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Timber Rivet Connections in U.S. Domestic Species

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Abstract

This paper discusses results of tests conducted to expand the data base on the performance of timber rivet connections in U.S. domestic species to verify existing and proposed design procedures. Eight-, 80-, and 200-rivet connections were tested. The 8-rivet joint tests illustrate the effects of material type, rivet length, and load direction on the behavior of rivet connections when gross wood failures are avoided. The 80-rivet connections, loaded perpendicular to grain, show the effect of rivet spacing as well as test support conditions on failure mode and strength. The 200-rivet joints, with load applied parallel to grain, provide data for previously reported failure modes, including the rivet yield/wood crush modes modeled by European yield model (EYM) and gross wood failures. The 200-rivet tests also show the effect of rivet spacing on joint strength and failure mode.

The tests were conducted in two phases. In Phase I, small specimens were made from Southern Pine and ponderosa pine solid sawn lumber, Hem–Fir and Southern Pine glulam, and parallel strand lumber. The small specimens failed by a combination of rivet yielding and wood crushing as described by EYM, rather than by a gross failure of the wood block. Joint yield load was determined by fitting test data to a curve and finding the load at 5% offset displacement. Basic trends can be seen in the data, but yield load is a poor predictor of ultimate load.

In Phase II, large specimens were made from Southern Pine glulam. Larger rivet spacing, wider specimens, and longer rivets generally increased joint capacity; end spacing had no significant effect. Short continuously supported beams had a higher capacity load than did longer simply supported beams. The results show that when wood failure modes occur, thicker glulam has higher capacity, contradicting the size effect of the design code.

Keywords: glulam rivet, timber rivet, connection, design model

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Introduction

The timber rivet connection has become common in Canadian glued-laminated (glulam) and sawn timber construction as a cost-effective alternative to bolted connections. Timber rivets are hardened steel nails from 40 to 90 mm long and 3.2 by 6.4 mm in oval–rectangular cross section. They are driven with their major cross-sectional dimension parallel to the wood grain. Timber rivets are installed through predrilled steel side plates (typically 6.4 mm thick) in rectangular arrays with minimum spacing of 15 to 25 mm. The rivet-pattern density (rivets/unit area) has a profound effect on the failure mode. Close spacing promotes a brash failure characterized by wood tear-out within the area defined by the rivet array. Wider spacing tends to cause a combined fastener yield and wood crushing mechanism to dominate, resulting in greater ductility. The latter failure mode is common to other dowel-type fasteners and is described by the European yield model (Aune and Patton–Mallory 1986).

Although timber rivets have been used in Canada for more than 30 years (Madsen 2000), they were first adopted in the United States through the 1997 edition of the National Design Specification for Wood Construction (NDS). Provisions in the NDS (AF&PA 2001) are based on, but less comprehensive than, the Canadian O86.1 code (CSA 2001). The NDS, for example, limits the use of rivets to only Southern Pine and Douglas Fir glulam, and it does not include the general connection design procedure for non-standard connection geometries that is included in the Canadian code as an appendix, which effectively limits applications for designers in the United States. Additional shortcomings of the Canadian and U.S. code design procedure are as follows:

1. The analysis of stresses around the fastener group, which leads to prediction of connection strength when wood failure controls, is well reasoned but too complex for a closed form solution; designers must refer to tables of constants.
2. The procedure includes a volume effect on shear strength, so predicted connection strength decreases as timber thickness increases. While the concept of a size effect is accepted in several areas of timber design, there are insufficient test data in the literature to support its inclusion in this analysis.
3. The procedure uses the capacity of a single rivet as an input, but it does not provide guidance on how to estimate this capacity for wood species not currently included in the code.

Objectives and Scope

This paper discusses the results of tests conducted to expand the data base on performance of timber rivet connections in U.S. domestic species. The primary objective was to provide a range of data for verifying existing and proposed alternative design procedures. Current design procedures consider failure mode as well as material strength in predictions of joint capacity. The tests were therefore required to exhibit failure modes dominated by wood fracture as well those dominated by rivet yield and localized wood crushing.

Test joints included a range of rivet sizes (40- to 90-mm lengths) and material specific gravity (0.4 to 0.55) and strength in U.S. domestic species. Joint tests included 8-, 80-, and 200-rivet connections. The 8-rivet joint tests illustrate the effects of material type, rivet length, and load direction on the behavior of rivet connections when gross wood failures are avoided. The 80-rivet connections, loaded perpendicular to grain, show the effect of rivet spacing and test support conditions on failure mode and strength. The 200-rivet joints, with load applied parallel to grain, provide data to compare the effects of wood tear-out failure modes on rivet yield.

Literature Review

The first test data were reported by McGowan (1966) and the development of the timber rivet was chronicled by Madsen (2000), but without doubt the most influential work on timber rivets is that of Foci and Long worth (1975). Foci and Long worth presented rational analyses of the conditions leading to a rivet yield failure mode and to a wood failure mode; they included limited testing to verify and calibrate the analyses. These authors presented a number of equations to predict the strength of timber rivet joints based on their geometry and material properties. The correlation of predictions and test results was remarkably good. The authors concluded that the wood tension failure mode should rarely, if ever, control and then only for unusually thin wood members. They also presented analogous developments for perpendicular-to-grain loadings. Their limited experimental work served to show that the analysis gives good predictions. The work by Foci and Long worth has proven to be quite robust—there have been no published alternatives to their basic analysis of concentrically loaded connections, and their procedure has been adopted by the Canadian and U.S. codes.

The first study of timber rivet behavior in solid timber presented promising results with an important caveat. In testing timber rivet connections parallel and perpendicular to grain, Karacabeyli and Fraser (1990) reported that the strength, load–displacement response, and failure modes of these connections in Douglas Fir solid timber and glulam were essentially the same. They noted, however, that the absence of major defects such as checks and splits from the solid timber specimens limited the value of their results as an indication of how rivet connections would behave in real solid timber.

Karacabeyli and others (1998) described a large testing program to evaluate the behavior of rivet connections in solid timber (Douglas Fir–Larch, Spruce–Pine–Fir, and Hem–Fir). Their solid timber specimens, like those in the study by Karacabeyli and Fraser 1990), were defect-free in accordance with testing norms (ASTM 1988). They noted that when rivet yielding is the failure mode, connections in solid timber are 80% to 90% as strong as connections in the same species of glulam. For connections with wood failure modes, the authors noted that these failure modes are similar for solid timber and glulam. They reasoned that the work of Foci and Long worth (1975) should therefore apply to solid timber.

As previously noted, the equations developed by Foci and Long worth (1975) use wood tensile and shear strength to determine strength of the riveted connection in wood failure modes. Shear strength values for solid timber are typically 40% to 50% of shear strength values for glulam of the same species group, as a result of cracks and checks in solid timber. Therefore, Karacabeyli and others (1998) concluded that riveted connections with solid timber should have a 50% reduction in design strength from connections with glulam of the same species group. The adjustments they suggested were adopted by the Canadian code.

Buchanan and Lai (1994) tested timber rivet connections in Monterey pine (*Pinus radiata*) and investigated application of the European yield model (EYM) for rivet connections. The EYM describes failure as a combination of fastener yield and localized wood crushing (Aune and Patton–Mallory 1986), and it has been accepted for use with all other dowel fasteners (AF&PA 1999, 2001). Buchanan and Lai (1994) showed that EYM predictions were quite good, but their work did not lead to changes in code.

Definition of Terms

The following terms describe the rivet connection configuration (see also Fig. 1):

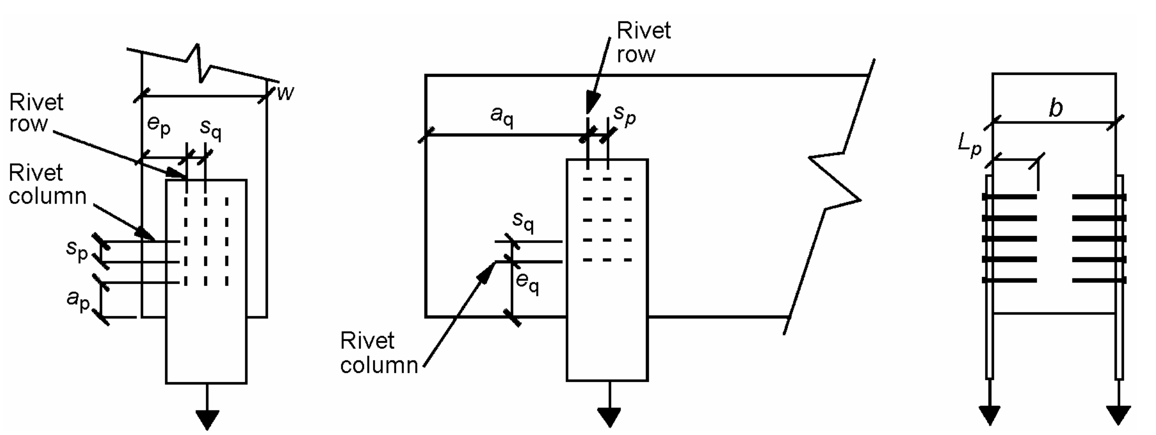

Figure 1—Connection geometry variables: (from left) parallel-to-grain connection, perpendicular-to-grain connection, and view through thickness of connection.

Row	line of rivets parallel to load direction
Column	line of rivets perpendicular to load direction
s_p	spacing of rivets measured parallel to grain
s_q	spacing of rivets measured perpendicular to grain
L	rivet length (standard lengths used in this study were 40, 65, and 90 mm)
p	rivet penetration into wood ($p = L$ – plate thickness – 3.2 mm)
a	distance from end of wood member to closest column of rivets for parallel-to-grain loading
e_q	distance from loaded edge of wood member to closest column of rivets for perpendicular-to-grain loading
e_p	distance from rivet to non-loaded edge for parallel-to-grain loading
e_s	distance from edge of steel plate to closest rivet

Procedures

Testing for this research was conducted in two phases. Phase I was intended to illustrate the effects of material type, rivet length, and load direction on the behavior of rivet connections when gross wood failures are avoided. Phase II was planned to provide a full range of previously reported failure modes—including gross wood failures and rivet yield/wood crush modes modeled by EYM.

Phase I consisted of 130 tests of small connections. The specimen geometry and test procedures were consistent with those used by previous researchers (Buchanan and Lai 1994, Karacabeyli and others 1998), so these data could be fairly compared with data in the literature.

Phase II included 45 tests of large connections in 22 configurations. These tests were intended to illustrate the effects of connection configuration, load direction, and support conditions on failure mode and capacity. The large connection test specimens were similar to those used by previous researchers (Buchanan and Lai 1994, Foci and Long worth 1975, Karacabeyli and others 1998, McGowan 1966), but our specimens had riveted plates on both faces of the glulam, making a symmetric connection that better simulates real applications.

Wood for all test specimens was preconditioned at 18°C and 65% relative humidity to achieve a target equilibrium moisture content of 12% prior to fabrication of the connection. After fabrication, the specimens were stored under the same conditions for at least 1 week until testing. Test joints were fabricated with plates applied to opposing surfaces of the wood members. All side plates, as called for by NDS specifications, were A36 steel with predrilled 7.14-mm holes. Rivets were driven either by hand or by a hand-held pneumatic hammer.

Phase I. Small Connection Tests

Small specimens (Fig. 2) were designed to fail by a combination of rivet yielding and wood crushing, as described by EYM, rather than by gross failure of the wood block. All specimens had 6.4-mm steel plates on opposite sides, with four rivets installed through predrilled holes in each plate. Rivet spacing was 25.4 mm parallel and perpendicular to grain. The specimens were supported at the bottom of the

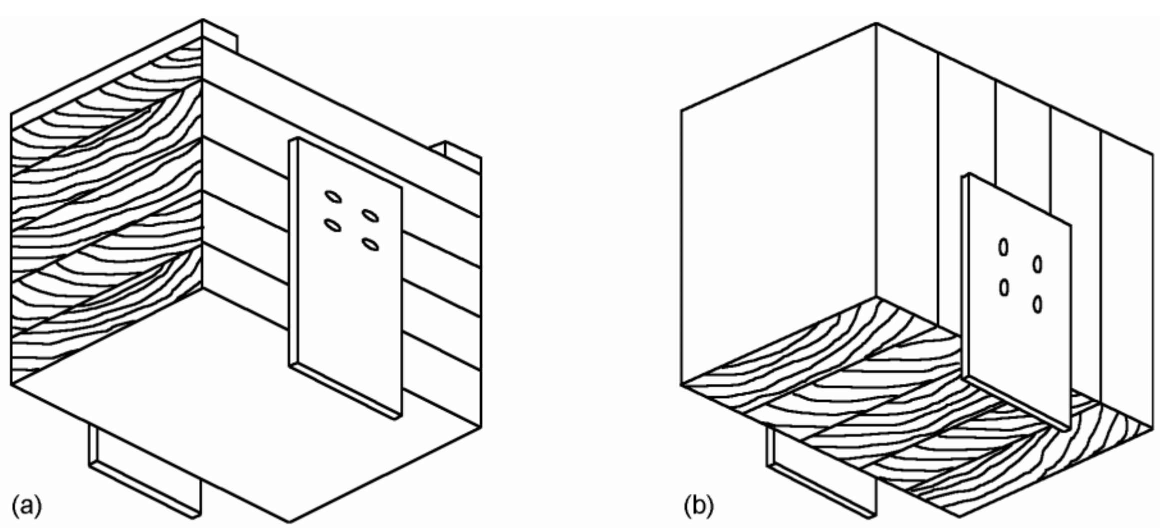

Figure 2—Small specimens for (a) perpendicular-to-grain and (b) parallel-to-grain loadings.

steel plates and loaded by pushing down on the top. We assumed that if gross wood failure is avoided there is no difference between compressive and tensile loading; either one is really shear or lateral loading on the fastener groups.

All specimens were cut from solid or glulam timber with cross-sectional dimensions of 140 mm wide (along glue lines) and 184 mm deep (perpendicular to glue planes). Specimens with 90-mm rivets were fabricated with the 140-mm and 184-mm dimensions switched so that the tips of the long rivets would not overlap at the center. Parallel-to-grain specimens were 152 mm long; perpendicular-to-grain specimens were 203 mm long. Specimens were made with solid sawn Southern Pine, solid sawn Ponderosa Pine, glulam Southern Pine, glulam Hem–Fir, and parallel strand lumber (PSL), a structural composite lumber product available in sizes large enough for timber rivet use. Table 1 shows the wood material, rivet length, and loading direction for the specimens. Ten replicates of each specimen were used.

All wood material was conditioned and cut at the Forest Products Laboratory and delivered to the Milwaukee School of Engineering for connection fabrication, final conditioning, and testing. The glulam was fabricated commercially.

All tests were conducted on an open-loop hydraulic test machine with manual control over the loading rate. Load was measured with a 90-kN capacity electronic load cell; deformation of the connection was measured with a pair of symmetrically mounted 12.7-mm linear variable differential transformers (LVDTs) (Fig. 3). The LVDTs were mounted by clamping the LVDT body into a fitting screwed to the wood specimen and clamping the core extension rod into a plexiglass fitting that was hot-glued to the steel plate.

The two displacement readings were averaged to produce a single measure of connection deformation. The rate of connection deformation was monitored during the test, and the loading rate was adjusted manually as necessary to keep the deformation rate close to the 2-mm/min target. For all tests, deviation from the target deformation rate was insignificant. Readings from the load cell and LVDTs were recorded at 1-s intervals. After testing, specimens were split apart with a chisel to observe the condition of the rivets.

Phase II. Large Connection Tests

The large rivet test connections were fabricated using Southern Pine glulam. Twenty-two joint configurations were tested; 14 configurations were tested with load applied parallel to grain and 8 with load applied perpendicular to grain. Joint configuration variables, summarized in Tables 2 and 3, included rivet length (L), spacing parallel (s_p) and perpendicular (s_q) to grain, end distance for parallel-to-grain (a) and perpendicular-to-grain (e_q) loading, and glulam thickness. For parallel-to-grain tests, most glulam specimens were 2.0 m long by 419 mm wide. The first four specimens tested (9–1, 9–2, 10–2, 10–2) were necked down from a width of 381 mm at the grip to a width of 279 mm at the rivet connection in an effort to reduce edge distance (e_p). Glulam

Table 1—Specimens for small connection tests

Wood material	Loading direction with respect to wood grain	Rivet length (L) (mm)
Solid-sawn Southern Pine	Parallel	40
		65
		90
	Perpendicular	40
		65
		90
Solid-sawn ponderosa pine	Parallel	65
	Perpendicular	65
Glulam Hem–Fir	Parallel	65
	Perpendicular	65
Glulam Southern Pine	Parallel	65
	Perpendicular	65
Parallel strand lumber	Parallel	65
	Perpendicular	65

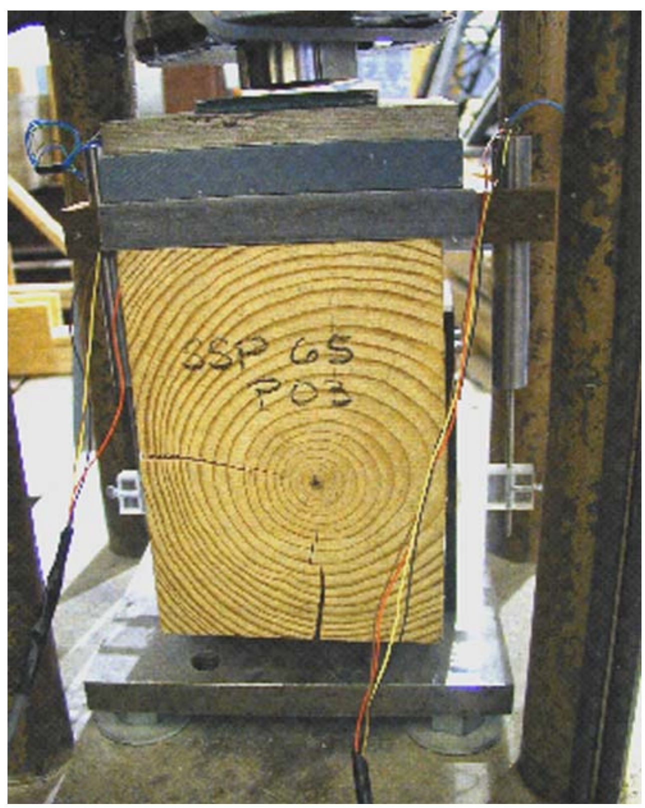

Figure 3—Setup for small connection tests.

Table 2—Configurations for large parallel-to-grain specimens (mm)

Joint ID[a]	Rivet pattern				Glulam		Steel side plates		
	s_p	s_q	*L*	*a*	Thickness	Width	Width	Length	Thickness
P3	25.4	12.7	40	50	79	419	229	508	6.4
P4				150	79	419	229	610	6.4
P5	31.8	25.4	40	50	130	419	254	584	6.4
P6				150	130	419	254	686	6.4
P7	25.4	12.7	40	50	130	419	229	508	6.4
P8				150	130	419	229	610	6.4
P9	31.8	25.4	65	50	130	279	254	584	9.5
P10				150	130	279	254	686	9.5
P11	25.4	12.7	65	50	130	419	229	508	6.4
P12				150	130	419	229	610	6.4
P13	31.8	25.4	90	50	216	419	254	584	9.5
P14				150	216	419	254	686	9.5
P15	25.4	12.7	90	50	216	419	229	508	6.4
P16				150	216	419	229	610	6.4

[a] Study plan included two joint configurations (joints P1 and P2) in 79-mm-thick glulam using 40-mm rivets spaced 32 mm parallel and 25 mm perpendicular to the grain. Although these tests were not conducted, the original numbering was retained to maintain compatibility between the final report, the raw data, and the study plan.

Table 3—Configurations for large perpendicular-to-grain specimens

Joint ID	Rivet pattern[a] (mm)				Glulam		Steel side plates (mm)		
	s_p	s_q	*p*	e_q	Thickness (mm)	Length (m)	Width	Length	Thick-ness
Q1	25.4	25.4	65	102	130	2.3	180	276	6.4
Q2				73	130	0.8	180	324	6.4
Q3	25.4	12.7	65	73	130	2.3	143	324	6.4
Q4				127	130	0.8	143	324	6.4
Q5	25.4	25.4	90	73	216	2.3	180	381	6.4
Q6				73	216	0.8	180	381	6.4
Q7	25.4	12.7	90	102	216	2.3	143	324	6.4
Q8				127	216	0.8	143	324	6.4

[a]See text for definition of terms.

specimens for the perpendicular-to-grain tests were fabricated with a width of 381 mm and length of 3 m. Each of these 3-m lengths was cut to provide two test samples—one 2.3 m long and the other 0.8 m long—to provide a basis for evaluating the effect of continuous support as opposed to simple span bending support.

Rivet patterns used for the test joints are summarized in Tables 2 and 3. For most test connections, the steel side plates were 6.4 mm thick; 9.5-mm-thick plates were used for parallel-to-grain test configurations predicted to develop ultimate loads higher than 500 kN. Rivet holes were drilled through the steel plates in rectangular 10×10 arrays for parallel-to-grain tests and 4×10 arrays for perpendicular-to-grain tests. For parallel-to-grain specimens, row spacing was 12.7 or 25.4 mm and column spacing was 25.4 or 32 mm; for perpendicular-to-grain specimens, row spacing was 25.4 mm and column spacing was 12.7 or 25.4 mm. Steel plates were sized to accommodate rivet patterns with a minimum edge distance of 12.7 mm.

Application of load parallel to grain required a grip to transmit large forces from the test machine to one end of the glulam specimen (Fig. 4). The grip consisted of two 9.5-mm steel plates 0.4 m wide by 1.1 m long, each containing a 3×4 matrix of 20.6-mm-diameter holes and a single row of three 23.8-mm-diameter holes. The plates were attached to the wood using 19-mm-diameter bolts with 102-mm-diameter shear plates inserted into seats drilled in the surface of the wood. The number of bolts varied with the expected capacity of the rivet connection. The grip and rivet plates were bolted to steel load blocks that were in turn attached to the test machine heads. The load blocks were 229 wide by 102 mm deep.

Two sets of blocks were used: one set was the thickness of the thickest specimen (216 mm) and the other was the thickness of the intermediate specimen (130 mm). The thinner block was also used for the thinnest (79-mm) glulam specimens. The grip and rivet plates were held against the load blocks by six 22.2-mm bolts. A 54-mm hole was drilled in each load block to accommodate a high-strength threaded rod, which connected the block to the load head of the tension machine. The rod passed through the hole and through a spherical washer, which could swivel to reduce any moment resulting from test eccentricities. Displacement was measured between the steel rivet plate and the glulam at the centerline of the rivet pattern (Fig. 5). The LVDT was attached to the steel plate at the geometric center of the rivet pattern and aligned with the load direction. Reference bars, oriented perpendicular to the LVDT, were held above the surface of the plate and fastened to the glulam beam at the exposed edges just beyond the plate edges.

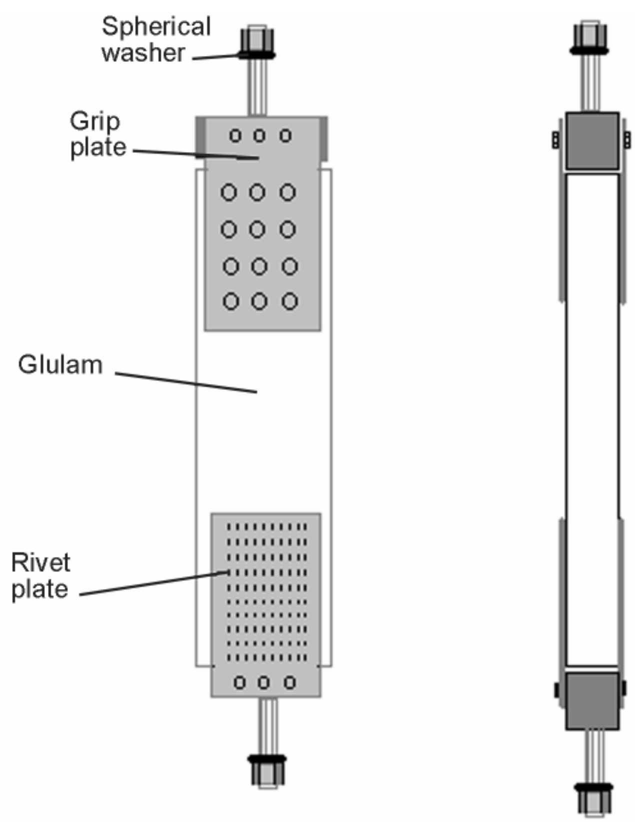

Figure 4—Setup for tension parallel-to-grain test.

Figure 5—Measurement of displacement parallel to grain.

For the tests conducted perpendicular to grain, two boundary conditions were compared (Fig. 6). In one case, the connections were tested using a continuous bearing support on the bottom edge of a 0.76-m-long specimen; in the other case, the connection was placed at the center of a 2.1-m beam span. In both cases, load was applied to edges of the plates extending above the top edge of the timber.

The load head was grooved to fit over the plate edge and provide lateral restraint while applying a vertical shear load. Displacement was measured as the movement of the load head relative to the top of the test specimen, using one LVDT on each side of the load head (Fig. 7).

For both parallel- and perpendicular-to-grain loadings, force was applied using a screw-type universal testing machine. Load and displacement channels were recorded three times per second. The test was stopped when load dropped off by 10% of the maximum value. For most loadings, loads were applied at a displacement rate of 2 mm/min; for parallel-to-grain loading beyond a load of 89 kN, the load rate was slowed to 1 mm/min.

As noted previously, placing rivet plates on both faces of a wood specimen eliminates a potentially troublesome source of eccentricity that does not exist in most real applications. To make the test connections behave even more like real connections, out-of-plane movement of the steel plates was restricted by bolting the plates to the load heads (for parallel-to-grain loading) or by grooves on the loading head (for perpendicular-to-grain loading). This simulates the restraining effect, in real applications, provided by the wood to which the other end of the steel plate is attached.

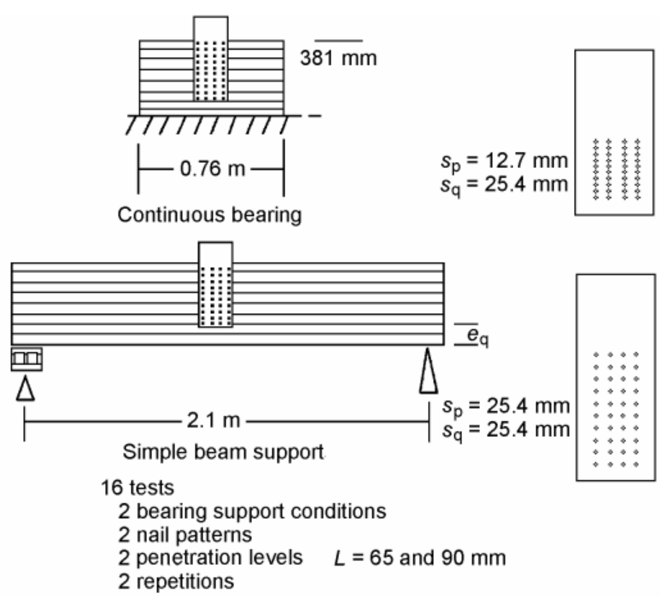

Figure 6—Specimens for perpendicular-to-grain tests.

Results

For each specimen, load and displacement measurements were recorded at specific intervals until a time well past the point of joint failure. These measurements can be plotted as data points to form a load–deflection (P–δ) curve (see Figs. 8 and 9). The first 5% to 10% of the graph (measured by load value) is not considered an accurate characterization of joint behavior for two reasons: (1) variances in joint construction require a small amount of load to distribute forces among the fasteners, and (2) measuring equipment is not considered accurate in its low ranges. The slope of the curve generally decreases steadily until one of two failure mechanisms takes effect, and the shape of the curve will indicate the general type of failure experienced by the joint. If the curve levels off and load decreases in value smoothly with increased deflection, ductile yielding of the rivets and bearing failure of the wood has taken place in the joint. If the load value drops in one or more steps as deflection increases, a brash and sometimes sudden wood failure has occurred.

Phase I. Small Connection Tests

All specimens failed by a combination of rivet bending and localized wood crushing. Representative sets of load–displacement plots are shown in Figures 8 and 9.

Figures 8 and 9 show parallel- and perpendicular-to-grain loadings, respectively, for solid Southern Pine with 65-mm

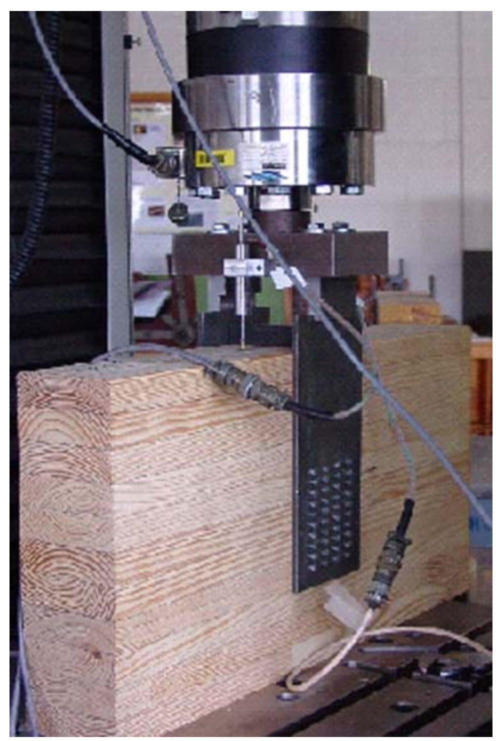

Figure 7—Test of rivets loaded perpendicular to grain.

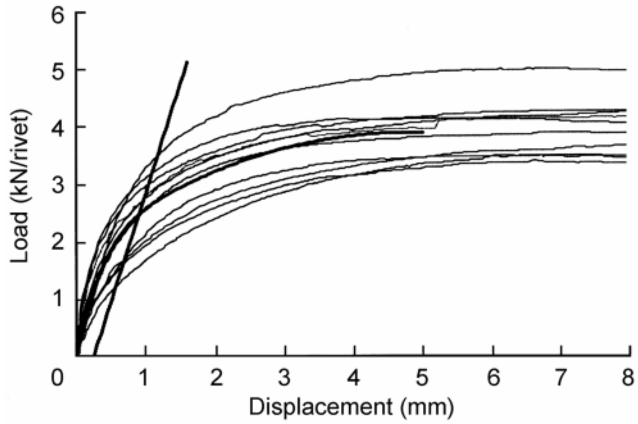

Figure 8—Typical results for small specimens loaded parallel to grain. Ten replicates of solid-sawn Southern Pine, 65-mm rivets. Fitted curve and 5% offset line used for analysis.

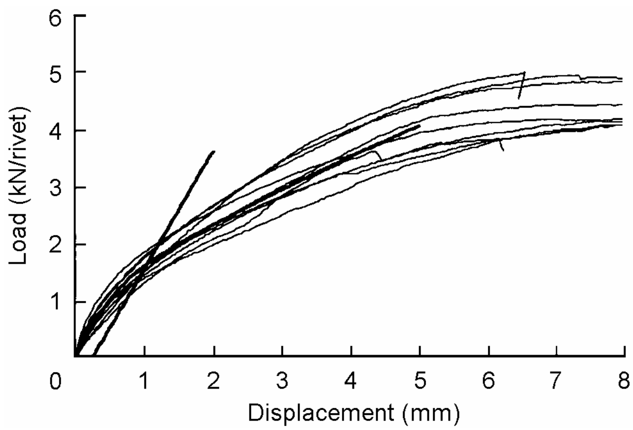

Figure 9—Typical results for small specimens loaded perpendicular to grain. Ten replicates of solid-sawn Southern Pine, 65-mm rivets. Fitted curve and 5% offset line used for analysis.

rivets. Two observations are noteworthy. First, the peak loads are similar. Second, the differences in curve for parallel loading (simple curve from initial slope to zero final slope, Fig. 8) compared with a perpendicular loading (complex curve with intermediate straight region between about 1.5- and 4.5-mm displacement, Fig. 9) are typical of all materials and rivet lengths tested.

Results for all small connection specimens are listed in Table 4. Data include the observed load when the test deflection reached 4.8 mm, which can be compared to results from previous studies by Buchannan and Karacabeyli, and the maximum load achieved during the test. The dominant yield mode was determined by inspection of the rivets after testing. Figures 10 and 11 illustrate typical yield modes.

The only unusual occurrence with regard to the glulam was that 6 of the 10 Southern Pine specimens for parallel-to-grain loading split severely while the rivets were being installed. This set of 10 specimens was discarded. This was the last batch of specimens to be tested, and it was the only set of specimens to exhibit this kind of behavior. We have no definitive explanation, but we suspect that the conditioning chamber was not properly monitored and the specimens were inadvertently over-dried prior to fabrication.

The only yield modes observed were modes III_m (single curvature) and IV (double curvature) (nomenclature from AF&PA 1999, 2001), both of which include a straight portion at the rivet head where rotation of the rivet is restrained by the fixity of the tapered head in the undersized hole in the steel plate. All specimens with yield mode data in Table 4 were split to inspect the rivets, and at least 25 of the 32 rivets had the designated yield pattern.

Phase II. Large Connection Tests

Peak loads parallel to grain ranged from 228 kN for a tightly spaced array of 40-mm rivets to 1,010 kN for wider spaced 90-mm rivets. Peak loads perpendicular to grain ranged from 175 kN for tightly spaced 65-mm rivets to 375 kN for wider spaced 90-mm rivets. Test results for large connections loaded parallel- and perpendicular-to-grain are summarized in Tables 5 and 6, respectively; more detailed information about each replicate is presented in the Appendix. The format of the data in Tables 5 and 6 matches that of Table 4 with the exception of failure mode description. For the large connection tests (Tables 5 and 6), the codes used to classify failure modes are R for rivet bending and localized wood crushing, and W for gross wood failure. The effect of failure mode on the load–displacement plots is shown in Figure 12.

While some failures were easily classified using this simple code (Fig. 13, for example), many of the observed failures exhibited a combination of failure modes. For perpendicular-to-grain tests, splits along the grain appeared in conjunction with rivet bending and wood bearing deformation. These failures are considered “wood” failures rather than “rivet” failures. For parallel-to-grain tests, it was difficult to tell which component failed first in a number of hybrid failures.

Wood failure was observed more commonly in the specimens that had closely spaced rivet patterns than in those with widely spaced patterns. Perpendicular-to-grain specimens with closely spaced rivets tended to have a single large crack extending along the grain from the top rivet column (column farthest from loaded edge), whereas specimens with wider spacing were more likely to have cracks along nearly every column (Fig. 14).

As noted previously, four parallel-to-grain specimens were necked down to minimize the horizontal edge distance. This created stress concentrations that appear to have caused one

Table 4—Small connection test results[a]

Wood[b]	Loading direction	L (mm)	Load at 5% offset[c] (kN/rivet)	Initial slope[d] (kN/mm/ rivet)	Max. load up to 4.8 mm (kN/rivet)	Maximum load (kN/rivet)	Dominant yield mode
SSP	Parallel	40	0.97	5.67	3.37 (4)	3.52 (4)	III_m
		65	1.81	6.99	3.75 (13)	3.97 (13)	III_m
		90	2.02	5.61	4.75 (10)	5.17 (10)	IV
	Perpendicular	40	0.69	2.61	2.50 (8)	2.93 (7)	III_m
		65	1.05	4.12	3.88 (11)	4.38 (10)	IV
		90	0.76	4.58	4.25 (10)	5.25 (9)	IV
SPP	Parallel	65	1.68	10.4	3.62 (7)	3.74 (9)	III_m
	Perpendicular	65	1.02	5.17	3.50 (10)	4.64 (8)	IV
GHF	Parallel	65	2.07	6.75	5.09 (5)	5.90 (9)	—[d]
	Perpendicular	65	1.47	3.15	4.04 (14)	4.93 (12)	—[d]
GSP	Perpendicular	65	0.63	5.02	4.13 (8)	4.94 (7)	—[d]
PSL	Parallel	65	2.10	7.01	3.83 (4)	3.92 (5)	—[d]
	Perpendicular	65	2.19	2.45	5.14 (4)	5.55 (5)	—[d]

[a]Average for 10 replicates. Values in parentheses are coefficients of variation (%).
[b]SSP is solid sawn Southern Pine; SPP, solid sawn ponderosa pine; GHF, glulam Hem–Fir; GSP, glulam Southern Pine; and PSL, parallel strand lumber.
[c]Initial slope and load at 5% offset were evaluated directly for average of 10 replicates; variability was not measured.
[d]Rivet yield modes not assessed for these specimens.

Figure 10—Yield mode IV is characterized by reverse curvature of rivet between tip and head (solid-sawn Southern Pine, 90-mm rivets).

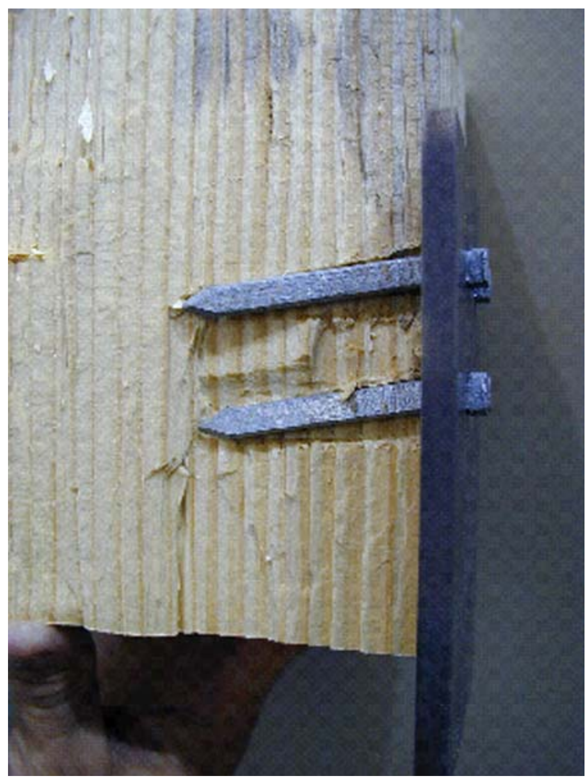

Figure 11—Yield mode III_m is characterized by single curvature of rivet below head (solid-sawn Southern Pine, 65-mm rivets).

Table 5—Large connection parallel-to-grain test results[a]

Joint ID	Load at 5% offset (kN/rivet)	Initial slope (kN/mm/rivet)	Max. load up to 4.8 mm (kN/rivet)	Maximum load (kN/rivet)	Failure mode[b]
P3	0.61	4.23	1.30	1.36	W
P4	0.89	3.30	1.50	1.57	W
P5	0.88	7.67	2.90	2.94	R
P6	1.02	6.87	2.52	2.53	R
P7	0.78	3.78	2.08	2.09	W
P8	0.80	4.57	2.34	2.34	W
P9	1.08	12.5	3.14	3.14	R
P10	1.11	7.86	3.16	3.16	R/W
P11	1.15	4.56	2.06	2.14	W
P12	1.23	5.62	2.09	2.09	W
P13	1.17	7.02	4.51	4.79	R
P14	1.14	9.02	4.48	4.71	R
P15	0.95	5.31	2.70	2.79	W
P16	1.33	5.10	3.66	3.66	W

[a]Averages for 2 or 3 replicates with 200 rivets/connection.
[b]R indicates rivet bending and localized wood crushing; W indicates gross wood failure.

Table 6—Large connection perpendicular-to-grain test results[a]

Joint ID	Load at 5% offset (kN/rivet)	Initial slope (kN/mm/rivet)	Max. load up to 4.8 mm (kN/rivet)	Maximum load (kN/rivet)	Failure mode
Q1	0.82	1.40	2.94	3.24	W
Q2	0.81	1.10	2.67	2.91	W
Q3	1.33	1.13	1.85	1.88	W
Q4	0.92	1.08	2.10	2.22	W
Q5	0.90	1.57	2.93	3.59	W
Q6	1.06	1.19	3.49	4.69	W
Q7	1.56	1.09	2.33	2.78	W
Q8	1.25	0.90	2.23	2.80	W

[a]Averages for 2 replicates with 80 rivets/connection.

specimen to break in the glulam at the cross-section transition rather than at the joint. Evaluation of the test load–deflection curve showed that the joint had reached its maximum load before the break, and thus the curve properly reflected joint behavior to maximum load.

Analysis of Results

Phase I. Small Connection Tests

Figures 8 and 9 show curves of the form

$$y = a \tanh(bx) + cx + dx^e \qquad (1)$$

where *a*, *b*, *c*, and *d* are constants and *e* is the integral of the natural logarithm. The curve represents the average of all tests in a particular set. The curves were fitted by the Davidon–Fletcher–Powell (Fletcher–Powell 1980–81) (quasi-Newton) algorithm. The initial slope of the curve is the derivative of Equation (1) at $x = 0$, $ab + c$. Figures 8 and 9 also show straight lines with this slope, offset by a displacement equal to 5% of the rivet "diameter," for which we use the average of the rivet cross-sectional dimensions to derive an offset of

$$0.05\frac{6.4\,\text{mm} + 3.2\,\text{mm}}{2} = 0.24\,\text{mm} \qquad (2)$$

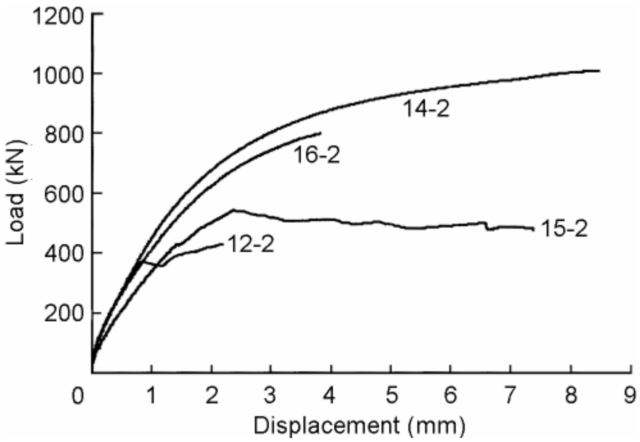

Figure 12—Typical load–displacement plots for large parallel-to-grain specimens. See Appendix for description of test specimens.

Figure 13—Typical failure mode for large parallel-to-grain specimens.

The "load at 5% offset" displacement in Table 4 is the load at the intersection of the average fitted curve with the offset straight line as described, consistent with the definition of nominal yield values used in NDS (AF&PA 2001). The displacement at this intersection is also reported.

Basic trends can be seen in the data, but none is completely consistent across all measures of capacity (Table 4). At the 5% offset measure, longer rivets produced higher load capacities, except 90-mm rivets perpendicular to grain. At the same measure, parallel-to-grain capacity was higher than perpendicular-to-grain capacity for all wood types except PSL. At the 4.8-mm measure, longer rivets produced higher load capacities and parallel-to-grain capacity was higher than perpendicular-to-grain capacity for all wood types except solid-sawn Southern Pine with 65-mm rivets and PSL. At the peak measure (maximum load), longer rivets produced higher load capacities, but there is no trend for parallel-to-grain capacity relative to perpendicular-to-grain capacity.

The load and displacement at 5% offset were determined as single values for each suite of 10 replicates, so variability is not reported. The code definition of nominal yield value as the load at 5% dowel diameter offset seems unfortunate. The correlation coefficient (r^2) for 5% offset load as a predictor of peak load is only 0.16. The load at a displacement of 4.8 mm, the average of rivet cross-sectional dimensions, is the measure of ultimate load used in the literature (Buchanan and Lai 1994, Karacabeyli and others 1998). The correlation coefficient for load at 4.8 mm as a predictor of peak load is 0.84. This suggests that if the goal of design guidelines is to achieve a desired reliability at ultimate load levels or to achieve an appropriate factor of safety at service load levels, then defining connector capacity at higher load levels makes sense.

Figure 14—Typical failure modes for large perpendicular-to-grain tests.

Phase II. Large Connection Tests

Statistical analysis of parallel-to-grain test results showed the effect of the design variables on connection performance. The peak load of the specimens with 32- by 25-mm rivet spacing was 64% higher than that of the specimens with 25.4- by 12.7-mm rivet spacing. The peak load of the 90-mm rivets was 52% higher than that of the 65-mm rivets and 95% higher than that of the 40-mm rivets. End distance had an insignificant effect on any dependent variable, though this finding would most certainly change if even smaller end distances were tested. Note that the end distance required by NDS (AF&PA 2001) for these connections is 102 mm.

The effect of glulam thickness can be seen by comparing joints P7 and P8 with P3 and P4, respectively. The maximum load of the 130-mm-thick glulam (P7 and P8) was 51% higher than that of the 79-mm-thick glulam (P3 and P4) (Table 5), consistent with common sense but contrary to predictions of the code analysis. As with the small specimens, the code use of the load at 5% offset is unfortunate because this load is a poor predictor of peak load ($r^2 = 0.36$). A much more sensible definition of connection capacity would be the maximum load achieved before deflection reached 4.8 mm.

Comparable analysis of perpendicular-to-grain results showed that the independent variables of vertical spacing, rivet length, and support type had a significant effect on peak load. The peak load for the 25.4-mm spacing was 57% higher than that for the 12.7-mm spacing (Table 6). Similarly, the peak load for the 90-mm rivets was 33% higher than that for the 65-mm rivets. The short continuously supported beams had a peak load that was 15% higher than that of the longer simply supported beams.

In some parallel-to-grain tests that were considered wood failures, inspection of the rivets showed significant plastic bending. The presence of bent rivets means that before the test was stopped, the rivets and the surrounding wood substrate were stressed beyond their elastic limits. Because tests were continued beyond peak load, one cannot be sure as to whether inelastic bending occurred before or after gross wood failure. Of course, at low load levels there is no reason to expect a difference in rivet behavior in a specimen that will eventually experience gross wood failure and one that will fail by an EYM mode.

As load levels increase, the rivets bend and the wood surrounding the rivets compresses. If the wood does not rupture, the rivets and surrounding wood will go into the inelastic range. If the wood still does not rupture, a classic EYM failure occurs (for example, Fig. 12, specimen 14-2). Such was the case for specimens with failure mode R (rivet bending and localized wood crushing) described in the Appendix. If wood rupture occurs before final EYM failure, either catastrophic sudden failure could occur (Fig. 12, specimen 16-2) in or a crack may redistribute forces so that loading could continue. Subsequent failure could occur by either EYM (Fig. 12, specimen 15-2) or additional wood rupture (Fig. 12, specimen 12-2).

For the parallel-to-grain rivets, per rivet values for the 200-rivet connections ranged from 80% of the values for the 8-rivet connections to 92% of the values for the 80-rivet connections. Similar results were found for perpendicular-to-grain per rivet values.

Conclusions

The tests described in this report are consistent with existing literature and therefore can be used in combination with the literature to provide verification for analytical models. This report includes the first published results for rivets in Southern Pine timber, thus providing important support to the NDS recognition of rivet connections in this species. The results suggest that the current code provisions are reasonable, although an alternative analysis could improve certain aspects of the code.

The results of testing large specimens loaded parallel to grain show the important behavioral differences between connections limited by EYM-type failure modes and those limited by wood failure modes. When EYM-type failures occur, the connection maintains positive stiffness to large displacements. When wood failure modes occur, the connection loses stiffness suddenly and can fail catastrophically, and at a lower per-rivet load than does a similar EYM-failed joint. The displacements associated with EYM-type failure are far beyond the usual range of serviceability, but they indicate that the connections may be suitable for use in seismic design if the designer can ensure that an EYM-type failure mode will control. Different strength reduction factors (for load resistance factor design, LRFD) or safety factors (for allowable stress design, ASD) might be justified for different modes. A primary requirement of any design procedure should be to predict whether a given connection will fail by EYM-type mode or wood mode.

Wood failure occurs when the energy built up in the connection exceeds the sum of the tensile and shear capacities of the wood fiber on the boundary of the rivet group before it exceeds the accumulated rivet–wood bearing strength of individual fasteners. Rivet bending and wood crushing lead to a more uniform stress redistribution and higher peak loads at larger displacements than do block shear failures.

The effects of rivet length and spacing are as one might expect: longer rivets provide increased capacity, and rivet spacing influences whether the connection will exhibit EYM-type failure or wood failure. Rivet spacing of approximately 32 mm along the grain and 25 mm across the grain seems to be adequate for rivets up to 90 mm in length. A more detailed study would be required to determine exactly what minimum spacing is required to ensure EYM-type failure for each rivet length.

Our results show that the NDS requirements for end distance are conservative, as connections with end distances of 50 and 150 mm performed similarly. Again, a more detailed study with end distances between 25 and 100 mm might be able to show true minimum end-distances to ensure EYM-type failures. The results show that when wood failure modes occur, thicker glulams have higher capacity. This finding contradicts the size effect in the code analysis.

The wood engineering community has devoted a significant amount of brain power and printed space over the years to establishing a standard definition for the capacity of a wood connection. The current NDS bases connection capacity on the load at yield, which is defined by the 5% offset method (values in NDS are calibrated down to approximate load at proportional limit, but that is somewhat beside the point). Test results show that load at yield is a poor predictor of ultimate load. While that may be a satisfactory state of affairs when design strictly follows an allowable stress approach, it is not reasonable today. Basic design for seismic events considers the ability of a structure to maintain load under significant displacements, so information about behavior beyond the 5% offset is critical. In addition, the LRFD philosophy provides a framework within which a designer can assess the suitability of a structure with regard to ultimate behavior where knowledge about behavior beyond the 5% offset is critical.

Literature Cited

AF&PA. 1999. General dowel equations for calculating lateral connection values. Tech. Rep. 12. Washington, DC: American Forest and Paper Association.

AF&PA. 2001. National design specification for wood construction. Standard ANSI/AF&PA NDS–2001. Washington, DC: American Forest & Paper Association.

ASTM. 1988. Standard test methods for mechanical fasteners in wood. Standard ASTM D1761–88. Philadelphia, PA American Society for Testing and Materials.

Aune, P.; Patton–Mallory, M. 1986. Lateral load-bearing capacity of nailed joints based on the yield theory: Theoretical development. Res. Pap. FPL–RP–469. Madison, WI: U.S. Department of Agriculture Forest Products Laboratory. 20 p.

Buchanan, A.H.; Lai, J.C. 1994. Glulam rivets in radiata pine. Canadian Journal of Civil Engineering. 21: 340–350.

CSA. 2001. Engineering design in wood (limit states design). Standard CSA–O86–01. Toronto, Ontario: Canadian Standards Association.

Fletcher–Powell, R. 1980–81. Practical methods of optimization. Vol. 1.Unconstrained optimization. New York, NY: John Wiley & Sons.

Foci, R.O.; Long worth, J. 1975. Analysis and design of grip lam nailed connections. ASCE Journal of Structural Division, 101(ST–12): 2537–2555.

Karacabeyli, E.; Fraser, H. 1990. Short-term strength of glulam rivet connections made with spruce and Douglas-fir glulam and Douglas-fir solid timber. Canadian Journal of Civil Engineering. 17: 166–172.

Karacabeyli, E.; Fraser, H.; Deacon, W. 1998. Lateral and withdrawal load resistance of glulam rivet connections made with sawn timber. Canadian Journal of Civil Engineering. 25: 128–138.

Madsen, B. 2000. Behaviour of timber connections. North Vancouver, BC, Canada: Timber Engineering Ltd.

McGowan, W.M. 1966. A nailed plate connector for glued-laminated timbers. Journal of Materials. 1(3): 509–535.

Appendix—Results of Large Connection Tests

Definitions of failure modes used in the tables:

BS (block shear)—Shear-block pull-out exhibiting shear failures in at least three planes and end-grain tensile failure. In most cases, the shear block was confined to an area beneath the plate, with edges perpendicular to the original surface defined by rivet holes.

DSP (double shear plane)—Two splits passing completely through the timber thickness. Tensile failures were not apparent in all instances. In some cases, the shear planes extended to the shear-plate seat in the timber grip. In other cases, the splits ran the length of the timber but did not pass all the way through the grip end.

NB (nail bearing)—Bearing deformation of the wood followed by surface splitting along interior nail rows. In some instances, surface splits were apparent along interior rivet rows 5 to 7.

SSP (single shear plane)—Single split in the timber extending through the thickness and along the length, often to the timber grip. This failure mode was not accompanied by tensile rupture. In most cases, the split occurred along an edge row of rivets. One end of the plate-displacement reference bar was fastened to the wood outside this split so that the load–displacement plot indicated an increase in the rate of plate displacement relative to the wood, despite the fact that no significant bearing deformation occurred at the rivet–wood interface. In some instances, the split could be attributed to shake or the existence of juvenile wood in the edge lamination, which was subject to the greatest shear stress.

TP (tension perpendicular to grain)—Longitudinal split passing through the nail pattern rather than along an edge. The split ran the length of the timber, wide at the connection end and tapering to an incomplete failure at the grip. One explanation is that load eccentricity, possibly resulting from surface splits in one edge lamination, caused the plate to rotate slightly. This slight rotation placed a combined tension perpendicular to grain and shear stress on the weak plane, causing a fracture to propagate toward the grip.

Results of 30 parallel-to-grain large connection tests (two plates with 100 rivets per plate)

Joint ID	s_p (mm)	s_q (mm)	L (mm)	a (mm)	Glulam thickness (mm)	Load at 4.8-mm displacement (kN)	Peak load (kN)	Displacement at peak load (mm)	Failure mode[a]
P3–1	25.4	12.7	40	50	79.4	310	348	5.91	DSP
P3–2				50	79.4	310	241	1.41	DSP
P3–3				50	79.4	310	228	2.40	SSP
P4–1				150	79.4	310	311	1.88	SSP
P4–2				150	79.4	310	274	1.05	SSP/TP
P4–3				150	79.4	313	356	6.59	BS
P5–1	32	25.4	40	50	130	547	558	7.05	NB
P5–2				50	130	614	616	11.26	NB
P6–1				150	130	490	492	6.15	NB
P6–2				150	130	518	519	6.34	NB
P7–1	25.4	12.7	40	50	130	518	383	3.52	BS, 2
P7–2				50	130	451	453	5.91	BS, 2
P8–1				150	130	451	401	4.55	BS, 1
P8–2				150	130	534	537	7.38	TP/SSP
P9–1	32	25.4	65	50	130	534	627	3.10	NB
P9–2				50	130	534	628	3.00	NB
P10–1				150	130	534	615	4.23	SSP
P10–2				150	130	534	647	3.91	NB
P11–1	25.4	12.7	65	50	130	379	408	5.35	BS
P11–2				50	130	379	446	2.22	BS
P12–1				150	130	379	406	2.06	SSP
P12–2				150	130	379	429	2.18	TP/SSP
P13–1	32	25.4	90	50	216	905	931	8.83	NB
P13–2				50	216	897	987	10.71	NB
P14–1				150	216	897	874	4.05	NB
P14–2				150	216	918	1,010	10.05	NB
P15–1	25.4	12.7	90	50	216	918	574	3.26	BS, 1
P15–2				50	216	504	542	7.38	BS, 1
P16–1				150	216	504	664	2.03	BS, 1
P16–2				150	216	504	800	3.81	BS, 1

[a]For block shear (BS) failure, numeral indicates number of planes affected.

Results of 16 perpendicular-to-grain large connection tests (two plates with 40 rivets per plate)

Joint ID	s_p (mm)	s_q (mm)	L (mm)	a (mm)	Glulam thickness (mm)	Load at 4.8-mm displacement (kN)	Peak load (kN)	Displace-ment at peak load (mm)	Failure mode
Q1–1	25.4	25.4	65	102	130	228	255	7.49	W
Q1–2				102	130	242	264	8.59	W
Q2–1				73	130	255	289	9.89	W
Q2–2				73	130	171	176	6.67	W
Q3–1	25.4	12.7	65	73	130	171	124	2.91	W
Q3–2				73	130	160	175	11.33	W
Q4–1				127	130	176	180	5.66	W
Q4–2				127	130	237	286	12.22	W
Q5–1	25.4	25.4	90	73	216	232	288	8.88	W
Q5–2				73	216	286	373	14.07	W
Q6–1				73	216	271	377	15.48	W
Q6–2				73	216	181	210	7.33	W
Q7–1	25.4	12.7	90	102	216	192	235	10.88	W
Q7–2				102	216	168	193	7.98	W
Q8–1				127	216	188	255	13.37	W
Q8–2				127	216	228	255	7.49	W