A wood I-section for post-frame building applications must be resistant to both primary bending loads and to secondary loads acting parallel to the flanges. In post-frame building construction, the wood lams may be broadly classified as either horizontally or vertically laminated assemblies. In a horizontally laminated assembly, the wood layers are continuous (i.e., do not contain end joints), of the same size, and similar in stiffness; the mechanical fasteners distribute virtually no load between layers and only function to hold the assembly together.

I-Sections

Structural components with material concentrated away from the primary axis of bending can more efficiently resist bending loads. Optimal concentration of material both above and below the primary bending axes results in an I-shaped component or "I-section." The material concentrated away from the axis of bending forms the flanges of the I-section. The material connecting these two flanges is referred to as the web. The taller an exterior wall, the greater the bending force to which it is subjected and the more logical it becomes to frame it using I-sections. This largely explains why most columns in low-rise steel-framed "pre-engineered" buildings are I-sections.

Although horizontally and vertically laminated mechlams may seem inherently similar, the structural properties of horizontally laminated mechlams are much more dependent on the shear stiffness of the connections. In horizontally laminated assemblies, connection shear stiffness controls the amount of composite action — the degree to which individual layers work together to resist externally applied forces. An increase in the rigidity of the connections between layers increases composite action; consequently, using more and/or stiffer fasteners generally can increase the flexural stiffness of a horizontally laminated mechlam.

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Laminated Strand Lumber (LSL)

LSL has an allowable shear strength of 14 pounds per square inch, which substantially exceeds that of dimension lumber flanges. Consequently, LSL has several characteristics that make it an ideal material for the web of a wood I-beam. First, it has good shear strength. When loaded in a direction parallel to the wide face of the strands, LSL has an allowable shear strength of 4 pounds per square inch. Consequently, LSL has an aspect ratio of 2.82:1, which is more than twice that of most dimension lumber. For a given thickness, the shear strength of plywood and OSB also is greater than dimension lumber, which partially explains
why they are commonly used for I-joist webs.

A second advantage of LSL is that it is straight and resists twisting, cupping, crooking and other warping after installation. This characteristic has resulted in LSL being the preferred material for wood studs in taller walls. No consideration was given to using LSL in the fabrication of post-frame building posts until around 2005, at which time I observed LSL being installed on 16-inch centers in an 18-foot-high wall in my neighbor’s house. If the neighbors can afford to use an LSL member every 16 inches in their residence, we should be able to afford one in every post-frame building post.

A third advantage of LSL is that when used as a web member in a horizontally-laminated I-section, the sawed edges of LSL provide an excellent adhesive bonding surface for flange attachment. The downside of LSL is that it costs approximately three times as much as similarly-sized dimension lumber.

Polyurethane Adhesive and Self-Drilling Construction Screws

In the mid 1990s I began using a one-component, polyurethane-based, moisture-curing construction adhesive called PL Premium for a number of construction applications. Given that PL Premium has significantly greater strength than PL 500 and similar elastomeric adhesives and almost all wood fractures in the 1988 I-section tests were precipitated by a PL 500 glue-line failure, it seemed obvious a switch to PL Premium should increase I-section strength above the levels registered during the 1988 tests.

Other major advantages of PL Premium polyurethane adhesive are that it contains only 4 percent volatile organic compounds by weight, contains no chlorinated solvents, cures to full strength overnight and does not shrink like solvent-based construction adhesives. It is also waterproof, paintable and cures even in cold temperatures.

PL 500 and PL Premium are both part of the PL product line now owned by the Henkel Corporation. For marketing purposes, Henkel recently added the “Loctite” trade name to its PL products. Henkel obtained the PL product line with its purchase of OSI in 2004. Henkel purchased Loctite in 1997. Currently, PL Premium and other polyurethane adhesives cost about 50 percent more than solvated rubber adhesives.

Our investigation into the behavior of the new I-section design involved both finite element analysis (FEA) and laboratory tests. The FEA work involved using MLBeam (Bohnhoff, 1992 ) to investigate the affect of screw spacing on bending behavior of I-sections fabricated with screws and the affect of the new I-section design on the stresses. This modeling work was pre-empted by a series of connection tests to determine the shear load versus interlapper slip relationship of both screws and the PL Premium polyurethane adhesive.

Table 1. Experimental Design for Laboratory Bending Tests

<table>
<thead>
<tr>
<th>Group Identification</th>
<th>Description</th>
<th>Replicates</th>
<th>Spruce-Pine-Fir (SPF)</th>
<th>Laminated Strand Lumber (LSL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-S</td>
<td>Single nominal 2 x 6-inch SPF member</td>
<td>30</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>I-A-S</td>
<td>Single nominal 2 x 6-inch LSL member</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 2. Physical Properties of Lumber

<table>
<thead>
<tr>
<th>Property</th>
<th>SPF (Nominal 2 x 6-Inch)</th>
<th>LSL (Nominal 2 x 6-Inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content</td>
<td>12%</td>
<td>12%</td>
</tr>
<tr>
<td>Density</td>
<td>46.8 lbs/cu ft</td>
<td>46.8 lbs/cu ft</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>1,495,000 psi</td>
<td>1,495,000 psi</td>
</tr>
<tr>
<td>Modulus of rupture</td>
<td>5,500,000 psi</td>
<td>5,500,000 psi</td>
</tr>
</tbody>
</table>

Figure 5: Screw locations for (a) each flange of I-section assemblies and (b) each side of three-layer, vertically laminated mechlam assemblies.

Laboratory Test

Material Specifications

One hundred thirty-two (132) 12-foot pieces of 1.5 x 5.5-inch (nominal 2 x 6-inch) No. 2 KD spruce-pine-fir (SPF) lumber and 46 12-foot pieces of 1.5 x 5.5-inch IJE Timberstrand LSL were acquired for this study. Screws were 0.19 inch x 3.13 inch T25 torx-drive construction screws with a shaft diameter of 0.14 inch, a thread pitch of 0.10 inch and an unthreaded shank length of 1.15 in. PL Premium polyurethane construction adhesive was obtained in quart tubes.

Experimental Design

Three different laminated assemblies were selected for testing: an I-section fabricated with screws—only, an I-section fabricated with both screws and polyurethane adhesive, and a conventional three-layer vertically laminated mechlam design. These designs will be identified as groups I-S, I-AS, and I-A, respectively.

To determine basic material properties, single SPF members (group 1S) and single LSL members (group 1L) were tested.

The experimental design is summarized in Table 1. Because the primary focus of this study was I-section behavior, more I-sections of each design (18) were tested than three-layer assemblies (10). With respect to single-member tests, fewer LSL members were tested because of an expected lower variability in their bending properties.

Methods

SPF lumber and LSL were stored in a temperature-controlled room until an equilibrium moisture content was attained. Each member was weighed and measured, and moisture content was recorded at three locations using a resistance-type moisture meter. Mean and coefficient of variation values associated with each of these measurements are shown in Table 2. This table shows in all categories, the LSL had significantly reduced variation relative to SPF lumber.

SPF lumber was allocated to groups so each group had a similar modulus of elasticity (E) distribution, i.e., similar mean E as well as similar coefficient of variation (COV); LSL was similarly assigned to groups. Lumber assigned to a particular group of assemblies was randomly assigned to individual specimens within the group.

I-sections (groups 1-S and 1-A-S) were constructed using a set of jigs to ensure consistency between replicates and to aid construction efficiency (Figure 4). The only difference in the fabrication of groups 1-S and 1-A-S was the placement of a continuous 1/4-inch diameter bead of PL Premium construction between each SPF flange and its associated LSL web. Screw spacing and location on the center third of the I-section and 4 inches for each end third. This screw pattern is shown in Figure 5a and is an outcome of earlier research (Bohnhoff & Siegel, 1991) demonstrating that screws in the center third of a single-supported beam under a one-third point loading (in regions of low or zero shear) do little to affect beam strength and stiffness.
Three-layer, vertically laminated mechlam (group 3S) were constructed by clamping three SPF members together and attaching them with a single 3.13-inch long screw every 12 inches as shown in Figure 5b. This larger spacing was chosen because vertically laminated assemblies rely little on inter-layer shear strength for their bending strength and stiffness. In fact, adding fasteners above a level needed for load sharing between layers actually may increase the probability of a fastener-induced slope-of-grain split. To further decrease the likelihood of such splits, screws were kept 1.5 inches away from alternating edges of the members to form an offset pattern.

All tests were conducted in accordance with ASTM D198 (ASTM International, 2009) using the third-point loading arrangement shown in Figure 6. Load head displacement was selected for each group to yield a failure in approximately 10 minutes. Midspan displacement was measured as outlined in ASTM D198 using a linear variable differential transformer (LVDT) and spring-tensioned wire to measure the vertical midspan displacement of the specimen relative to its displacement at support points. LVDTs were also attached to web ends to measure the inter-layer slip between the web and flange of all I-section specimens.

Specimens fabricated with adhesive (group I-AS) were tested 1 month (~28 days) after fabrication and specimens assembled only with screws (groups I-S and 3S) were set aside after fabrication for at least 1 week before being tested.

Test Results and Discussion

Single LSL and SPF members behaved as expected. As shown in Table 3, the two groups had a similar mean modulus of rupture (MOR), but the COV for the MOR of the LSL members was half that for the SPF members (20.2 percent versus 41.3 percent). The average apparent modulus of elasticity based on edgewise bending tests for the SPF lumber was calculated to be 1.43 million pounds per square inch, which was not significantly different from the 1.42 million pounds per square inch (Table 2) calculated from flatwise bending tests. Conversely, E values for LSL lumber from edgewise bending tests (1.11 and 1.51 million pounds per square inch, respectively) were significantly different. One possible explanation is that material is slightly denser on the faces of an LSL billet than at locations midway between the faces.

Applied load versus average midspan displacement for the three laminated assembly types (groups 3S, I-S, and I-AS) are shown in Figure 7. The dashed lines in the figure represent upper and lower bounds for I-section stiffness. They were calculated assuming complete composite action and in composite action between S-P-F flanges with an E of 1.43 million pounds per square inch and LSL web with an E of 1.36 million pounds per square inch. These E values are the apparent values calculated from the single member bending tests (Table 2). When predicting the behavior of I-sections exhibiting complete composite action, a more appropriate E value for flange modeling would be obtained from an axial loading test. It is evident from looking at Table 7 that I-sections fabricated with adhesive exhibited near-complete composite action. At total loads less than 610 lbf, I-sections fabricated with screws only also exhibited near-complete composite action. However, above the 600 lbf level, composite action within the assemblies dropped off sharply.

The three laminated assembly types were characterized by different failure modes. All three-layer mechlam (group 3S) failures could be classified as tension-perpendicular-to-grain failures associated with grain deviations around tension side knots, high slope of grains, and/or screwing-induced stress. A typical 3S assembly failure is shown in Figure 8.

The strength of I-sections with screws only (group I-S) was limited by the bending strength of the LSL web (Figure 9), and the strength of I-sections with screws and screws-only adhesive (group I-AS) was limited by the tensile strength of the flanges. As shown in Figure 10, I-AS assembly failure almost always occurred at a natural defect in the tension flange near midspan.

Distribution characteristics for the ultimate midspan bending moment, deflection at maximum load, and initial stiffness for the three laminated assembly types are compared in Table 4. Values in Table 4 are presented in terms of ultimate moment resistance and stiffness rather than MOR and E. This is because MOR and E have no physical meaning in horizontally-laminated assemblies (e.g., the wood I-sections) that have complex stress distributions because of inter-layer slip.

Ultimate midspan bending moment distributions for groups 3S, I-S, and I-AS are plotted in Figure 11, and the relationships between ultimate midspan bending moment and midspan displacement at failure for the three groups are plotted in Figure 12. A comparison of values in Table 4 and Figure 11 shows the I-sections assembled with polyurethane adhesive and screws (group I-AS) significantly outperformed the other two assemblies. The mean bending strength of group I-AS assemblies was 115 percent greater than that for group I-S assemblies and 95 percent greater than for 3S assemblies.

The strong performance of I-AS assemblies can be attributed to the near-complete composite action they exhibited. When two different assemblies exhibit complete composite action, they will have bending strengths roughly in proportion to their section moduli. An I-section exhibiting complete composite action with flanges and webs with a similar modulus of elasticity and a size identical to those tested would have an assigned section modulus of 53.1 cubic inches. This is 133 percent greater than the 22.7-cubic-inch section modulus that would be assigned to the three-layer mechlam.

Design values are typically based on 5 percent point estimates. Two-point estimates are given in Table 3 — a nonparametric estimate and an estimate that assumes a normal distribution. Based on these numbers, the design bending strength of the I-sections with adhesive and screws should be at least 75 percent greater than the design bending strength of I-sections with screws only. Of greater significance is that the normal and nonparametric 5 percent point estimates show that group I-AS specimens should have a design bending strength 340 percent greater and 175 percent greater, respectively, than for the three-layer mechlam (Table 4).

The near-complete composite action of the I-sections with adhesive resulted in flange strength dictating the bending strength of the assemblies. Given that all but the three strongest I-AS assemblies exhibited a flange failure, the use of a higher grade flange material should significantly increase both the mean and 5 percent point estimates of bending strength. The low strength of the screwed-only I-sections (group 1-S) was due to a much higher inter-layer slip and a much lower level of composite action. As the inter-layer slip increased during testing, bending moment was increasingly resisted by the LSL web, the component in the assembly with the highest individual bending stiffness. This resulted in the ultimate bending strength of the I-AS assemblies being limited by the flexural strength of the webs.

Although the mean bending strength of the three-layer mechlam was 4 percent greater than that for the screwed-only 1-sec-
Table 4

<table>
<thead>
<tr>
<th>Property</th>
<th>Single LSL (1S)</th>
<th>Single LSL Screwed (2S)</th>
<th>Single Stack (3S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean, 6-kips</td>
<td>8.10</td>
<td>8.10</td>
<td>8.10</td>
</tr>
<tr>
<td>95th, 6-kips</td>
<td>17.67</td>
<td>17.67</td>
<td>17.67</td>
</tr>
<tr>
<td>5th, 6-kips</td>
<td>5.35</td>
<td>5.35</td>
<td>5.35</td>
</tr>
<tr>
<td>Coefficient of Variation (CV) %</td>
<td>6.6</td>
<td>17.1</td>
<td>14.0</td>
</tr>
<tr>
<td>Nonparametric 5% point estimate, 6-kips</td>
<td>7.5</td>
<td>13.2</td>
<td>2.9</td>
</tr>
<tr>
<td>Nonparametric 95% point estimate, 6-kips</td>
<td>7.5</td>
<td>13.2</td>
<td>6.8</td>
</tr>
<tr>
<td>Midspan deflection at maximum load</td>
<td>1.01</td>
<td>1.01</td>
<td>1.01</td>
</tr>
<tr>
<td>Mid. dev., in.</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
</tr>
<tr>
<td>COV, %</td>
<td>10.0</td>
<td>19.7</td>
<td>29.6</td>
</tr>
<tr>
<td>Mean, 15-kips</td>
<td>6.31</td>
<td>6.31</td>
<td>6.31</td>
</tr>
<tr>
<td>mid. dev., 15-kips / in.</td>
<td>0.78</td>
<td>1.74</td>
<td>2.66</td>
</tr>
<tr>
<td>COV, %</td>
<td>11.6</td>
<td>34.1</td>
<td>20.4</td>
</tr>
</tbody>
</table>

Figure 11. Cumulative distributions for ultimate midspan bending moment for single members, I-sections, and three-layer mechlam. Fitted curves are normal CDFs.

Figure 12. Ultimate midspan bending moment versus midspan deflection at failure for single members, I-sections and three-layer mechlam. Dashed horizontal lines identify nonparametric 5% point estimates.

Other factors that likely contributed to the high COV for the MOR of group 3S specimens include a relatively low wood moisture content at fabrication and a slight overdriving of screws. Both of these factors likely contributed to higher screwing-induced wood stresses, as failures in many 3S assemblies were characterized by splits running through screw connections (Figure 8).

Future Research

Given the somewhat impressive test results for I-sections fabricated with adhesive, additional research is warranted to minimize screw density (i.e., maximum screw spacing), investigate strength gains associated with use of a higher-grade flange material, and determine long-term adhesive durability.

Options for attachment of secondary framing to 1-sections should also be explored. One possible method for girt attachment is shown in Figure 13. Note bay spacing can be fixed by butting the girt to the LSL web. The expansion space between the flange and the girt allows for variations in flange size and for the fact a flange is unlikely to be perfectly centered on the web along the entire length of the assembly.

Summary

To address warping and other shortcomings of an I-section design fabricated from three pieces of dimension lumber, the dimension lumber web was replaced with a laminated strand lumber web. Dimension lumber flanges were attached to the LSL web with a combination of polyurethane adhesive and screws. This new I-section design was found to exhibit near-complete composite action and had a bending strength significantly greater than a three-layer, vertically laminated mechlam fabricated from the same dimension lumber used for the 1-section flanges. I-sections fabricated without the polyurethane adhesive were significantly weaker and more flexible.

In addition to its superior strong-axis bending strength, the I-section has superior weak-axis bending strength relative to a three-layer mechlam assembly, making it a much better option for columns that lack lateral support in both directions. As interior columns, I-sections also better accommodate plumbing and electrical runs.

Other advantages I-sections columns have over rectangular members are they are more thermally efficient, provide...
better options for girt attachment, and (as shown in a recently concluded study at University of Wisconsin-Madison) can be attached to smaller concrete piers more efficiently and effectively.

Because LSL is not manufactured for exterior use and the durability of polyurethane adhesive under cyclical temperature and wood moisture conditions has not been studied, use of the I-section design should be limited to dry-use conditions.

Acknowledgements
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References


STATEMENT OF OWNERSHIP, MANAGEMENT AND CIRCULATION
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