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Timber Rivets in Structural Composite Lumber

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Abstract

Timber rivet connections, originally developed for use with glulam construction, may be a viable option for use with structural composite lumber (SCL) products. Tests were conducted on small samples to assess the performance and predictability of timber rivet connections in parallel strand lumber (PSL) and laminated strand lumber (LSL). The test joint configurations were designed to exhibit "rivet failures"—some combination of rivet yield and bearing deformation in the composite—as opposed to wood failure modes, such as block-shear tear-out or splitting.

Results suggest that per-rivet design values should fall between 1 and 2 kN, depending on species and density of the composite and load direction with respect to grain of the composite strands. Timber rivets performed better in LSL than in PSL and better in yellow poplar PSL than in Douglas-fir or Southern Pine PSL; 40-mm rivets in yellow poplar LSL gave roughly equivalent performance to 65-mm rivets in yellow poplar PSL.

Comparing rivet yield predictions following the National Design Specification recommendations for round nails and the much simpler approach of using 2/3 the maximum load suggests that the latter approach provides a more consistently reliable evaluation of yield strength for timber rivets.

Additional study is necessary to assess rivet connection performance in SCL when rivet density exceeds 1 rivet/in^2.

Keywords: connections, timber rivet, SCL, Southern Pine, yellow poplar

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Introduction

Timber rivets were originally developed for use in glulam and solid-sawn timber. Recent developments in the area of engineered composites, however, have produced a number of alternative structural products that can be used in similar structural applications. In order to use timber rivets in these materials, tests must be conducted to characterize strength, ductility, and effects of moisture, temperature, and load cycling.

Objective

The objective of this study is to provide information on rivet shear load capacity in structural composites parallel strand lumber (PSL) and laminated strand lumber (LSL). The focus was on characterizing an average per rivet load capacity under conditions where the failure mode was limited to bearing deformation in the wood-based composite combined with bending in the nail. Variables considered in this study, include species, composite type, rivet orientations and load direction.

Scope

This was a pilot study to obtain timber-rivet connection shear capacity for two types of structural composite lumber (SCL) products: PSL and LSL. Parallel strand lumber is a composite consisting of parallel strips of veneer. These strips often exceed a meter in length and are roughly 3 mm thick with widths that range from 15 to 20 mm. Laminated strand lumber consists of much thinner and shorter elements (<120 mm). Although LSL elements are layered (that is, with width dimension in parallel planes), they are not all oriented with grain parallel to the machine direction of the composite product. In all cases, the surface parallel to the strand width dimension is referred to in this paper as the wide strand face.

Material used to fabricate test samples was collected to represent mill production. Samples of SCL 0.91 m long were collected at different times from four different fabricating plants over a 1- to 3-week period. The test sample included 20 to 30 pieces of each product. These included the following three species of PSL and one species of LSL:

PSL—2.0E Douglas-fir (DF)—Vancouver Plant, British Columbia

2.0E Southern Pine (SP)—Colbert Plant, Georgia

2.0E yellow poplar (YP)—Buckhannon Plant, West Virginia

LSL—1.7E yellow poplar (YP)—East Kentucky Plant, Hazard, Kentucky

Tests were confined to the determination of shear capacity when load is applied either parallel or perpendicular to the grain of the SCL product. For the PSL products, tests were conducted for nails applied both perpendicular and parallel to the wide strand face (WSF) (Fig. 1). For the LSL product, nails were tested only in an orientation perpendicular to the wide strand face.

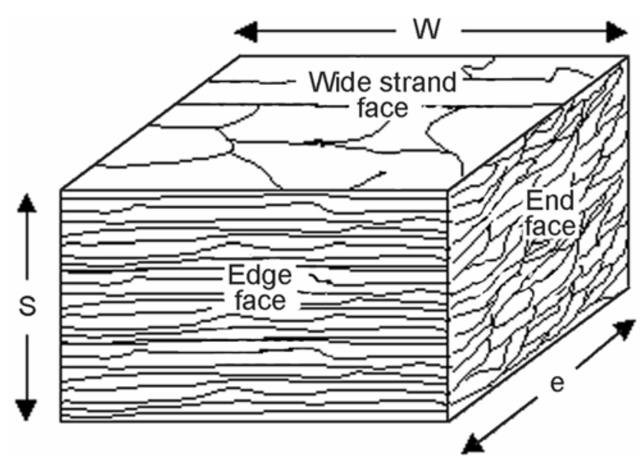

Figure 1—Structural composite lumber section.

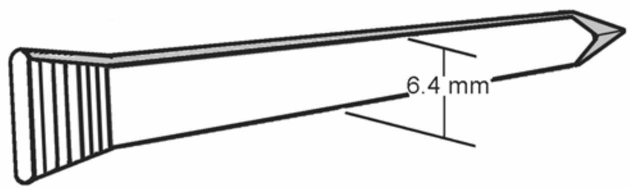

Figure 2—Timber (glulam) rivet.

Methods

Individual timber rivets were tested in bending following the ASTM F 1575 standard for determination of nail bending yield. Sixty rivet tests, including both 40- and 65-mm rivets, provided a basis for verifying published yield strengths

The rivet connection test configuration was two steel plates fastened on opposite faces of the SCL sample using four rivets per plate. The PSL connections were made using 65-mm- (2-1/2-in.-) long rivets, and the LSL connections used 40-mm (1-1/2-in.) rivets. In all cases, the plates were 6-mm- (1/4-in.-) thick cold roll steel plate.

Timber rivets (Fig. 2) are different from conventional nails in that they have a round corner rectangular cross section rather than a round one. The width-to-thickness ratio of these rivets is roughly 2:1. They are normally driven through round holes in steel side plates so that the width dimension is oriented parallel to the fiber direction in the wood or SCL product. Holes in the steel side plates range from 6.7 to 7 mm in diameter. When the rivet head is driven into the hole, the combination of a Rockwell hardness ranging from 32 to 39 and a wedge shape deforms the steel and anchors the head end in the steel plate. The rivet head (8.7 mm wide) is rarely driven flush to the surface of the steel plate.

The SCL samples were representative of mill production. Samples of various cross sections and lengths of 0.91 m were obtained from three Trus Joist plants. The cross-sectional dimensions (*e* and *S* in Fig. 1) were kept as supplied by the manufacturer. These were rectangular in shape, with the smaller dimension ranging from 133 to 140 mm and the larger dimension ranging from 178 to 184 mm. PSL samples were selected so that the dimension that would be parallel to the rivet axis was the longer dimension (*S* or *e* Fig. 1). For the LSL tests, the rivets (40 mm long) were always oriented parallel to the *S* dimension (Fig. 1), which for these specimens was 89 mm. The *e* dimension for these specimens was 133 mm. The SCL samples were cut to lengths of 150 mm for samples loaded parallel to the grain and 200 mm for those loaded perpendicular to the grain.

Four basic rivet–plate orientations are shown in Figure 3. In each case, the load was applied parallel to the long dimension of the steel plate, shown as a white rectangle with four holes. Timber rivets are always inserted with their wide dimension parallel to the grain of the wood. For the SCL connections, they are oriented either parallel (A) or perpendicular (E) to the wide strand face. This is the first digit in

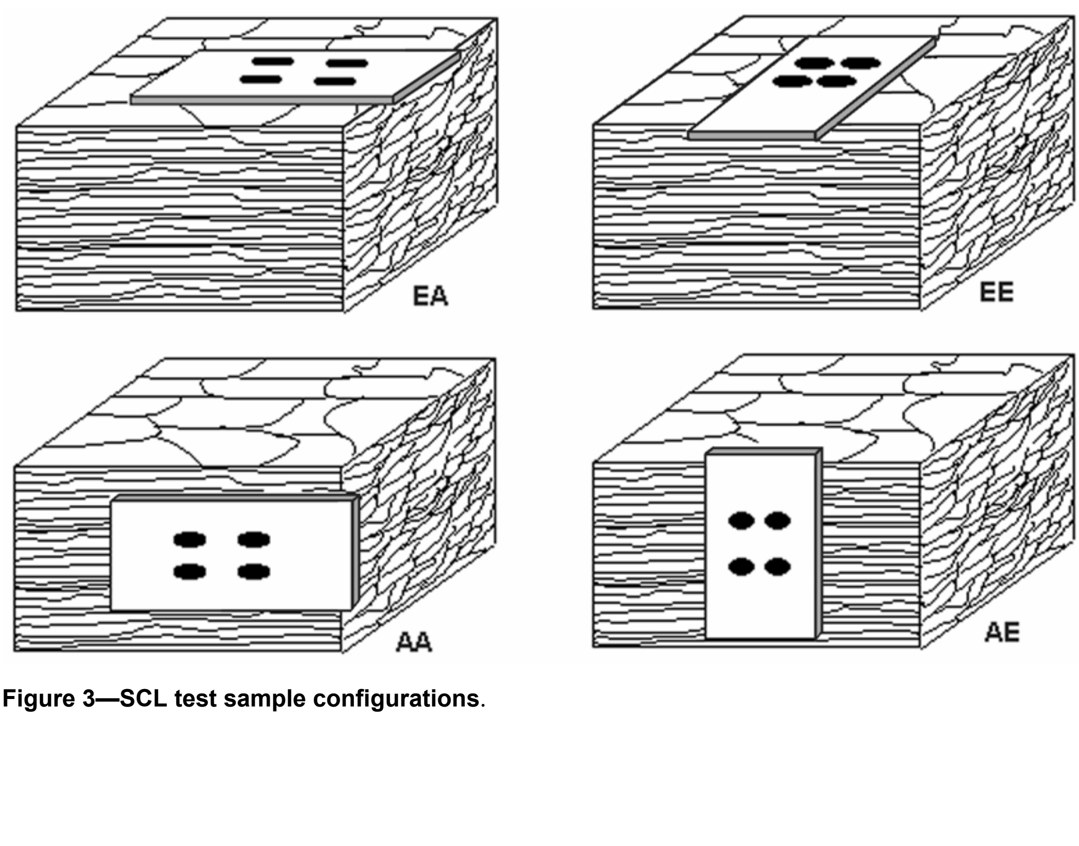

Figure 3—SCL test sample configurations.

Table 1—Summary of connection tests showing SCL product and species and orientation of rivet with respect to the wide strand face and load with respect to fiber orientation

Product/Species	Orientation[a] Rivet	Load	Reps
PSL— Douglas-fir	E	A	10
		E	11
	A	A	7
		E	6
PSL—Southern Pine	E	A	8
		E	10
	A	A	6
		E	6
PSL—yellow poplar	E	A	10
		E	10
	A	A	6
		E	5
LSL—yellow poplar	E	A	15
		E	15
		Total	125

[a]A, parallel; E, perpendicular.

the orientation code shown in Figure 3. Load direction with respect to wood fiber length is denoted by the second letter in the orientation code as being either parallel (A) or perpendicular (E) to the wood fiber.

Of 136 samples prepared to be tested, 11 were rejected due to presence of split or uneven plates. A summary of the 125 rivet tests conducted is provided in Table 1.

All test joints were fabricated in the dry condition and stored in a conditioning room maintained at 21°C, 65% RH until the time of testing.

Steel plates, 76 mm wide by 100 or 127 mm long were machined to have four holes drilled on a 2- by 25-mm matrix. Each hole was centered 25 mm from a long edge, and two of the holes were 25 mm from one end. The plates were fastened on opposing faces of each sample, with one end protruding 19 mm above the edge of the test sample. These were tested by applying a downward force on the plates, imparting shear force and bending moment on the rivets and bearing stress in the wood.

Figure 4—Mode IV (left) and mode III nail failures.

Results

The maximum loads for each of the tests conducted are listed in Appendixes A to D.

Joint strength was sensitive to load orientation, exhibiting higher capacity when load was applied normal to the 6-mm dimension of the rivet (AE and EE). This also corresponds to a load normal to the length dimension of the wood fibers. When loaded in this direction, the rivets compressed and densified the wood under the wide face and were bent at two locations. The deformed rivet exhibited the characteristic “S” shape of a mode IV failure (Fig. 4). When load was applied parallel to the wide dimension of the rivet and parallel to the grain (AA and EA), the rounded narrow face of the rivet had a tendency to cleave the wood fiber. In this case, the rivets in the PSL bent at only one location (mode III) corresponding to the interface between the wood and the steel plate. For the denser LSL, where the rivets were only 40 mm long, the rivets did not bend but remained rigid in the side plates and deformed the wood fiber. This corresponds more to a mode “Im” type failure (ANSI/AF&PA 2001, CWC 2001).

The PSL exhibited greater splitting than did the LSL when loaded perpendicular to the grain. Splits generally followed strand contours. They were not always along the glue line, but rather ran between gaps where strand ends met. The bearing stresses pushed strands apart and outward from the surface. Surface fractures ran perpendicular to the load direction well beyond the boundaries of the rivet pattern. The LSL exhibited fewer lateral splits; failures appeared to be confined to bearing deformation.

Analysis of Results

Tests of the timber rivets showed a steel yield strength of 0.96 GPa (average of 60 tests). The values were calculated as the bending yield moment divided by section moduli of 30 mm^3 and 15 mm^3 for strong- and weak-axis loading, respectively.

Table 2—Yield and maximum load for timber rivets in SCL

SCL	Yield (kN)	COV (%)	Max load (kN)	COV (%)
DF-PSL-AA	22.2	5	32.0	6
DF-PSL-AE	27.5	8	43.3	6
DF-PSL-EA	24.8	7	37.2	6
DF-PSL-EE	28.9	18	44.6	5
SP-PSL-AA	19.9	12	27.8	7
SP-PSL-AE	30.0	24	44.2	8
SP-PSL-EA	28.1	7	37.6	7
SP-PSL-EE	31.4	14	46.2	5
YP-PSL-AA	26.9	19	42.1	12
YP-PSL-AE	37.3	12	49.3	7
YP-PSL-EA	27.9	12	41.9	6
YP-PSL-EE	35.5	11	48.4	5
YP-LSL-EA	27.4	12	41.5	9
YP-LSL-EE	34.6	31	49.0	9

The average yield and maximum load values of the test connections are summarized in Table 2. The yield values were derived as the point of intersection of the measured load–displacement (P–δ) curve and a straight line whose abscissa intercept is offset from that of the P–δ curve by a distance equal to 5% of the nail diameter and whose slope is derived as a straight line fit to the load–displacement data between 20% and 40% of the maximum load achieved. The offset used was 0.32 mm for the AA and EA configurations and 0.16 mm for the EA and EE configurations. The intersection point of these lines is expected to occur at roughly two-thirds the maximum load. The average ratio of yield-to-maximum load values shown in Table 2 is 0.69.

Figure 5 shows relative values of yield and maximum load for each test configuration of timber rivets in SCL. In all cases, rivets loaded about the weak axis (normal to the wide face) had the higher maximum load capacity. It is interesting to note that rivets in yellow poplar PSL had an apparent higher capacity than those in Douglas-fir and Southern Pine PSL. At the 90% confidence level, the strength of 40-mm rivets in yellow poplar LSL fell above the 90% confidence bound on mean strengths for all the rivet connections in Douglas-fir PSL, for the Southern Pine AA and EA connections, and for yellow poplar PSL AA and EA connections.

This difference might be due to the superior tension-perpendicular-to-the-grain strength of yellow poplar. Yellow poplar tension-perpendicular-to-the-grain strength listed in the USDA Wood Handbook (Forest Products Laboratory 1999) is 15% greater than that of Southern Pine and 54% greater than that of Douglas-fir. A possible explanation for this may lie in the prevalence of reaction wood in yellow poplar. Reaction wood fibers generally have a thicker "gelatinous" S2 layer with a larger fibril angle than normal wood. When stressed perpendicular to its axis, such a fiber may have a greater tendency to deform and stretch rather than bend, transfer axial stress, and tear away from adjacent fibers. The result is energy dissipation through local deformation rather than bond failure.

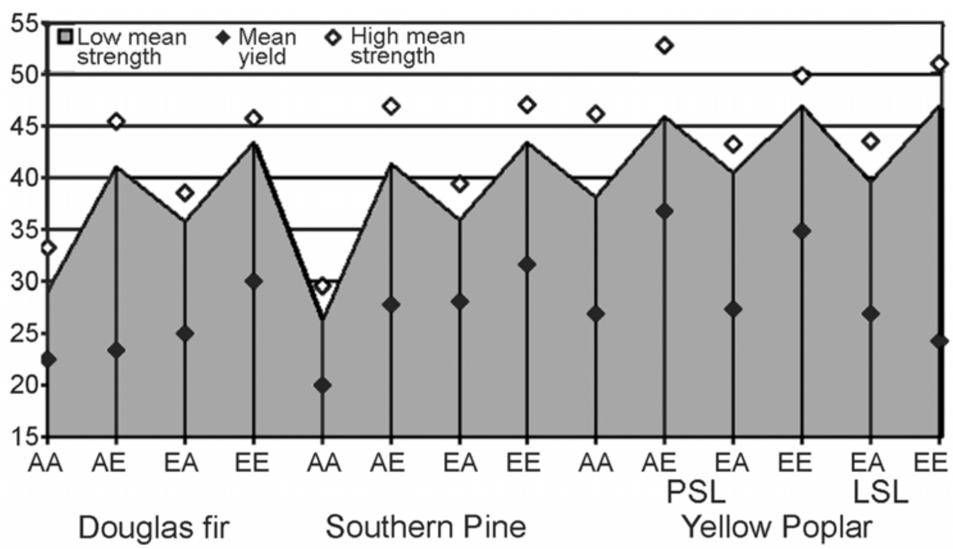

Figure 5—Yield and 90% confidence bounds on mean strength of timber rivets in three species of PSL and yellow poplar LSL.

It should be noted that a shorter rivet (40 mm) was used with the higher density yellow poplar LSL than was used with the PSL samples. These shorter rivets had less tendency to bend and rotate in the composite, and the failures were closer to that of a mode I.

The load capacity varied with species and joint configuration. For Southern Pine and Douglas-fir, the weakest connections were those having the rivet oriented parallel to the WSF with the load applied parallel to the rivet width (AA); the strongest connections were those having rivets perpendicular to the WSF with load perpendicular to the rivet width (EE). Yellow poplar PSL exhibited little effect of rivet orientation relative to the wide strand face. Per-rivet average values in PSL ranged from 3.5 to 5.7 kN for Southern Pine PSL, 4.0 to 5.6 kN for Douglas-fir, and 5.3 to 6.2 kN for yellow poplar. The yellow poplar LSL with 40-mm rivets actually had higher rivet maximum loads than did PSL with 65-mm rivets. They averaged 5.2 kN when loaded parallel to the rivet width and 6.1 kN when loaded perpendicular to the rivet.

Design Values

The guideline for derivation of design values for round nails (National Design Specification for Wood Construction, or NDS) uses as its basis an estimate of the connection yield capacity. The theoretical derivation of the NDS equations is discussed by Aune and Patton–Mallory (1986). The NDS estimate of design load for nails and spikes varies depending on the expected failure mode and the properties of the materials being fastened together. In general, the equations given in the NDS predict a yield strength adjusted by a calibration factor (K_D), which gives a design value roughly equivalent to the historic reference of 1/3 the maximum load capacity or a displacement of 0.015 in.

The NDS provides equations for estimating design values for round nails. The following Equations (1) to (3) are derived from the NDS equations, with modifications made to estimate yield strength for timber rivets in composite materials. First, the calibration factor was removed to give an estimate of yield strength rather than a design value. Second, the diameter (D) was modified (Eqs. (1), (2)) to reflect different bearing and bending moment resistances related to the rivet shape. For the calculation of the contribution of rivet bearing force, we used effective diameters equal to the width (DB_w = 6.4 mm) and thickness (DB_t = 3.2 mm), depending on whether load is applied normal to or parallel to the rivet width dimension. For calculation of the contribution of rivet bending strength, the values used were those that provide an equivalent round section modulus. The value for bending about the width axis is DS_w = 4 mm and for bending about the thickness axis is DS_t = 5mm. Finally, due to the different failure mechanisms for parallel (cleavage of fibers) and perpendicular (bearing and densification) to the fiber length of the composite, we introduced the factor γ as an adjustment on dowel bearing. This was necessary in order to get predictions that agreed with the failure modes observed.

Mode Im failure $$Z = DB_i p\gamma F_{em} \tag{1}$$

Mode IIIm failure $$Z = \frac{k_1 DB_i p\gamma F_{em}}{(1+2R_e)} \tag{2}$$

Mode IV failure $$Z = \sqrt{\frac{2F_{em}F_{yb}DS_i^3 DB\gamma^2}{3(1+R_e)}} \tag{3}$$

where

$$k_1 = -1 + \sqrt{2(1+R_e) + \frac{2F_{yb}(1+2R_e)(DS_i^3/DB_i)}{3\gamma F_{em}p^2}}$$

R_e is F_{em}/F_{es},

P penetration of the rivet into the main member = L (65 or 40 mm) – 0.7 mm (head) – 4.8 mm (point),

γ dowel bearing adjustment (0.7 for parallel to fiber and 1 for perpendicular),

F_{em} dowel bearing strength of main member (holding point), derived following the dowel bearing–specific gravity (SG) relationship inherent in the NDS table for F_e values [16612(SG$^{1.84}$)(6.894 KPa/lb/in^2)], where the equivalent SG is 0.5 (ASTM 2001),

F_{es} dowel bearing strength of side member (310 MPa for ASTM A653 steel plate),

F_{yb} bending yield strength of the rivet = 0.97 GPa = 140,000 lb/in^2,

DB equivalent nail diameter for bearing, and

DS equivalent nail diameter for bending.

To get good agreement between the predicted and observed failure modes, a γ value (Eqs. (1) to (3)) of 0.7 was used to adjust the F_{em} value for parallel-to-the-grain loading. This worked well for the PSL, providing good agreement to the observation that all connections loaded parallel to the width dimension of the rivet exhibited mode III and all those loaded perpendicular to the wide face exhibited mode IV failures.

Yield strength is not nearly as easily identified as maximum strength, but it is generally perceived to be more meaningful as a basis for setting a design limit state. If the ratios of maximum load to yield do not vary widely between different

Table 3—Connection strength-to-yield ratios[a]

	Southern Pine PSL		Douglas-fir PSL		Yellow poplar PSL		Yellow poplar LSL	
	3.2 mm (load A)	6.4 mm (load E)	3.2 mm (load A)	6.4 mm (load E)	3.2 mm (load A)	6.4 mm (load E)	3.2 mm (load A)	6.4 mm (load E)
Predicted yield								
Z-III (kN)	15	44	15	41	15	39	13	22
Z-IV (kN)	18	22	16	22	16	22	18	22
Weighted average 8-rivet strength	33	45	34	44	42	49	41	49
Strength:predicted yield	2.19	2.04	2.26	1.99	2.75	2.20	3.12	2.21
Measured yield (kN)								
Rivet A	20	28	22	27	27	37		
Rivet E	28	31	25	28	27	35	27	23
Measured strength								
Rivet A	28	44	32	43	42	49		
Rivet E	38	46	37	45	42	48	41	49
Strength:measured yield	1.37	1.52	1.47	1.58	1.55	1.36	1.54	2.09

[a]Observed strength equaled or exceeded 2 times the predicted yield. Observed strength-to-yield ratios averaged 1.55, ranging from 1.33 to 1.67 across all PSL sample

types of nailed connections, however, basing the design on maximum load would eliminate variability due to data interpretation. Historically, the design value of connections was set in the range of 1/3 the maximum load capacity or the load that gives a limit state displacement in the range of 0.38 mm. The NDS calibration factors ranging from 2.2 to 3.0 suggest that 1/3 of ultimate is roughly equal to 1/2 of yield or that the maximum load should be 1.5 times the yield value.

Table 3 compares theoretical and empirical yield values and the ratios of connection ultimate load capacity to these yield values. Assuming that rivet orientation with respect to the WSF did not have a significant effect on joint capacity, connection strengths were evaluated as a weighted average for all specimens tested with the same load-to-rivet orientation in each SCL material. Dividing the ultimate load by the predicted yield value gave ratios ranging from 2.0 to 2.3 for all values except the yellow poplar SCLs with load applied in the A orientation. The yellow poplar PSL appeared to have higher bearing values than did the other species. The yellow poplar LSL exhibited roughly the same yield and strength values as did the PSL despite a smaller penetration (40 mm rivet compared with 65 mm rivet). In the case of load parallel to the width dimension of the rivet (AE), the failure mode (mode I) was bearing deformation in the LSL with no rotation or bending of the rivet.

The last row of Table 3 shows the ratios of measured ultimate strength to measured yield. These values average 1.46, ranging from 1.3 to 1.6 in PSL materials and the yellow poplar LSL loaded parallel to the grain. In this case, yellow poplar ratios for load parallel were 1.55 for PSL and 1.54 for LSL. These results suggest that yield strength could be characterized as 2/3 the ultimate strength. The apparent consistency suggests it would be appropriate to use the ultimate strength as a basis for deriving a design value. For the yellow poplar LSL loaded perpendicular to the strands, the yield value is slightly less than half the strength. To gain agreement between the theoretical and empirically derived yield values, it may be necessary to provide some adjustment to the yellow poplar properties, such as an increase in the equivalent specific gravity (SG).

A higher equivalent SG for the yellow poplar SCLs would increase their predicted yield value and reduce their ratio of ultimate to predicted yield strength. If the SG value used was closer to the measured values, the average ratio of measured ultimate strength to predicted yield would be reduced by 27%, but it would change the predicted failure mode to a mode III. For these connections, there was no apparent rivet bending.

Although NDS currently supports the European yield model (EYM) for nails, it does not seem practical at this time to use it for timber rivets in SCL. First, there is no consistent method of determining yield strength for the wide variety of engineered wood composites. We need better data on bearing values and their variations within orthotropic composites. Second, the maximum load capacity will be interpreted the same by everyone looking at a given set of data, whereas yield may have a range of interpretations. It makes more sense to focus on consistency and use a factored adjustment applied to the average per-rivet maximum or some lower exclusion strength rather than some subjectively derived yield point on a nonlinear curve.

A design value per rivet derived using the ultimate load capacity values in Table 3 divided by 3.3 would fall in the range of 1 to 2 kN. Using the NDS predicted yield values divided by 2.2 give design values in the range 0.85 to 1.25 kN. These results suggest that the EYM model gives conservative estimates of the per-rivet load capacity when bearing values are based on equivalent SG.

Conclusions

Timber rivet connections are a viable option for engineered use of SCL. The 8-rivet connection tests evaluated in this study suggest that per-rivet design values should fall in the range 1 to 2 kN, depending on the species and density of the composite and the load direction with respect to the grain of the composite strands.

Timber rivets performed better in LSL than in PSL. In yellow poplar PSL, the 65-mm rivets had per-rivet lateral shear strengths ranging from 5.2 to 6.2 kN, compared with a range of 5.2 to 6.1 kN for 40-mm rivets in yellow poplar LSL.

The higher tension-perpendicular-to-the-grain strength of yellow poplar appeared to contribute to significantly higher rivet strengths. This, in combination with higher density, appeared to give the LSL an advantage over PSL.

Per-rivet design value predictions based on the NDS yield equations for nails require a more refined derivation of rivet bearing stress than is obtained using the NDS estimate as a function of specific gravity. The greater tendency for splitting when loaded parallel to the fiber direction with the narrower dimension of the rivet suggests that shear or cleavage stresses have a greater influence than does bearing.

Ultimate load capacity provides a better basis for the derivation of design values than the more subjectively derived yield strength.

This study focused only on an evaluation of per-rivet strength, with all failures attributed to either rivet bending or wood bearing deformation. If the rivet density is increased, it is expected that failures may be attributed to block shear tear out, which is a function of the tension and shear properties of the SCL.

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Appendix A—Timber rivets in Douglas-fir PSL

No. test	Ident. no.	Nails/load orientation	Yield load ($\times 10^3$ lb/in^2)	Max. load ($\times 10^3$ lb/in^2)	Slope ($\times 10^3$ lb/in^2/in)
1	82a	AA	4.88	6.99	95.62
2	82b	AA	5.12	7.45	85.69
3	84a	AA	5.14	8.00	147.88
4	84b	AA	5.01	7.13	61.85
5	86a	AA	4.44	6.46	55.33
6	86b	AA	5.18	7.13	106.91
7	94d	AA	5.17	7.16	83.79
1	82c	AE	(a)	8.63	29.05
2	84c	AE	5.85	9.75	41.97
3	84d	AE	6.28	9.84	36.25
4	86c	AE	6.68	10.48	40.82
5	86d	AE	5.47	9.66	45.14
6	94c	AE	6.60	10.00	34.28
1	78a	EA	5.40	8.07	74.82
2	79a	EA	4.97	7.43	90.49
3	79b	EA	5.40	7.68	112.09
4	87a	EA	5.52	8.00	53.66
5	88b	EA	5.83	8.85	67.59
6	90a	EA	6.18	8.83	89.70
7	92a	EA	5.71	8.44	64.89
8	92b	EA	5.59	8.54	96.44
9	94a	EA	6.02	8.82	90.16
10	94b	EA	5.24	8.87	92.34
1	78d	EE	6.50	10.37	56.46
2	79c	EE	6.42	9.63	56.46
3	79d	EE	5.09	9.75	27.45
4	80c	EE	5.64	9.82	37.80
5	80d	EE	6.29	10.20	36.57
6	82d	EE	7.70	10.58	47.07
7	88c	EE	8.51	10.76	38.64
8	88d	EE	5.72	9.62	39.97
9	90c	EE	4.34	10.02	31.36
10	92c	EE	7.60	10.38	38.37
11	92d	EE	6.33	9.17	43.95

[a]P–δ curve deflection error.

Appendix B—Timber rivets in Southern Pine PSL

No. test	Ident. no.	Nails/load orientation	Yield load ($\times 10^3$ lb/in^2)	Max. load ($\times 10^3$ lb/in^2)	Slope ($\times 10^3$ lb/in^2/in)
1	25a	AA	3.99	6.18	70.82
2	25b	AA	3.77	5.54	54.92
3	27a	AA	4.56	6.14	94.68
4	27b	AA	5.04	6.80	81.36
5	29a	AA	5.08	6.71	83.67
6	29b	AA	4.46	6.15	79.34
1	25c	AE	6.10	9.70	33.00
2	25d	AE	5.11	8.94	36.10
3	27c	AE	6.17	10.19	36.16
4	27d	AE	7.01	10.72	45.00
5	29c	AE	(a)	9.22	47.36
6	29d	AE	9.32	10.79	29.18
1	13a	EA	5.96	8.07	73.59
2	13b	EA	6.59	8.71	109.77
3	18a	EA	6.49	8.09	73.06
4	18b	EA	5.64	7.72	106.43
5	20a	EA	6.58	9.08	114.72
6	20b	EA	6.69	9.42	114.50
7	22a	EA	5.91	7.95	74.45
8	22b	EA	6.67	8.52	83.70
1	13c	EE	6.34	10.02	44.06
2	13d	EE	7.06	10.36	48.69
3	15c	EE	8.59	9.94	36.65
4	15d	EE	7.99	10.58	47.18
5	18c	EE	6.22	9.49	50.83
6	18d	EE	7.13	10.14	50.68
7	20c	EE	6.32	11.32	45.66
8	20d	EE	6.20	11.12	71.90
9	22c	EE	8.53	10.67	33.41
10	22d	EE	6.31	10.33	40.55

[a] P–δ curve deflection error.

Appendix C—Timber rivets in yellow poplar PSL

No. test	Ident. no.	Nails/load orientation	Yield load ($\times10^3$ lb/in^2)	Max. load ($\times10^3$ lb/in^2)	Slope ($\times10^3$ lb/in^2/in)
1	32a	AA	6.85	10.19	136.05
2	32b	AA	7.25	10.13	85.46
3	34a	AA	4.11	8.33	66.65
4	34b	AA	5.35	7.81	72.97
5	36a	AA	6.20	10.54	76.30
6	36b	AA	6.50	9.84	117.64
1	32c	AE	9.94	10.58	25.67
2	32d	AE	7.91	11.14	38.26
3	34c	AE	7.29	10.80	34.35
4	34d	AE	8.82	10.45	31.40
5	36d	AE	7.93	12.46	44.56
1	42a	EA	6.10	9.11	115.96
2	42b	EA	5.71	8.77	86.79
3	45a	EA	5.40	9.43	109.51
4	45b	EA	5.73	9.48	111.25
5	48a	EA	6.26	9.02	79.75
6	48b	EA	7.27	10.05	71.93
7	50a	EA	6.21	9.15	76.83
8	50b	EA	5.86	8.96	80.83
9	53a	EA	7.81	10.52	88.11
10	53b	EA	6.40	9.60	77.05
1	42c	EE	8.24	11.34	41.30
2	42d	EE	8.21	10.65	44.29
3	45c	EE	7.88	12.13	49.52
4	45d	EE	8.85	10.88	34.75
5	48c	EE	7.24	11.03	44.01
6	48d	EE	7.37	10.14	38.78
7	50c	EE	7.80	10.48	30.81
8	50d	EE	7.18	10.73	39.11
9	53c	EE	9.88	11.05	69.00
10	53d	EE	7.27	10.39	44.82

Appendix D—Timber rivets in yellow poplar LSL

No. test	Ident. no.	Nails/load orientation	Yield load ($\times10^3$ lb/in^2)	Max. load ($\times10^3$ lb/in^2)	Slope ($\times10^3$ lb/in^2/in)
1	66b	EA	6.16	8.50	98.53
2	66d	EA	5.80	8.91	82.23
3	69b	EA	6.75	9.53	120.44
4	71a	EA	7.52	8.43	41.54
5	71c	EA	6.81	9.17	68.47
6	73b	EA	5.87	8.96	103.39
7	73c	EA	4.95	9.88	100.66
8	73d	EA	7.23	9.02	50.28
9	75a	EA	5.55	9.91	144.04
10	75b	EA	5.18	7.78	74.10
11	75c	EA	6.43	9.53	93.79
12	75d	EA	5.67	9.22	76.06
13	77a	EA	6.05	9.18	152.00
14	77c	EA	6.56	10.89	108.15
15	77d	EA	5.97	10.98	97.65
1	68a	EE	8.49	11.25	40.97
2	68b	EE	7.43	11.57	52.21
3	68c	EE	6.22	11.01	65.92
4	72a	EE	4.13	10.00	57.48
5	72b	EE	11.14	12.18	31.02
6	72c	EE	7.02	11.65	48.65
7	72d	EE	11.41	12.09	38.45
8	74a	EE	9.94	11.65	60.31
9	74b	EE	11.3	11.34	30.99
10	74c	EE	5.20	10.42	44.89
11	74d	EE	5.35	9.94	55.93
12	76a	EE	5.45	8.60	77.29
13	76b	EE	9.67	12.06	53.93
14	76c	EE	7.22	10.28	43.52
15	76d	EE	6.78	11.06	62.15