Parallel-laminated veneer: processing and performance research review

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Abstract

The use of parallel-laminated veneer (PLV) for critical structural elements has proven commercially feasible for more than a decade. The uniformity of this material's mechanical properties has made it popular for truss components, I-beam flanges, scaffold planks, and other engineered members.

Research during the last 15 years has indicated a number of correlations between processing parameters and PLV product performance such as veneer quality influence upon tensile and bending properties and the efficiency of various jointing methods. In addition to summarizing these findings, this paper contains recommendations for further study.

This paper presents an overview of the parallel-laminated veneer (PLV) processing and performance technology developed and reported on in the last 15 years. The variety of PLV's product applications (not documented herein) provides an indication of its general appeal. As our raw material supply diminishes in quality and volume, PLV's higher yield potential and adaptability to engineered end-use design will be welcomed by manufacturers and users alike.

Approximately 10 years have passed since PLV products first appeared in the marketplace, in trusses, as substitutes for select structural lumber components. Since that time, PLV has been used for joists, box beams, planks, and ladder rails.

PLV is processed in a manner similar to plywood, but contains only parallel laminations. Also called laminated veneer lumber (LVL), its machinability and uniformity of mechanical properties have been appreciated by the furniture industry for several decades to produce curved furniture parts.

Parallel-laminated Sitka spruce veneer was studied in the 1940s (30) for constructing high-strength wood aircraft members. At that time, its additional manufacturing cost was justified by its dependable performance. Since that time, dwindling supplies of high-quality saw logs have made PLV attractive and economically feasible in products formerly constructed of the highest grades of solid wood.

One attribute of PLV processing is the increased yield made possible by peeling a given log, as compared to the kerf losses associated with traditional sawing techniques. Its highly dependable design strength makes it competitive with stress-graded lumber. Strength is achieved mainly because, when the material in a low-grade log is reconstituted into PLV, strength-reducing defects are distributed throughout the volume of the member, minimizing the amount of low-strength wood in any cross section.

The variables that must be taken into account in predicting the mechanical properties of a PLV product include the number of veneer laminations, the size and distribution of defects, the efficiency of veneer end joints, the quality of the bond, the strength of the clear wood, and the depth and frequency of knife checks. Accurate analytical models for predicting mechanical properties have yet to be published, but stiffness tests (stress-wave timing) and visual veneer-grading methods are used to nondestructively bracket mechanical properties. Increasing the number of laminations in a specific configuration creates a more uniform product, but increases production costs.

Processing PLV

Basic processing schemes

Nearly all schemes presented to produce PLV for structural use somewhat resemble those of established plywood operations. Veneer is rotary peeled, dried, spread with adhesive, laminated in the desired con-
figuration, pressed either in conventional plywood presses or on a continuous or step basis, then ripped to width. Processing innovations have been developed largely to accommodate the performance requirements of specific end products.

Continuous pressing of PLV is currently used in commercial manufacture of MICRO=LAM® (22) and by Metsaliiton Teollisuus Oy, Finland, for producing Kertowood® (14). Descriptions of these processes are unpublished, except for the use of phenol-formaldehyde resin and 1/8- to 1/10-inch veneers.

To produce its Press-Lam®, the Forest Products Laboratory (FPL) rotary peeled veneer, press dried it, spread the sheets with adhesive, hot laminated them with staggered butt joints, and step pressed them in a cold end loading press (12, 13). One major drawback of this process was its reliance on residual drying heat in order to cure the adhesive; this necessitated short assembly times, but resulted in short press cycles. To make Press-Lam’s manufacture feasible required two pieces of new equipment: a continuous press dryer for veneer and a continuous cold-press.

Continuous hot-pressing (2) was used to press 1/4-inch cold veneer into a 1-1/2-inch-thick panel; veneers were laminated sequentially to form 1/2-inch-, 1-inch-, and finally 1-1/2-inch-thick products. An end-loading hot-press and an intermittent press sequence were also used (2) for producing continuous PLV panels. Methods of end jointing 3/4-inch-thick 8-foot panels have been investigated (5, 6, 36), in order to make PLV production feasible in existing plywood plants, since the end jointing of 8-foot panels requires less capital investment than does that of a continuous-press system.

Butt joints.—Though they are inherently simple to manufacture, butt joints have numerous drawbacks (Fig. 1a). The joints cross the entire veneer width, subjecting each lamina to an artificial defect every 100 inches. Acceptability depends on the number of laminations and the quality of the veneer. Press-Lam®’s 1/4-inch and thicker veneers were particularly degraded in nominal 2-inch thicknesses due to its few laminations. Stresses around butt joints, analyzed photoelastically (15), indicated that lateral separation of joints by 16 lamination thicknesses prevented stress interaction of adjacent butt joints.

Tensile failures at butt joints were shown to differ significantly (21) in 1/4-inch veneer and 1/10-inch veneer PLV. A 1/10-inch veneer joint failed from its outer butt joint straight through the cross section of the member, while the 1/4-inch failure turned 90 degrees from the outer butt joint and followed the bondline to the next butt joint. More study of butt joint mechanics is needed to quantify the influences of veneer thickness, joint spacing, and veneer quality on the performance of butt joints in PLV products.

Lap joints.—The crushed lap joint (Fig. 1b) is currently used on the commercial product MICRO = LAM®. No performance research data have been published other than code-approved stress values (33) for products in which lap joints are staggered within a cross section. The high processing pressures that are used to crush these overlapping veneer joints may result in some springback (with resultant interply cleavage) after the material reaches equilibrium in moisture content (MC). These processing pressures also increase the overall density of the PLV product.

Scarf joints.—Scarf joints for individual veneers (Fig. 1c) were (31) used as the outer plies in creating 1/8-inch veneer PLV 2 by 4’s. In that application, 1:12 slopes were cut on the veneer ends, which were then bonded with a phenol-resorcinol adhesive. Strip-tension tests of this joint indicated that a median strength of 8,000 psi could be achieved.

In a limited test (31) of the use of scarf jointing in the outer lamination of an otherwise staggered butt joint C-grade veneer PLV 2 by 4, tensile strength proved more than 25 percent greater than in 2 by 4’s that had butt joints throughout. The percentage of initial failure in outer ply joints was approximately 60 percent in the

![Figure 1](image-url)
butt jointed 2 by 4's but only 20 percent for members with scarf jointed outer plies. Eliminating the outer ply's butt joints did more to improve product performance than could be attributed solely to the structural scarf joint.

**Graphite-fiber reinforced butt joints.**—Butt joints were reinforced (Fig. 1d) with high-strength 0.015-inch-thick unidirectional graphite-fiber composite impregnated with a phenol-formaldehyde resin (27). Tension tests were performed on specimens made of four 3/8-inch Douglas-fir veneers that contained one butt joint in a middle veneer. No statistically improved strength was substantiated using a single layer of reinforcement on each side of the butt joint. However, the use of two layers of reinforcement did result in approximately 10 percent more tensile strength than in the unreinforced material. When the joint was analyzed by finite-element methods, joint stresses were shown to relate to changes in reinforcement stiffness and length of overlap. In these experimental joints, failures initiated at the butt joints, and the reinforcement supported additional loading until the specimens failed completely.

**PLV jointing.**—End jointing, using conventional plywood manufacturing techniques, of nominal 1-inch-thick PLV produced in 4- by 8-foot panel sizes was studied (5, 6, 36) primarily to find suitable jointing technology to produce structural-length tension-laminated stock from panel-length PLV. The joints investigated included commercially produced 1:9 slope scarf joints (Fig. 2a), horizontal finger joints (Fig. 2b), and vertical finger joints (Fig. 2c). C-grade Douglas-fir veneer in 1/10-inch thickness was laminated to produce nominal 1-inch material. Limited sample sizes require that tension-test results be compared to unjointed PLV as control.

Tensile strength retained by the joints averaged nearly 95 percent (compared to unjointed PLV) for the scarf joint, 83 percent for the vertical finger joint, and 71 percent for the horizontal finger joint. Nominal 2-inch material jointed with the offset plain scarf (Fig. 2d) and with the three-stage scarf joint (Fig. 2e) both showed tensile strength retention greater than 95 percent.

Preproduction testing was carried out on the Lamineer® PLV, which has vertical finger joints between panel-length PLV pieces. Results justified a tensile design stress $(F_t)$ of 2,200 psi for the jointed product and 2,400 psi for the unjointed (7) (Table 1).

**Adhesive bonding**

Basic plywood bonding technology can be used in PLV processing, so little additional development was required. High laminating costs have led to studies of several cost-cutting methods since the rising costs of

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**Figure 2.** — Structural end joints for PLV panels: a) scarf, b) horizontal finger, c) vertical finger, d) offset plain scarf, and e) three-stage scarf (folded).

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**TABLE 1.** — Code-approved allowable design figures for commercial products made of 1/8- to 1/10-inch Douglas-fir veneer.

<table>
<thead>
<tr>
<th>Commercial name</th>
<th>Specimen size</th>
<th>Veneer joint</th>
<th>Modulus of elasticity $(10^3 \text{ psi})$</th>
<th>Design allowable tensile stress $(\text{psi})$</th>
<th>Design allowable flexural stress $(\text{psi})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamineer® 22 $F_t$ tension ply lumber (7)</td>
<td>1.5 by 5.5 1.5 by 5.5</td>
<td>None</td>
<td>2.2</td>
<td>2,200</td>
<td>2,600</td>
</tr>
<tr>
<td>- Used as outer 5% of glulam$^b$</td>
<td></td>
<td>None</td>
<td>2.2</td>
<td>2,400</td>
<td>3,000</td>
</tr>
<tr>
<td>- Used in 8-ft. lengths (no end joints)</td>
<td></td>
<td>None</td>
<td>2.2</td>
<td>2,400</td>
<td>3,000</td>
</tr>
<tr>
<td>MICRO = LAM$^a$ laminated veneer lumber (33)</td>
<td>.75 by 3.5</td>
<td>Crushed-lap</td>
<td>2.1</td>
<td>2,200</td>
<td>2,800$^a$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.0</td>
<td>2,000</td>
<td>2,500$^a$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.7</td>
<td>1,500</td>
<td>1,900$^a$</td>
</tr>
</tbody>
</table>

$^a$For 12-in. depth; for other depths $(d)$, multiply by $(12/d)^{1/3}$.  
$^b$With proof loaded finger joints.
petroleum-based exterior adhesives in the last decade have made it difficult to demonstrate the economic feasibility of producing this product.

An attempt was made (16) to reduce energy use and press-time requirements in PLV laminations when processing thick sections, by using residual heat from veneer drying to speed the cure of adhesives. The veneer was initially heated by press drying at 375°F. After drying, its surfaces remained bondable without surfacing. A wide range of species with greatly varied MC tolerated hot gluing with a phenol-resorcinol adhesive while maintaining durability. The process was shown to be feasible if assembly time was controlled. Unfortunately, because of the short assembly time, manufacturers have rejected the use of residual heat curing.

Due to the high cost of adhesives, a simple method of reducing production costs is to reduce the amount of adhesive used in laminated veneer products. Glueline shear strengths of specimens were measured (17) against decreasing adhesive spread rates. As expected, a 1:1 relationship was found between spread rate and shear strength up to a spread rate which produced 100 percent wood failure. Future work should attempt to quantify acceptable minimum shear strengths for products according to their uses and to determine rates of environmental degrade for low spread-rate bondlines.

**Yield**

Rotary peeling of veneer for PLV has been reported as an excellent opportunity to improve timber yield over sawn-lumber processing. After predictions (24) that rotary peeling, compared to slicing, would yield a 30 percent increase in usable veneer, actual yields from second-growth Douglas-fir were demonstrated (2) by comparing volumes of nominal lumber and dressed lumber from sawn and PLV processes.

Using nominal or dressed dimensions and assuming lumber recovery from the core, laminated veneer lumber yielded more than 47 percent more than sawn lumber. In a number of species, green-veneer yields were found (12,131 to average 65 percent of bolt volume for bolts 12 to 20 inches in diameter, and 75 percent for 20- to 28-inch diameter. Mill studies (9, 10) on second-growth Douglas-fir showed green-veneer yields of 62 percent and veneer recoveries of 65 percent with 20-inch logs.

Losses in producing PLV are similar to those in plywood processing with the exception of panel trim and sanding losses. In processing PLV, these two types of losses can be significantly reduced by continuous pressing of long lengths and thick billets. Differences in yield between plywood and PLV can be accounted for by fewer crosscuts and less surface to sand. Some discrepancies found in past research are the result of mixing old and new lumber and veneer-processing facilities. To eliminate these discrepancies, a study is needed of yields in a commercial operation that processes logs into PLV.

**PLV structural performance**

Because raw-material defects are dispersed in PLV, the product has been shown to have greater uniformity of mechanical properties than solid-sawn wood. The extent to which these properties can be improved over those of clear wood depends on veneer quality, number of plies, veneer joint type, and numerous other processing variables. But the diversity of PLV configurations makes it difficult to compare the various studies.

**Tensile strength and stiffness**

Tensile strength is an important consideration in applications such as tension chords for trusses and I-beam flanges. In one examination of tensile strength (31), 1/8-inch C-grade Douglas-fir and southern pine veneers were segregated into high- and low-quality classes according to aggregate knot size, and then nominal 2 by 4 PLV members were fabricated. The members contained staggered butt joints with 8-inch spacing.

No statistical difference could be found between high- and low-quality Douglas-fir, which averaged 5,450 psi in tension test results. Southern pine 2 by 4 PLV members made of high-quality veneer averaged 5,490 psi while low-line C-grade veneer members averaged 4,560 psi. Lack of any observable difference in tensile strength between the two veneer quality levels was concluded to be due to the small range of knot distribution in the Douglas-fir. In the southern pine, good correlation was found between knot area and tensile strength ($R = 0.81$). The choice of raw material influenced the observed tensile moduli of elasticity (MOE) more than did its knot size.

In tensile testing (34) of 1/8-inch Douglas-fir veneer product having face plies of A-B grade veneer and inner plies of C-D veneer, average strength values were found to be 5,020 psi for 2- by 3-inch specimens and 5,600 psi for 2- by 6-inch specimens. More recently (26), tensile strengths of MICRO=LAM® were shown to average 6,435 psi for specimens 1.5 by 2.3 inches in cross section. The product’s coefficient of variation (COV) was limited to 12 percent while machine stress rated (MSR) and visually graded structural sawn lumber had COV’s of approximately 25 percent and 35 percent, respectively. MICRO = LAM® was found capable of a 2,000 psi allowable design stress in tension.

An evaluation was made of nominal 2 by 4 PLV members made of 1/4-inch Douglas-fir veneers having staggered butt joints, with No. 2 saw logs as the veneer source and with no further quality control criteria (3). Testing revealed that this material was capable of exceeding the allowable tensile stress for select structural grade material.

Tension tests (6) of various thicknesses and grades of Douglas-fir veneer utilized an unjointed 3/4-inch PLV configuration with nominal widths of 4 inches, 8 inches, and 12 inches. Results indicated that width had no significant effect, but greater strengths and MOE could be created by decreasing veneer thickness and using higher veneer grades.

In ultrasonic stress-wave timing of various qualities of veneer (19), tensile strength and stiffness were reported for 1/4-inch Douglas-fir veneer PLV. A summary of these and other findings is compiled in Table 2. Commercially available product design allowables are listed in Table 1.
TABLE 2. — Investigations of parallel-laminated veneer tensile properties

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Specimen size</th>
<th>Veneer joint</th>
<th>Species</th>
<th>Thickness</th>
<th>Raw material quality</th>
<th>Average ultimate tensile strength (psi)</th>
<th>Coefficient of variation (percent)</th>
<th>MOE (psi x 10^6)</th>
<th>No. of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bohlen (4)</td>
<td>1.5 by 3.5</td>
<td>Butt</td>
<td>DF</td>
<td>1/4</td>
<td>No. 2 sawlogs</td>
<td>4,205</td>
<td>2.20</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td>Bryant (6)</td>
<td>.75 by 3.5</td>
<td>None</td>
<td>DF</td>
<td>3/16</td>
<td>C-grade</td>
<td>4,080</td>
<td>20</td>
<td>2.03</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1/8</td>
<td></td>
<td>5,650</td>
<td>14</td>
<td>2.05</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1/10</td>
<td></td>
<td>5,650</td>
<td>16</td>
<td>2.17</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3/16</td>
<td>D-grade</td>
<td>2,660</td>
<td>26</td>
<td>1.61</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1/8</td>
<td></td>
<td>3,810</td>
<td>23</td>
<td>1.75</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1/10</td>
<td></td>
<td>5,520</td>
<td>18</td>
<td>1.80</td>
<td>21</td>
</tr>
<tr>
<td>Jungb (19)</td>
<td>1.5 by 3.5</td>
<td>None</td>
<td>DF</td>
<td>1/4</td>
<td>Randomb</td>
<td>6,010</td>
<td>17</td>
<td>2.63</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Low</td>
<td></td>
<td>5,500</td>
<td>15</td>
<td>2.27</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Medium</td>
<td></td>
<td>6,080</td>
<td>17</td>
<td>2.32</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>High</td>
<td></td>
<td>6,700</td>
<td>11</td>
<td>2.94</td>
<td>14</td>
</tr>
<tr>
<td>Kunesh (26)</td>
<td>1.5 by 2.3</td>
<td>Crushed-lap</td>
<td>DF</td>
<td>1/8-1/10</td>
<td>C- and D-grade</td>
<td>6,435</td>
<td>12</td>
<td>2.04</td>
<td>382</td>
</tr>
<tr>
<td>Moody (31)</td>
<td>1.5 by 3.5</td>
<td>Butt</td>
<td>DF</td>
<td>1/8</td>
<td>High-C</td>
<td>5,320</td>
<td>5.7</td>
<td>2.07</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Low-C</td>
<td></td>
<td>5,580</td>
<td>12</td>
<td>2.08</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>High-C</td>
<td></td>
<td>5,490</td>
<td>11</td>
<td>2.00</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Low-C</td>
<td></td>
<td>4,560</td>
<td>11</td>
<td>1.93</td>
<td>9</td>
</tr>
</tbody>
</table>

Species are Douglas-fir (DF) and southern pine (SP).
Jung's veneer quality levels were determined by segregating according to stress-wave timing results.

Shear strength

A long-standing concern in using PLV for structural products stems from its reduced shear strength along the grain as a result of veneer checks induced by rotary peeling, drying, and pressing. Early tests (32) of 1/2-inch southern pine veneer Press-Lam® indicated a shear strength perpendicular to the glueline at 50 percent of clear solid-wood strength. A vacuum-pressure soak ovendrying treatment (VPS-OD) of block shear specimens resulted in Press-Lam® that achieved 60 percent of solid-wood strength. Shear strength in a plane perpendicular to the lathe checks (parallel to the glueline) tested higher than shear strength in the plane of the checks (perpendicular to the glueline) by approximately 20 percent, but still only 60 percent of dry solid-wood strength. This thick veneer demonstrated a "worst case" condition, due to the depth of lathe checks.

Commercially produced 2- by 8-inch PLV members of 1/4-inch Douglas-fir veneer were used (4) to thoroughly assess shear properties of structural size PLV members and smaller specimens. Standard 2- by 2-inch blocks were tested for shear strength in the three orthogonal planes. In addition, 2- by 8-inch specimens were subjected to short beam shear tests using flatwise and edgewise bending orientations. Despite indications of bonding difficulty, possibly due to overdrying of the veneer, results indicated that this material could exceed the North American timber standard (1) of 95 psi allowable shear stress value for Douglas-fir dimension lumber. However, it could not satisfy allowable values for wide-face loading, as in plank applications, or for shear critical sections of glue-laminated beams (165 psi) (1). Butt joints did not influence shear strength in edge-loaded members.

PLV produced from thin Douglas-fir veneer (1/8 to 1/10 in.) met allowable horizontal shear design values of 285 psi when stressed in a plane perpendicular to the glueline, and 190 psi when loaded parallel to the glueline (33). These figures exceed the design values for solid Douglas-fir. Another test (7) resulted in horizontal shear design allowables for a 1/8-inch veneer PLV product of 210 psi perpendicular and 125 psi parallel to the glueline. Performance improvements perpendicular to the glueline were most likely caused by penetration of the adhesive into the veneer's lathe checks. Processing pressure most assuredly influences shear strengths parallel to the gluelines.

Bending strength and stiffness

Early tests (12, 13, 19, 23, 24, 32) of thick-veneered (>3/16 in.) PLV members all utilized butt jointed veneers. When 1/2-inch clear southern pine veneer was used in vertical laminations (32), the predominant bending failure mode was found to be flexural shear. As discussed previously, deep lathe checks seriously degraded shear strength of these thick veneer members. Thin-veneered (<3/16 in.) configurations were tested in bending (26). Table 3 summarizes flexural testing of PLV materials; Table 1 lists allowable design specifications for code-approved products.

Fasteners

An important aspect to consider in using PLV structurally is the performance of mechanical fasteners in the material. Limited investigations (13) showed significant reduction in both withdrawal and lateral strength of nails and staples inserted perpendicular to the gluelines when compared to solid Douglas-fir or southern pine. However, contradictory results were re-
TABLE 3. — Flexural test data for various parallel-laminated veneer materials.

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Specimen size</th>
<th>Veneer joint</th>
<th>Species</th>
<th>Veneer thickness (in.)</th>
<th>Raw material quality</th>
<th>Average Modulus of rupture, edge (psi)</th>
<th>Average Coefficient of variation (percent)</th>
<th>Average Modulus of elasticity, edge (psi x 10^7)</th>
<th>Average Modulus of rupture, flat (psi)</th>
<th>Average Coefficient of variation (percent)</th>
<th>Average Modulus of elasticity, flat (psi x 10^7)</th>
<th>No. of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jung</td>
<td>1.5 by 3.5</td>
<td>None</td>
<td>DF</td>
<td>1/4</td>
<td>Random</td>
<td>10,150 (11)</td>
<td>2.55</td>
<td>8,640 (30)</td>
<td>2.41 (14)</td>
<td></td>
<td></td>
<td>14</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Low</td>
<td></td>
<td>8,420 (12)</td>
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<td>8,470 (29)</td>
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<td></td>
<td>14</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Medium</td>
<td></td>
<td>9,520 (13)</td>
<td>2.48</td>
<td>7,860 (19)</td>
<td>2.45 (14)</td>
<td></td>
<td></td>
<td>14</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>High</td>
<td></td>
<td>10,400 (12)</td>
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<td>9,060 (14)</td>
<td>2.80 (14)</td>
<td></td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>Koch</td>
<td>1.5 by 3.5</td>
<td>Butt</td>
<td>SP</td>
<td>1/4</td>
<td>Wood's run</td>
<td>9,310 (20)</td>
<td>1.91</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>92</td>
</tr>
<tr>
<td>Kunesh (26)</td>
<td>1.5 by 2.3</td>
<td>Crushed-joint</td>
<td>DF</td>
<td>1/8-1/10</td>
<td>C-and-D</td>
<td>--</td>
<td>--</td>
<td>2.31</td>
<td>11,430 (11)</td>
<td>2.34 (33)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moody and Peters (32)</td>
<td>2 by 2</td>
<td>None</td>
<td>SP</td>
<td>1/2</td>
<td>“Clear” logs</td>
<td>11,720 (14)</td>
<td>2.04</td>
<td>12,480 (12)</td>
<td>2.13 (24)</td>
<td></td>
<td></td>
<td>24</td>
</tr>
</tbody>
</table>

For species — DF denotes Douglas-fir; SP is southern pine.
Jung's material quality was determined by stress-wave timing methods as discussed in the text under “Grading and quality control.”

Ported (20) for tests in which three thicknesses (4/10, 3/16, 1/8 in.) of Douglas-fir veneer were used to make nominal 2-inch PLV members.

With few exceptions, performance of mechanical fasteners was no different from performance in solid wood. With truss-plate connections, a 16 percent reduction in strength was found for the 4/10-inch veneer product. However, when staples, bolts, and split-ring connectors were inserted perpendicular to the gluelines of the 3/16- and 1/8-inch veneers products, these PLV's performed better than solid-wood components, due to reduced laithe check depth, higher material density, and reinforcement of the glue line by the adhesive. Ten-penny connections, nailed perpendicular to the glue line, showed lateral resistance of approximately 20 percent below required design values in all veneer thicknesses.

Therefore, in most cases, fastening problems should not be anticipated for PLV in commercially available veneer thicknesses. When using lateral loading, however, design values should be verified before using the product.

Impact and fracture toughness

Interest in using laminated veneer materials for aircraft structures prompted investigation (30) into static and impact strengths of 1/7-inch veneer Sitka spruce PLV. Results showed decreased work to failure in static bending for the laminated material compared to solid wood. Impact tests showed increased toughness rather than reduced shock resistance for material loaded perpendicular to the plane of the laminations.

Comparing the cleavage properties of solid wood with those of rotary-cut 1/8-inch Douglas-fir veneer PLV (8), the PLV was shown to retain only 30 to 50 percent of solid-wood cleavage strength. Failures were gradual, unlike solid wood's tendency toward fast fracture. Better cleavage characteristics were found in 1/10-inch PLV (8) than in the 1/6-inch PLV, due in part to healing of laithe checks by adhesive penetration and slight deviation of grain alignment in adjacent plies. PLV's made of 1/32-inch laminates were higher in fracture toughness than solid wood, while 1/8- and 1/16-inch laminates were weaker (29).

Dimensional stability

Warping of nominal 2-inch PLV's was at first (12) thought to be minimal, but continued study indicated some warping and cupping (13). Symmetric placement of tight or loose veneer faces in the finished construction minimized dimensional instability of large or deep members. To minimize or prevent cupping when production constraints require veneer layup in one direction only (tight side up or tight side down), a single ply of cross-banding on each face of nominal 1-1/2-inch PLV may be necessary.

Comparison of PLV and solid-sawn lumber leads one to believe that, similarly, dimension changes are related to changes in MC. To this writer's knowledge, no corroborative data has been published. Thickness swell (TS) characteristics are surely critical for PLV products processed with heat and pressure. Plywood products have shown up to 6 percent TS upon placement in 90 percent relative humidity (RH) conditions. Evaluations of PLV dimensional properties are a needed addition to the literature.

Durability

Minimal delamination of PLV bondlines was found (28) when 1/8-inch PLV laminations, after accelerated exposures, were compared to delaminations formed in solid-sawn lumber's bondlines. Prior to exposure, PLV shear strength was lower than in solid-sawn material, but following accelerated cycling, the two did not differ significantly.

This lack of relative degradation was explained by the fact that the exposed surfaces of rotary-cut veneer are predominately tangential. Thus, laminations have similar growth-ring orientations when bonded, are relatively stress-free, and microchecks initiated by the laithe checks are limited to one or two veneer thick-
nesses. Solid-sawn material, on the other hand, has widely divergent growth-ring alignments when bonded into glulam members. When the materials are wetted, moisture-induced expansion causes differential movement between laminations which, in turn, causes the severe splits and checks that were found in the solid-wood laminations.

In efforts to improve the weathering resistance of PLV, 15 surface coatings and edge treatments are currently being studied (11). They include epoxy tar, neoprene asphalt, water repellents, paints, veneer overlays, and resin-impregnated kraft paper. Inspection at three sites after 1-year exposure has shown veneer and kraft-paper overlays to be most effective in reducing degradation.

**Grading and quality control**

One of the most promising structural qualities of PLV is the capability to insure product performance through control of constituent veneers. Species and grade of log were the only quality controls placed on raw materials in early studies (2, 12, 13, 23, 24, 32) which were aimed at total utilization of lower grade logs, not at obtaining a high stress-grade product with low population variance.

Veneer quality has been graded using three methods: visual inspection, mechanical testing of veneer MOE, and veneer stress-wave timing (SWT). Visual grading has been most widely used due to its presence in plywood veneer standards, but because it depends upon visual evidence of defects, it is somewhat subjective and therefore not totally satisfactory for screening veneers used in stress-rated PLV.

Veneer tensile MOE has been tested mechanically only in research situations (25). Commercial implementation is probably not feasible. Veneer MOE was first assessed indirectly (25) through SWT in an attempt to assign stiffness values for optimal placement of the veneers in a PLV beam section. Grouping of stiff veneers in outer faces of these beams reportedly resulted in beams one-third stiffer and with allowable bending stresses one-third greater than using beams with randomly arranged veneers. Though the SWT equipment was under development at the time, sufficient benefit was shown to recommend development of production scale machines that could test veneer MOE.

One commercial grading system (used in TrusJoist's MICRO=LAM® (35) for a mix of C-grade (MOE = 2.15 million psi) and D-grade (MOE = 1.80 million psi) veneers) employs SWT to categorize veneer into four stiffness classes for inclusion into various PLV stress grades. One test (18) of SWT application to veneer classification studied veneer sheets 10 inches wide and 48 inches long with signal travel over the entire 48-inch length. Inaccurate results were obtained due to failure to detect diving grain and inability to detect knots which were masked as the waves traveled around the defect, but these inaccuracies were overcome by reducing the distance between sender and receiver and by separating the lo-inch-wide sheet into 2-inch strips.

PLV performance and predictability of properties were considered (19) when utilizing SWT-tested veneer. Using 1/4- by 5-inch by 8-foot Douglas-fir veneer, stress-wave transit time was measured for the entire B-foot length. A dynamic MOE was calculated after correction for mass density of the piece of veneer. Pieces were then segregated into four groups: a) randomly selected from the population, b) high-predicted MOE, c) median-predicted MOE, and d) low-predicted MOE. Nominal 2 by 4 PLV members were subsequently fabricated from these veneer groups and were tested in flexural and tensile modes. Predictions of mechanical stiffnesses were found to correlate fairly well with measured SWT values (edgewise, \( r^2 = 0.82 \); flatwise, \( r^2 = 0.88 \); tensile modulus, \( r^2 = 0.66 \)). Ultimate strength predictions yielded poor correlations from both SWT MOE and mechanical-test MOE measurements. Segregation of veneers into the three SWT classes did result in three distinctive stiffness performance groups, but the strength classes were not statistically different (at 95% level).

**Summary**

Tests and structural applications of parallel-laminated veneer (PLV) show that it can be a compatible substitute for stress-rated solid-sawn lumber. Continuous processing of veneers, as envisioned by PLV's first researchers, has been successfully implemented in commercial operations. Feasibility of production would be greatly enhanced by yield improvements, but the increased yields projected by early studies still require verification from actual industry yields.

Fabrication of butt joints within PLV members has received considerable study, though research into the basic mechanics of such joints is lacking. Crushed lap and scarf joints between veneer should be investigated for strength, durability and, in the case of scarf joints, feasibility of production. End jointing of nominal 1- and 2-inch PLV with finger joints or scarf joints has been assessed to be feasible in joining panel-length PLV material produced in conventional plywood operations. The development of methods or techniques that reduce adhesive-bonding costs could have a significant effect on PLV manufacturing as well as other adhesive-sensitive wood processing.

The flexibility available for producing PLV makes mechanical properties difficult to assess except on a case-by-case basis through physical testing. High research priority should be given to developing statistically based models which would allow evaluations of changes in veneer thickness, species, and veneer quality. Studies of shear strength, fastener performance, and fracture toughness should be pursued to identify the degrading mechanisms which have been hypothesized in preliminary research. Accurate assessments should be made of the level of durability required to assure product performance at expected levels. In addition, the development of more sensitive veneer-grading criteria is essential to allow consistent appraisal of PLV performance. If population variance is kept to a minimum, the reward will be high allowable design stresses.
Literature cited


6. ________. T. L. LAUFENBERG, AND J. A. YOUNGQUIST. End jointing of laminated veneer lumber for structural use. (To be published.)


