A wood I-section for post-frame

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A wood I-section featuring dimension lumber flanges attached with polyurethane adhesive and screws to a laminated strand lumber (LSL) web was fabricated and tested along with a similar I-section fabricated without the polyurethane adhesive and a three-layer, vertically-laminated mechlam design. The I-section design fabricated with the adhesive had significantly greater strong-axis bending strength than the mechlam assembly. This, along with several other advantages, makes the I-section an appealing alternative to several post designs currently in use.

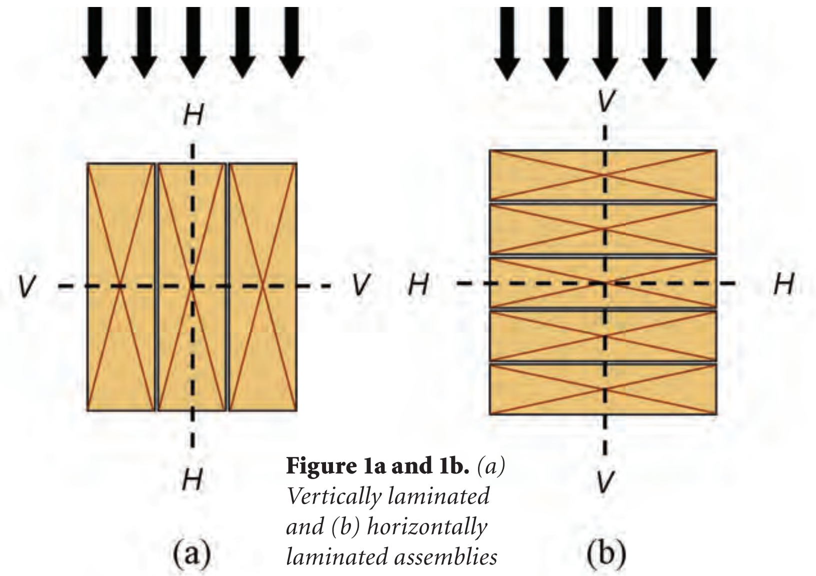


Figure 1a and 1b. *(a) Vertically laminated and (b) horizontally laminated assemblies*

Horizontally and Vertically Laminated Assemblies

Structural components featuring wood layers connected with mechanical fasteners (e.g., bolts, nails, screws) are referred to as mechanically laminated or mechlam assemblies. Like glued-laminated or glulam assemblies, mechlams may be broadly classified as either horizontally or vertically laminated depending on their orientation with respect to the direction of the primary bending load. An assembly designed to resist primary bending loads acting parallel to inter-layer planes is referred to as a vertically laminated assembly. As shown in Figure 1a, this is an assembly bent about axis V-V. Conversely, a horizontally laminated assembly is designed to resist primary bending about axis H-H (**Figure 1b**).

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 connection between layers increases composite action; consequently, using more and/or stiffer fasteners generally can increase the flexural stiffness of a horizontally laminated mechlam.

The majority of post-frame building posts are constructed using vertically laminated mechlams. The mechanical connections in these assemblies do not have near the influence on bending strength and stiffness as those in horizontally laminated mechlam. In fact, in designs in which the vertically laminated 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 axis 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.

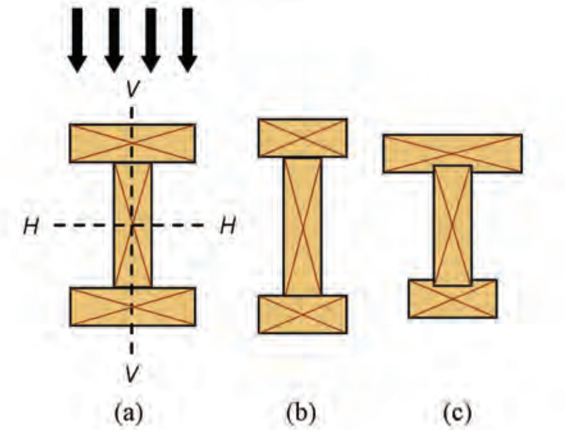
Although steel I-sections have been widely used in building construction for years, use of wood I-sections is relatively recent and is largely restricted to smaller glued-laminated components that feature plywood or oriented strand board (OSB) webs. Because of their relative size, they are predominately used as ceiling and floor joists and are commonly marketed as I-joists.

Forming I-sections by mechanically laminating three pieces of nominal 2-inch solid-sawn lumber (subsequently referred to as 2x lumber) is proposed from time to time and is a topic that I researched in the late 1980s (Bohnhoff & Siegel, 1991). Based on this past work, I conclude I-sections are not formed from three pieces of 2x lumber for three primary reasons:

1. Formation of an I-section from three pieces of dimension lumber results in a horizontally laminated assembly as seen in **Figure 2a**. As previously mentioned, the bending strength and stiffness of such an assembly generally will be controlled (and is largely limited) by the mechanical fasteners used to join the flanges to the web.

2. The straightness of I-sections made from dimension lumber largely is dictated by the characteristics of the member forming the web. If this member is crooked and/or twisted, the final assembly will be crooked and/or twisted. Given that crooks and twists become more dominate in longer members, it is difficult to fabricate long straight I-sections with 2x lumber webs.

3. The shear strength of lumber is relatively low compared to its tensile and compressive strengths, consequently the shear strength of a 2x lumber web will typically limit the strength of an I-section where the rigidity of the flange-to-web connections is sufficient.



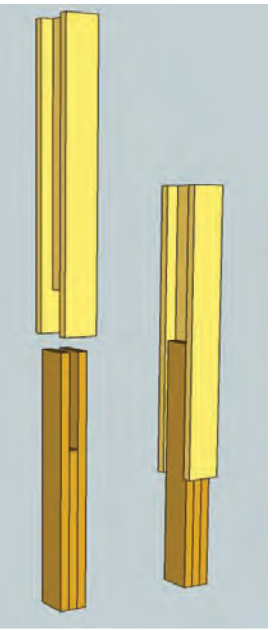


Figure 2. *I-section of (a) three identical-sized members, (b) with flanges and webs that differ in size, and (c) in which all three members vary in size and flanges are notched to accept the web.*

Figure 3. *Use of a three-layer preservative-treated stub post to support a wood I-section.*

Past I-Section Research

As part of my 1988 I-section research, several assemblies were laboratory tested, comparing test specimens with flanges nail-connected to the webs to specimens with flanges fastened to webs with both nails and an elastomeric adhesive (i.e., PL500 construction adhesive). An underlying objective of this research was to experimentally validate MLBeam — a finite element method of analysis developed (Bohnhoff, 1992) to predict the nonlinear behavior of horizontally laminated mechlams. I found:

1. The addition of the elastomeric adhesive significantly increased the amount of composite action. In fact, at low loads, the assemblies behaved no differently than they would have if a rigid adhesive had been used to bond the pieces together.

2. High nail slip and failure of the elastomeric adhesive at higher loads resulted in a loss of composite action, forcing web members to carry virtually all the bending load. This limited the bending strength of 90 percent of the assemblies to the bending capacity of the web.

3. Adhesive curing time had a significant effect on both bending strength and stiffness. Mean ultimate load increased 37 percent and average stiffness about 80 percent when the elastomeric adhesive was allowed to cure 57 days instead of 14 days.

4. Where the elastomeric adhesive did not fail, I-section strength was limited by the shear strength of the web.

5. Horizontally laminated mechlam behavior can be accurately predicted with MLBeam.

The PL500 construction adhesive used in the 1988 tests is a solvent-cured rubber (i.e. elastomeric) adhesive. It was selected because of its formulation for heavy-duty exterior construction, which enables the fabrication of I-sections for outside exposure and/or below-grade embedment. Many construction adhesives are not intended for exterior use, so they could not be used to fabricate I-sections for embedment. An option I presented in the late 1980s was to support such I-sections with three-layer preservative-treated stub post as shown in Figure 3. In this design, the web of the I-section rests on the shorter, middle ply of the stub post. The outer plies of the stub posts are fastened to both the web and flanges of the I-section.

A New Wood I-Section Design

During the years since my original I-section testing, a number of newer building materials have emerged into fairly prominent use, and greater emphasis has been placed on environmentally friendly (a.k.a. "green") construction. The combination of these two factors led to the development and subsequent testing of the wood I-section shown in Figure 4 — an assembly with dimension lumber flanges attached to a laminated strand lumber (LSL) web using polyurethane adhesive and self-drilling construction screws.

Laminated Strand Lumber (LSL)

LSL is a structural composite lumber fabricated from thin wood strands up to about a foot in length, combined with a waterproof adhesive under pressure to form large billets that subsequently are sawn into desired lumber sizes. Hardwoods such as birch, poplar, aspen and maple typically are used. LSL was introduced in 1992 by Trus Joist MacMillan (which subsequently was bought out by Weyerhaeuser). Trade-named LSL products include Weyerhaeuser's iLevel TimberStrand and Louisiana Pacific Corporation's SolidStart.

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 approximately 400 pounds per square inch, 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

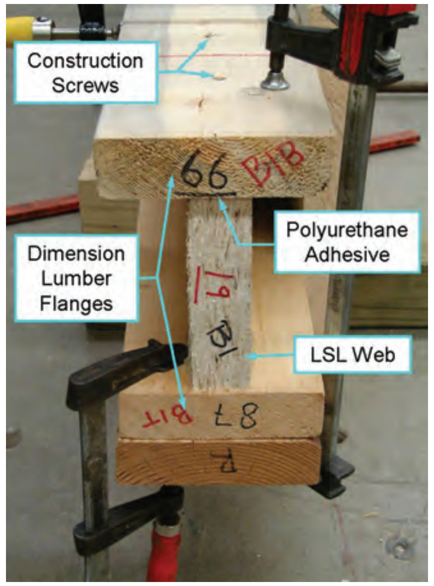


Figure 4: *End view of a new wood I-section design during fabrication.*

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. Henkle obtained the PL product line with its purchase of OSI in 2004. Henkle purchased Loctite in 1997. Currently, PL Premium and other polyurethane adhesives cost about 50 percent more than solvent-cured rubber adhesives.

All construction adhesives are more effective when the members being glued are held together under pressure while the adhesive cures. This can be accomplished effectively by using screws capable of drawing the components together; that is, screws whose unthreaded (i.e., smooth) portion of the shank is slightly longer than the thickness of the member being attached (i.e., ~1.5 in. for a 2x member). Since my 1988 testing, the use (and availability) of self-drilling construction screws has exploded, providing an excellent alternative to the nails used to assemble the 1988 specimens.

Environmental Friendliness

In addition to the emergence of LSL, polyurethane adhesive, and self-drilling construction screws, the development of the new wood I-section also was driven by increased emphasis on environmentally friendly construction, which spurred research on precast concrete piers and focused greater attention on thermal envelope design.

As a replacement for preservative-treated wood, precast concrete piers are viewed as a more durable and easier to recycle material option. Because of increased interest in precast concrete piers, we have conducted several tests on them at University of Wisconsin-Madison. Much of this research is centered on increasing the moment capacity of the concrete pier-to-wood post connection. In a recently concluded study we found that increasing the biaxial bending strength and stiffness of the concrete-to-wood connection can be accomplished more efficiently and effectively when I-sections are used instead of rectangular-shaped wood members.

Another advantage that I-sections have over rectangular members is they are more thermally efficient. I-section webs (which are only 1.5 inches thick) represent the only spot in the wall at which wood runs uninterrupted between exterior and interior building surfaces. For a 9-foot bay spacing, this is equivalent to only 1.4 percent of the total wall area. Current mechlam posts not only have three to four times this area, but the space between laminations allows unimpeded air infiltration through the wall. Stopping this airflow requires at least as much construction adhesive as would be required to fabricate an I-section of the same length.

Preliminary Modeling

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 without adhesive. This modeling work was pre-empted by a series of connection tests to determine the shear load versus interlayer slip relationship of both screws and the PL Premium polyurethane adhesive.

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 1.3E 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 3S, respectively.

To determine basic material properties, single SPF members (group 1S) and single LSL members (group 1L) also 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 I-S and I-AS) 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 I-S and I-AS was the placement of a continuous 1/4-in. diameter bead of PL Premium construction between each SPF flange and its associated LSL web. Screw spacing for flange attachment was 8 inches for 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 simple-supported beam under a one-third point loading (in regions of low or zero shear) do little to affect beam strength and stiffness.

Table 1

Table 1. Experimental Design for Laboratory Bending Tests

Group Identification	Description	Replicates	Required Number of Members: Spruce-Pine-Fir (SPF)	Required Number of Members: Laminated Strand Lumber (LSL)
1S	Single nominal 2 x 6-inch SPF member	30	30	0
1L	Single nominal 2 x 6-inch LSL member	10	0	10
3S	3-layer, vertically laminated mechlam fabricated from nominal 2 x 6-inch SPF lumber	10	30	0
I-S	I-section with nominal 2 x 6-inch SPF flanges screwed to a 1.5 x 5.5-inch LSL web	18	36	18
I-AS	I-section with nominal 2 x 6-inch SPF flanges attached with adhesive and screws to a 1.5 x 5.5-inch LSL web	18	36	18
	Total	86	132	46

Table 2

Table 2. Physical Properties of Lumber

Property	46 Pieces of 1.3E Timberstrand Laminated Strand Lumber (LSL)	132 Pieces of No. 2 Spruce-Pine-Fir (SPF)
Mean thickness, in. (coefficient of variation [COV], %)	1.495 (0.3)	1.468 (1.0)
Mean width, in. (COV, %)	5.495 (0.4)	5.375 (0.9)
Mean moisture content, % (COV, %)	8.00 (2.9)	7.73 (5.9)
Mean specific gravity (COV, %)	0.604 (7.9)	0.439 (11.5)
Mean apparent modulus of elasticity[a], 10^6 lbf/in.^{2} (COV, %)	1.51 (11.1)	1.42 (19.5)

[a] Based on static flatwise bending assuming a theoretical size of 1.50 x 5.50 in.

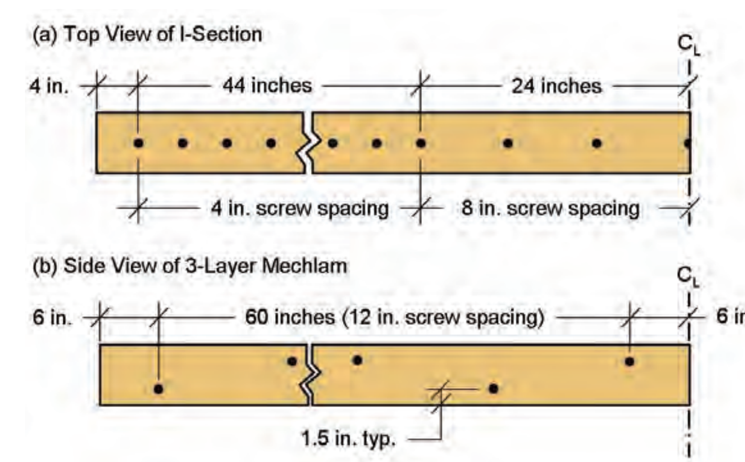


Figure 5: *Screw locations for (a) each flange of I-section assemblies and (b) each side of three-layer, vertically laminated mechlam assemblies.*

Three-layer, vertically laminated mechlams (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

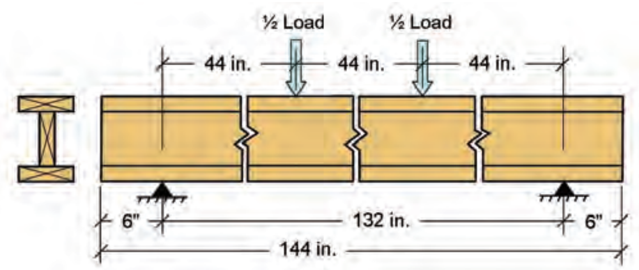


Figure 6: *Location of load points and supports for all bending tests.*

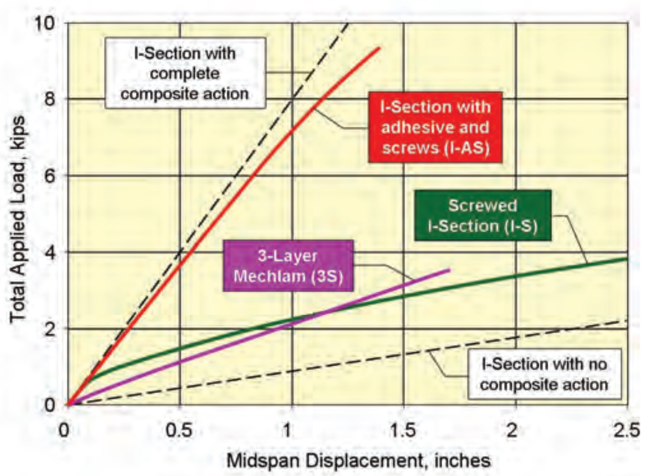


Figure 7. *Total applied load versus average midspan displacement for the laminated assemblies. Dashed lines represent predicted upper and lower bounds for I-section stiffness.*

Table 3

Table 3. Bending Properties of Single Members and Three-Layer Mechlams

Property	Statistic	LSL Single Members (1L)	SPF Single Members (1S)	3-Layer Vertically Laminated Mechlam (3S)
Ultimate midspan bending moment	Mean, ft.-kips	3.61	3.54	8.53
	Std. dev., ft.-kips	0.73	1.46	3.41
Midspan deflection at maximum load	Mean, in.	3.03	2.76	2.50
	Std. dev., in.	0.43	0.77	0.74
	Coefficient of Variation (COV), %	14.0	28.0	29.6
Modulus of rupture	Mean, lbf/in.^{2}	5730	5620	4510
	Std. dev., lbf/in.^{2}	1160	2320	1800
	COV, %	20.2	41.3	40.0
	Normal 5% point estimate, lbf/in.^{2}	3829	1795	1543
	Nonparametric 5% point estimate, lbf/in.^{2}	4690	2461	2548
Apparent modulus of elasticity [a]	Mean, 10^6 lbf/in.^{2}	1.36	1.43	1.46
	Std. dev., 10^6 lbf/in.^{2}	0.13	0.34	0.30
	COV, %	9.7	23.8	20.4

[a]Based on static edgewise bending assuming a theoretical size of 1.50 x 5.50 inches for all members.

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 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 value (Table 2) calculated from flatwise bending tests. Conversely, E values for LSL lumber from edgewise and flatwise bending tests (1.36 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 no composite action between S-P-F flanges with an E of 1.43 million pounds per square inch and LSL webs 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 Figure 7 that I-sections fabricated with adhesive exhibited near-complete composite action. At total loads less than 600 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 grain, 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 polyurethane 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 Figures 11 and 12 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 mechlams.

Design values are typically based on 5 percent point estimates. Two such 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 for the I-sections fabricated 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 mechlams (Group 3S).

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

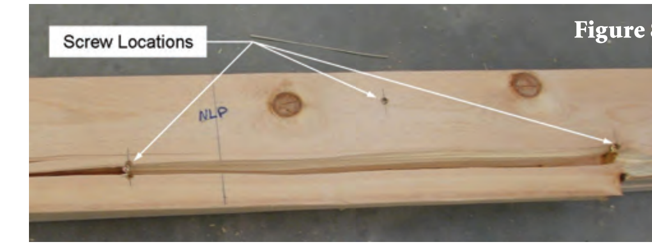


Figure 8. *Typical 3S failure displaying splitting of outer plies through screw locations.*

Figure 9. *Typical I-S failure of the web in flexure (fracture identified by blue line below load block).*

Figure 10. *Typical I-AS failure through a knot in the tension flange near midspan.*

mean and 5 percent point estimates of bending strength.

The low strength of the screwed-only I-sections (group I-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-S assemblies being limited by the flexural strength of the webs.

Although the mean bending strength of the three-layer mechlams was 4 percent greater than that for the screwed-only I-sec-

Table 4

Table 4. Bending Properties of I-Sections and Three-Layer Mechlams				
Property	Statistic	I-Section with Screws Only (I-S)	I-Section with Adhesive and Screws (I-AS)	3-Layer Vertically Laminated Mechlam (3S)
Ultimate midspan bending moment	Mean, ft.-kips	8.19	17.67	8.53
	Std. dev., ft.-kips	0.52	3.02	3.41
	Coefficient of Variation (COV), %	6.4	17.1	40.0
	Normal 5% point estimate, ft.-kips	7.3	12.7	2.9
	Nonparametric 5% point estimate, ft.-kips	7.5	13.2	4.8
Midspan deflection at maximum load	Mean, in.	3.06	1.43	2.50
	Std. dev., in.	0.31	0.28	0.74
	COV, %	10.0	19.7	29.6
Initial stiffness[a]	Mean, kips/in.	6.53	7.45	2.24
	Std. dev., kips/in.	0.76	1.74	0.46
	COV, %	11.6	23.3	20.4

[a]Initial stiffness calculated as total applied load at a midspan displacement of 0.1 in. divided by the 0.1-in. displacement.

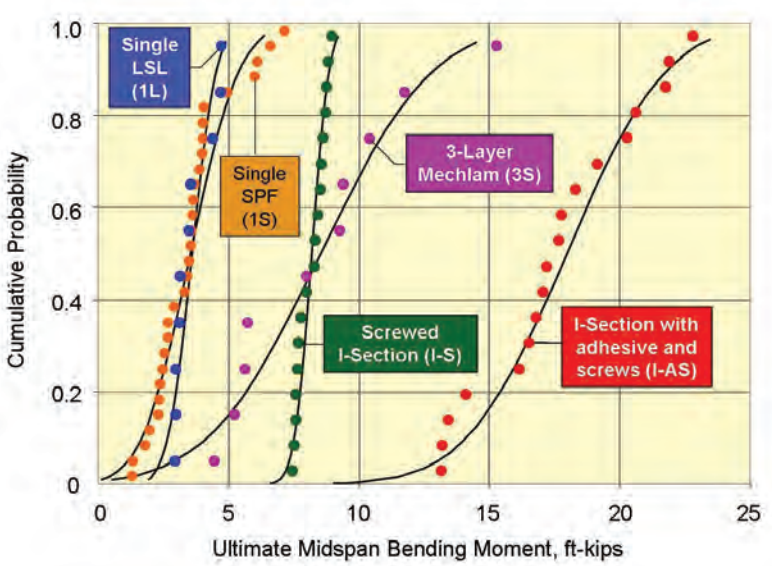


Figure 11. *Cumulative distributions for ultimate midspan bending moment for single members, I-sections, and three-layer mechlams. Fitted curves are normal CDFs.*

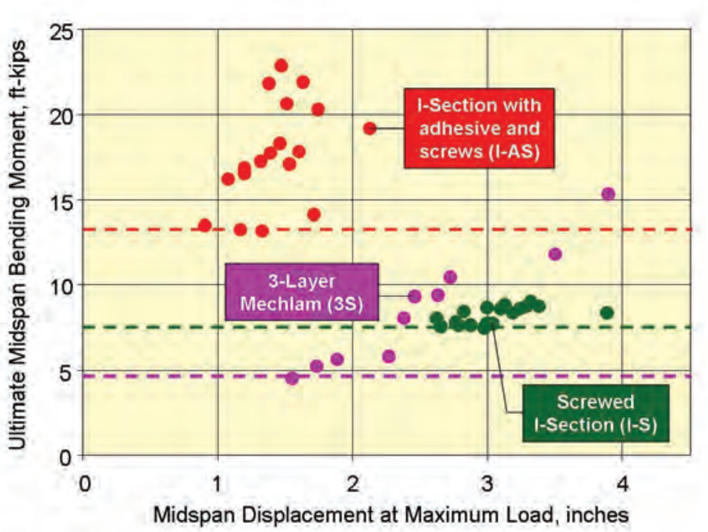


Figure 12. *Ultimate midspan bending moment versus midspan deflection at failure for I-sections and three-layer mechlams. Dashed horizontal lines identify nonparametric 5% point estimates.*

tions, the 5 percent point estimates of bending strength for the screwed-only I-sections significantly exceeded those for the three-layer mechlams. This was due to the relatively low variation in bending strength of the screwed-only I-sections, which in turn was due to their bending strength being controlled by the bending strength of their LSL webs. Not surprisingly, this control resulted in 1) the screwed-only I-sections failing at the same 3.0-inches mean maximum displacement as the single LSL members and 2) a very similar standard deviation on mean ultimate bending strength for the screwed-only I-sections and the single LSL members.

One of the unexpected results of this study was that the COV for the modulus of rupture for the three-layer mechlams (40 percent) was nearly the same as that for the single SPF members (41.3 percent), resulting in similar 5 percent point estimates on MOR. Normally we expect the vertical lamination of lumber to reduce the variability of both MOR and E, with the COV decreased inversely as the square root of the number of layers (Bohnhoff, Moody, Verrill, & Shirek, 1991). For a three-layer assembly, this would be a reduction in COV from that of single members of approximately 42 percent.

The high COV for the MOR of the three-layer mechlams was primarily attributed to the lumber assignment process. Although individual members were randomly assigned to the different group 3S specimens, several low E members ended up being group together, and several high E members were grouped together. This resulted in the COV of modulus of elasticity for the 3S specimens being only slightly lower than that for the single members (20.4 percent versus 23.8 percent, respectively). Theoretically, the COV of E for group 3S should have been around 14 percent. Because of the high correlation between MOR and E, the grouping (during assembly layup) of low E members with low E members and high E members with high E members will result in laminated assemblies with an MOR distribution that is more similar to that of the individual members.

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

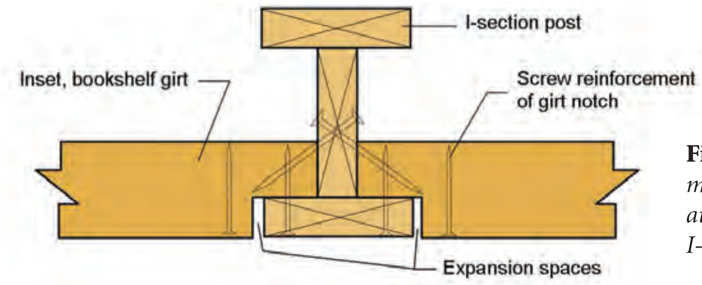


Figure 13. *Possible method for girt attachment to an I-section post.*

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 I-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 I-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-section 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.

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