Exposure effects upon performance of laminated veneer lumber and glulam materials

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Abstract
Parallel laminated veneer lumber (LVL) has demonstrated tensile strengths comparable to structural lumber but with far lower variance, thus allowing higher design values. These properties have made LVL an ideal material for the tension laminations of glulam beams. This study was undertaken to study the deterioration of Douglas-fir LVL and solid-sawn glulam specimens following accelerated exposure. LVL and solid-sawn laminated specimens were tested for glueline shear strength, tension perpendicular-to-the-glueline strength, and percentage of delamination prior to and following exposure to a vacuum-pressure soak-dry schedule. The solid-sawn material exhibited higher dry strengths than the LVL but following exposure the materials differed only slightly in strength. Measurement of the percentage of delamination revealed that the solid-sawn glulam had twice the amount of splitting/separating found in the LVL. Finite-element analyses of the moisture-induced strains in the laminated materials revealed that failure of the solid-sawn sections could be caused by the variation of ring angle between laminations. The LVL was judged to be more stable than the solid-sawn material as indicated by its low incidence of delamination and high retention of glueline shear and tensile strengths.

Parallel laminated veneer lumber (LVL) has proven to be a viable means of providing the market with a high-yield structural product. Lumber-type products can be produced by parallel laminating rotary-peeled veneer into thick panels for subsequent sawing to a desired width. A higher strength product can be produced by this method from low-grade logs, due to the dispersion of defects from veneer to veneer, than could be realized by sawing the same low-grade log (13). The commercial product reported on by Nelson (10) nearly 10 years ago has demonstrated the potential of manufacturing high-tensile strength LVL from thin laminated veneers.

A recent paper by Braun and Moody (6) elucidated the benefits of utilizing this reconstituted wood product for tension reinforcement of glue-laminated beams. Design strengths of these beams were 10 to 20 percent higher than beams with traditional lumber tension laminations. The LVL material has, in general, higher allowable stresses due to reduced property variance and possibility for production of virtually unlimited lengths.

An important facet in assessment of LVL substitution for critical glulam members is the comparison of the effects of weathering upon the strength and appearance of these products. A particular concern which was addressed by this study is the use of abrasive planers for surfacing LVL. A study by Jokerst and Stewart (8) has indicated that gluelines with abrasive-planed surfaces were similar to knife-planed glued surfaces in shear strength and were higher in percentage of wood failure but lower in resistance to glueline separation upon accelerated aging.

Microscopic examination revealed that abrasive planing caused crushing and tearing of the wood surface while knife planing produced an undamaged surface. They attributed the lower resistance to glueline separation of the abrasive-planed material to excessive swelling of the crushed cells upon wetting and the lower strength in the damaged area both of which allowed delaminations to form.

A recent study by Sandoe et al. (12) utilized a tension perpendicular-to-the-glueline test to investigate glued-laminated beam strengths following an accelerated exposure. This test was purported to be a more sensitive indicator of gluebond integrity than the standard shear-block test. Due to these findings, the tension
perpendicular-to-the-glueline test was also used for evaluating the various gluelines of concern in this investigation.

This study was undertaken to study the deterioration of Douglas-fir LVL and solid-sawn glulam specimens following an accelerated exposure test to simulate severe service conditions. The shear and tension perpendicular-to-the-bondline strengths were measured prior to and following exposure to a vacuum-pressure soak (VPS)-dry schedule. Qualitative observations were made of the resistance to VPS exposure of the two material types. Analysis of the moisture-induced stresses in radially and tangentially laminated members by finite-element techniques provided a quantitative explanation for the differing integrities of solid-sawn and laminated veneer members.

Materials and methods

Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) lumber and veneer were used to fabricate the beams. Fabrication of the LVL and glulam beams was performed by production personnel using production methods and equipment to obtain materials with properties representative of those that could be expected on the market.

The LVL material consisted of nine plies of Grade C (Product Standard PS 1-74) (14) rotary-peeled veneer nominally 0.08 to 0.10 inch thick. The veneer was bonded using a commercial hot-press phenolic adhesive mixture which represented usual plywood industry formulations, with a spread rate of 62 pounds per thousand square feet of double-spread glueline. Pressing time was 11 minutes, at 285°F, with 140 to 175 pounds per square inch (psi). The 4- by 8-foot panels of LVL were subsequently abrasively planed with 36, 60, and finally 80 grit to yield a finished thickness of 3/4 inch. Face plies of the LVL were a minimum 0.03 inch thick following the abrasive planing. Ripping of the LVL panel produced a nominal 1- by 6-inch lumber product.

The solid-sawn lumber (SSL) used in fabricating the beams required consisted of select structural grade (16) nominal 2-by 6-inch pieces of Douglas-fir. Surfacing of the lumber with a production knife planer produced 16 knife marks per inch.

Lamination of the 3/4- by 6-inch LVL and 2- by 6-inch lumber provided four beams of the configuration shown in Figure 1(a) and eight of the type shown in Figure 1(b). A phenol-resorcinol adhesive was applied to the laminations with an extruder at a spread rate of 65 lb./1,000 ft.² of glueline. Total open and closed assembly time did not exceed 30 minutes with the pieces at 70°F and moisture content of the SSL at 10 percent, LVL at 8 percent. The curing schedule was 4 hours at 70°F followed by 6 hours at 90°F while under pressure.

Specimen fabrication, conditioning, and testing

For evaluation of tension perpendicular-to-the-glueline and shear strength specimens of the configurations of ASTM D 143 (2) and ASTM D 905 (3) were prepared (Fig. 2a, b). The gluelines which were tested were of four types: a) veneer/veneer (within the LVL), b) LVL/LVL (between LVL), c) LVL/SSL, and d) SSL/SSL. Eight replicates were fabricated from each of three beams for each glueline type and mechanical test. This provided 12 specimens for dry testing and 12 for testing after VPS exposure. In addition, specimens for measurement of delamination after VPS exposure by the procedures of ASTM D 2559 (4) were obtained (Fig. 2c). Eighteen replicates produced a total of 360 inches of end grain glue-joint for each glueline type.

Briefly, the VPS exposure consisted of:

**Cycle 1** – Submerge specimens in 75°F water bath, draw vacuum for 5 minutes, then apply pressure of 75 psi for 1 hour. Repeat the vacuum-pressure cycle again followed by 21 hours of drying at 150°F in air with less than 15 percent relative humidity (RH).

![Figure 1. – LVL/Lumber glulam beam configurations: a) Solid-sawn, knife-planed and b) LVL/solid-sawn composite.](image)
a) Tension perpendicular to glueline specimen

b) Shear strength along glueline specimen

c) Glueline resistance-to-delamination specimen

Figure 2. – Specimen geometries.

Cycle 2 – Steam specimens at 212°F for 90 minutes, submerge in 75°F water at a pressure of 75 psi for 40 minutes, and dry as in Cycle 1.

Cycle 3 – Repeat Cycle 1 but dry specimens to approximately 30 percent moisture content (MC) prior to measuring delamination. The higher MC in the center portion of the specimens will hold the separations and splits of the dry exterior open to facilitate their measurement.

Conditioning of the dry mechanical test specimens was limited to placing them in a conditioning chamber at 80°F, 65 percent RH until their MC stabilized. Accelerated exposure of the remaining tension and shear specimens was accomplished by subjecting them to two periods of Cycle 1, described previously. Thereafter, these exposed specimens were allowed to reach equilibrium at 80°F, 65 percent RH.

Mechanical testing was performed in accordance with ASTM D 143 (2) (tension perpendicular to grain) and ASTM D 905 (3) (glueline shear strength). Recordings were made of the glueline load at failure and the percentage of wood failure for each specimen.

The resistance to delamination specimens was probed to determine the length of separations which occurred within 0.10 inch of the glueline. A feeler gage 0.005 inch thick and 0.10 inch wide was used to probe each glueline of consideration. The procedure for this measurement is described more fully in ASTM D 2559 (4), with the exception from the standard being the inclusion of separations which were parallel to, but within 0.10 inch of, the glueline.

An additional measure of delamination was also made. The side grain delaminations and splits which propagated from a specimen edge were to be disregarded according to ASTM D 2559 specifications for measurement of separated gluelines. These edge separations were measured in this study to provide comparative data between the various glued materials. The edge split results in a stress concentration and a reduction in effective horizontal shear capacity which makes it a more critical structural defect than an interior separation (11).

Results

A summary of the test results and statistics is given in Table 1. Means and standard deviations are given for shear and tensile strengths with an average percentage of wood failure. Delamination during accelerated exposure is represented by a percentage of the total glueline evaluated. The Smith-Satterthwaite test (9) was used to compare the means of each test for significantly similar results at a 95 percent confidence level.

Data from the tension perpendicular-to-the-glueline tests indicated:

1. Dry tension strengths of the SSL/SSL specimens were higher than other glueline types and exhibited 100 percent wood failure.
2. The SSL/SSL bondline failed with a higher average percentage of wood failure than other gluelines.
3. Following VPS exposure, the test statistics could not identify any significant difference in tensile strengths for the four glueline types.

Figure 3 illustrates these findings with the use of a 95 percent confidence interval for each glueline both before and after VPS exposure.

Block shear test results did not reveal any conclusive statistics other than to substantiate what the tension tests had revealed, that the SSL/SSL glueline deteriorated to a greater extent, percentagewise, than the other gluelines when comparing data from exposed and unexposed specimens. However, in all cases, the SSL/SSL bonds retained higher strengths than the other types. Figure 4 shows the 95 percent confidence intervals for the shear tests. The percentage of wood failure could not be used to differentiate LVL and SSL in the shear tests as was the case for the tension tests.

Delamination data from specimens subjected to the ASTM 2559 (4) test (Table 1) show the increased
### Table 1. Results and statistics for mechanical and delamination tests.

<table>
<thead>
<tr>
<th>Test</th>
<th>Condition</th>
<th>A (VEN/VEN)</th>
<th>B (LVL/LVL)</th>
<th>C (LVL/SSL)</th>
<th>D (SSL/SSL)</th>
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<tr>
<td>Tension perpendicular</td>
<td>Dry X (psi)</td>
<td>97&lt;sup&gt;a&lt;/sup&gt;</td>
<td>110&lt;sup&gt;c&lt;/sup&gt;</td>
<td>138</td>
<td>232</td>
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<td>ASTM D 143</td>
<td>S (psi)</td>
<td>33</td>
<td>29</td>
<td>35</td>
<td>48</td>
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<td></td>
<td>Wood</td>
<td>93</td>
<td>70</td>
<td>75</td>
<td>100</td>
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<tr>
<td></td>
<td>Aged X (psi)</td>
<td>93&lt;sup&gt;a&lt;/sup&gt;</td>
<td>86&lt;sup&gt;c&lt;/sup&gt;</td>
<td>88&lt;sup&gt;a&lt;/sup&gt;</td>
<td>117&lt;sup&gt;a&lt;/sup&gt;</td>
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<td></td>
<td>S (psi)</td>
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<td></td>
<td>Wood</td>
<td>81</td>
<td>86</td>
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<tr>
<td></td>
<td>Percent of dry strength</td>
<td>96</td>
<td>78</td>
<td>64</td>
<td>50</td>
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<td>Shear</td>
<td>Dry X (psi)</td>
<td>998&lt;sup&gt;a&lt;/sup&gt;</td>
<td>869&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1,126</td>
<td>1,252</td>
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<td>ASTM D 905</td>
<td>S (psi)</td>
<td>207</td>
<td>190</td>
<td>190</td>
<td>362</td>
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<td>Wood</td>
<td>86</td>
<td>69</td>
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<td></td>
<td>Aged X (psi)</td>
<td>401&lt;sup&gt;b&lt;/sup&gt;</td>
<td>841&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1,005&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>Wood</td>
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<td>86</td>
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<td></td>
<td>Percent of dry strength</td>
<td>100</td>
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<td>89</td>
<td>86</td>
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<td>Aged delamination</td>
<td>Percent delams internal</td>
<td>3.5</td>
<td>3.3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.8&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>ASTM D 2559</td>
<td>Percent edge delams</td>
<td>0.0</td>
<td>2.3</td>
<td>0.7</td>
<td>2.9</td>
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</table>

<sup>a,b</sup>Indicates other similar marked values in the same row are from the same population when analyzing at a 95% significance with the Smith-Satterthwaite (9) test corrected for the number of degrees of freedom.

Tendency of the SSL/SSL glueline to delaminate or split. The other three gluelines are statistically similar to each other and have approximately half of the percentage of separation detected in the SSL/SSL bondline. Edge delamination data reveal the SSL/SSL and LVL/LVL gluelines to have the greatest percentages of separations. The LVL/SSL and veneer/veneer bondlines exhibited little and none of the edge separations, respectively.

Examination of the various gluelines at the microscopic level revealed a fairly smooth, undamaged surface produced by the knife planer. Veneer peeling produced an irregular surface with only slight damage to individual surface cells. The abrasive planer created a slightly irregular surface with cell crushing evident at a four- to eight-cell depth in the earlywood. The latewood of the abraded surfaces showed a minor tearing of the outermost cells only, not the extent of crushing as in the earlywood.

### Discussion

Testing of various veneer, LVL, and SSL Douglas-fir gluelines has brought several interacting phenomenon to light. Tension perpendicular-to-the-glueline testing showed knife-planed SSL material to be higher in tensile strength than veneer and LVL. Knife checking and uneven surfaces due to the peeling operation, as well as the surface degrade of the abrasive planing, are probable causes for the lower tensile strength of these bondlines. After the VPS exposure, the SSL knife-planed material, the veneer, and the LVL material exhibited statistically similar tensile strength perpendicular to the glueline. Evidently, the mechanisms which caused reduction of the SSL tensile strength were very different from those which affected the LVL or veneer. VPS exposure caused 4, 22, 36, and 50 percent strength losses for the veneer/veneer, LVL/LVL, LVL/SSL, and the SSL/SSL bondlines, respectively.

Shear testing of the various bondlines in the dry condition resulted in data which reflected the low shear strength of the veneered material. Following the accelerated exposure aging, the degradation of the veneered materials was low (less than 3%) while the SSL/SSL bondline lost an average of 14 percent.

Measurement of bondline separation after exposure by the cycle specified in ASTM D 2559 supplied results...
which provided correlation with the mechanical testing. Excessive delamination of the edges and interior of the SSL/SSL gluelines was probably the cause of the reduction in tensile and shear strengths exhibited by the exposed SSL material. Edge delaminations recorded for the LVL could probably be attributed to the surface degradation of abrasive planing as observed microscopically.

An apparent disparity between the results of Jokerst and Stewart (8) and this study is that in the previous work larger amounts of glueline separation were measured for the abrasive-planed material than for the knife-planed. An obvious reason for this difference is that all of the previous work used 2- by 6-inch SSL which is subject to checking upon wetting and drying due to moisture induced differential straining as shown in (17). LVL material apparently reacts quite differently in that microchecks induced by the veneer-peeling operation prevent excessive stresses from arising and the defect dispersal of laminating minimizes potential stresses at the outset.

In an attempt to explain the apparent difference in mechanisms acting to produce delaminations and splitting in LVL and SSL, a finite-element analysis (15) was performed to quantify the stresses acting within a glulam section as a result of moisture-induced differential expansion. Basically, the model simulated 2- by 6-inch members with differing ring angles bonded together while at 10 percent MC. These members were then assumed to be wetted to 27 percent MC, the fiber saturation point. Differential expansion of the 2- by 6-inch members, due to the introduction of moisture, was calculated using the results of Comstock (7) for coast-type Douglas-fir.

The maximum shear and tensile stress perpendicular-to-the-glueline which were predicted by the finite element analysis to occur in the structural model of a glulam cross section are plotted in Figure 5(a). The limiting values of tension perpendicular-to-the-glueline strength (Table 1) and rolling shear strength (5) are also shown. Both the tensile and shear stresses exceeded the SSL strengths by a ratio of 8:1 or more when a flat-sawn member is laminated to a quartersawn piece as shown in Figure 5(b). The induced stresses vanish when the two members have the same ring angle. SSL strength and induced stress are coincident at ring angles of 65 degrees for rolling shear and 75 degrees for tension perpendicular to the glueline (Fig. 5(a)).

In practical terms, the analysis shows that adjacent laminated members whose ring angles differ by more than 15 degrees are likely to split or delaminate when wetted to the fiber saturation point. In addition, the analysis shows that the induced stresses are greatest at the outside edge of the beam near the bondline; thus, most horizontal splits should occur in that vicinity.

In SSL laminated members, diversity of grain angle is usual, thus leading to high stresses, checking, and delamination upon being subject to cyclic moisture environments. The LVL members, on the other hand, do not possess large variations in grain angle. Due to their rotary-cut nature, the majority of veneer materials behave as flat-sawn members upon wetting. Also, the veneer materials are extensively checked prior to assembly thus providing stress relief. Lastly, due to the low grain angle, stresses that do develop if the LVL were bonded to a higher grain angle member would be compressive, not tensile, closing any existing checks.

Figure 6 illustrates the level of degradation in the specimens subjected to the VPS exposure of ASTM D 2559. Note the extent of bondline splitting of the SSL cross section (Fig. 6(a)). Distortion of the normally straight edge is a direct consequence of the differential expansion of each member in the beam cross section. In comparison, the composite beam section of Figure 6(b) has less dramatic bondline separations but more extensive veneer checking. The majority of these veneer checks are probably produced in peeling the veneer.
Figure 5a). — Maximum predicted stresses induced in a saturated laminated member versus growth ring angle from glueline. b) Predicted stresses induced in a quarter-sawn member laminated to a flat-sawn member.

Figure 6. — Cross sections of beams after VPS exposure and partial drying: a) SSL glulam and b) LVL/SSL glulam.
Edge separations in the LVL material are quite evident at the LVL/LVL bondline with low occurrence at the veneer/veneer bond (Table 1). This may be a consequence of the abrasive planing of the LVL surfaces or the use of a different adhesive in these bondlines.

Application of this study's results to answer questions concerning LVL performance must be limited to qualitative comparisons. The LVL exhibited lower shear strength than the SSL, both dry and after VPS exposure. This observation should be tempered with the knowledge that the LVL/LVL bondline retained 97 percent of the dry shear strength following accelerated exposure, while the SSL/SSL retained only 86 percent.

The maximum horizontal shear stress allowed for Douglas-fir in laminated beams is specified by AITC (1) as 95 psi. This figure is meant to reflect the “conservative assumption of the most severe checks, shakes, or splits possible, as if a piece were split full length.” One of the clear inferences of this research is that LVL does not display the extent of splitting and checking seen in solid wood. Analysis indicated the cause of these deteriorations in laminated solid lumber. Effects of the moisture-induced swelling in the solid-sawn laminated section overshadowed any comparison which could have been made between knife-planed or abrasive-planed surfaces.

Conclusions

The results of this study justify the following conclusions:

a. Tension perpendicular-to-the-glueline strengths were higher for solid-sawn knife-planed material than for veneer or laminated veneer lumber (LVL) gluelines; but, all gluelines exhibited approximately the same strength following VPS exposure.

b. Dry shear strengths were higher for the solid-sawn knife-planed materials, though after VPS exposure the differences between materials were lessened.

c. More delaminations were detected for the solid-sawn knife-planed material following VPS exposure.

d. Increased tendency for the sawn material to delaminate and to exhibit extensive degradation of material and glueline strengths was attributed to moisture-induced differential expansion of the laminated members.

e. Due to its resistance to splitting, checking, and delamination, LVL appears capable of exceeding the performance criteria now set for exposed glue-laminated solid-sawn members.

Literature cited


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