necessity of considering a size effect.

- The small-scale QA specimen configuration and test setup used in this study can be used for edgewise QA shear tests.

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