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DESIGN OF MULTIPLE BOLTED CONNECTIONS FOR LAMINATED VENEER LUMBER

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ABSTRACT: The design of multiple bolted connections in accordance with Appendix E of the National Design Specification for Wood Construction (NDS) has incorporated provisions for evaluating localized member failure modes of row and group tear-out when the connections are closely spaced. Originally based on structural glued laminated timber (glulam) members made with all L1 Douglas fir-Larch laminating lumber, the NDS provisions were confirmed by additional analysis, which indicates the applicability of the provisions to glulam with reduced design shear values. Due to the similarity to glulam in the grain orientation and layup strategy, laminated veneer lumber (LVL) is subject to similar failure modes. As a result, a study was initiated by APA – The Engineered Wood Association and the LVL industry, in collaboration with the Forest Products Laboratory (FPL) of the U.S. Department of Agriculture (USDA) to evaluate if a reduced design shear stress is necessary for LVL under similar multiple bolted connection configurations. This paper describes the test results obtained from the study, which indicate that an adequate load factor exists for LVL multiple bolted connections without a reduction in the LVL design shear stress when designed in accordance with Appendix E of the NDS.

KEYWORDS: Multiple bolted connections; Laminated veneer lumber; Group tear-out; Failure modes

1 INTRODUCTION

The design of multiple bolted connections in accordance with Appendix E of the National Design Specification for Wood Construction (NDS) has incorporated provisions for evaluating localized member failure modes of row and group tear-out when the connections are closely spaced [1]. Originally based on structural glued laminated timber (glulam) members made with all L1 Douglas fir-Larch laminating lumber, the result from studies of multiple bolted connection experiments revealed that the design provisions relying only on minimum prescriptive row and bolt spacing could result in ultimate connection strengths that were 60% of design [2]. The NDS provisions, which incorporate reduced glulam design shear values, were confirmed by additional analysis [3] that indicates the applicability of the provisions to glulam.

A subsequent study by Rammer and Line [4] suggested that when using a design approach that chooses the minimum load calculated by either the yield theory or the NDS Appendix E limit states expressions for wood, the experimental load never fell below the design load. Furthermore, the overall margin of safety increased 32% through the use of the wood failure expressions. More significantly, the inclusion of the NDS Appendix E limit state checks for wood increased margin of safety for connections, reduced the variability of the design predictions, and, at the same time, did not penalize connections with relatively high levels of safety.

Three different multiple bolted joint configurations were tested in the study conducted by Rammer and Line to failure using largest bolt diameter and minimum spacing requirements. The combination of largest bolt diameter and minimum spacing requirement represents the worst-case scenario for multiple bolted connection configurations. A final configuration was tested that used a lower number of bolts, but were spaced further apart, to produce fastener yield mechanisms before wood failure.

Multiple bolted connection experiments in structural composite lumber (SCL) are limited. Very little information is published on the capacity of multiple large-diameter bolts in SCL. Therefore, there is a question if multiple fastener connections in SCL would have the same level of safety as traditional timber and glulam products when wood failure mechanisms actually govern the connection capacity. Allowable shear stress values used for the determination of wood failure mechanisms in glulam connections based on the NDS Appendix E is

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reduced by a factor of 0.72 from traditional shear block values. This approach was rectified by a review conducted by Linville et al [3] based on experiments conducted on glulam members made with all L1 Douglas fir-Larch laminating lumber. However, LVL is not currently required to use reduced allowable design shear values when designing multiple bolted connections in accordance with the NDS Append E.

2 OBJECTIVES

The main objectives of this study were to evaluate the likely failure modes of multiple large-diameter bolted connections when installed in a close fastener spacing using LVL, and to determine if the design shear values of the LVL are required to be reduced to provide an acceptable factor of safety in connection design. The study was initiated by APA – The Engineered Wood Association and the LVL industry in the U.S., in collaboration with the Forest Products Laboratory (FPL) of the U.S. Department of Agriculture (USDA) using the same multiple bolted connection configurations as those used in the previous study with glulam.

3 MATERIALS AND METHODS

Forty 44 mm x 381 mm x 3658 mm (nominal 1-3/4 in. x 15 in. x 12 ft) commercially available 2.0E Douglas fir LVL materials were obtained from the routine production of a manufacturer. The materials were delivered to the FPL in the summer of 2012 for connection testing. Another set of materials that were individually end-to-end matched was delivered to the APA Research Center in Tacoma, WA at the same time for tension and block shear tests to determine the tensile strength and shear strength of the LVL. Upon arrival, the LVL materials at both laboratories were placed in a moisture conditioning room at 20 ± 6ºC (68 ± 11ºF) and 65 ± 5 % relative humidity (RH) until moisture equilibrium before testing.

Steel side plates of 9.5 mm (3/8 in.) in thickness were fabricated from ASTM A36 steel at the FPL. Bolts were 25 mm (1 in.) in diameter by 152 mm (6 in.) in length and conformed to ASTM 307 Grade B specifications [5].

3.1 BOLTED CONNECTION FABBRICATION

After moisture conditioning, the LVL materials were end-trimmed and the hole patterns were fabricated using a CNC machine at the FPL. Since the connections at both ends contain a significant number of bolts, a long specimen length of 2591 mm (102 in.) was needed to distribute the forces uniformly at the connections. To optimize the testing results, joint test configurations were fabricated on each end of the specimen. This resulted in two identical connections that were tested in each specimen and the ultimate strength of each specimen represented the lower connection strength from both connections in each specimen. This data censoring was considered during the final data analysis.

3.2 CONNECTION CONFIGURATIONS

Four multiple bolted joint configurations (i.e., Configurations A through D) were used in this study, as shown in Figure 1.

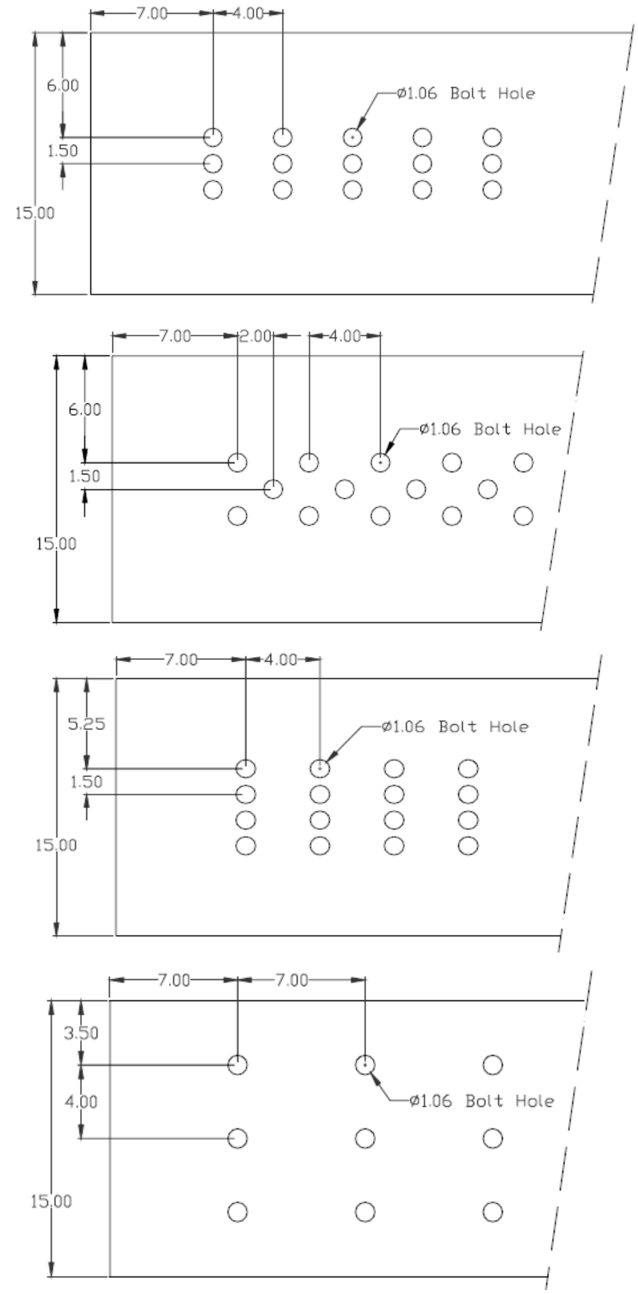


Figure 1: *Connection Configurations A through D (top to bottom) in inches (for SI: 1 inch = 25.4 mm)*

All configurations consisted of a wood main member and two 9.5-mm (3/8-in.) thick steel side plates bolted with 25-mm (1-in.) diameter bolts. The bolt length was such that no threads bore on the main or side member of the connection. Configuration A consisted of three rows of bolts with five bolts in each row. Configuration B consisted of staggered rows, two outer rows with five bolts in each row and one inner row of four bolts. Configuration C consisted of four rows of bolts with four bolts in each row. Configuration D consisted of three rows of bolts with three bolts in each row.

Configurations A through C were fabricated with minimum end distance, minimum spacing between bolt rows, and minimum spacing between bolts in a row as specified in the NDS for the full design value. The 1.5d (d is the bolt diameter) minimum requirement for spacing between bolt rows caused interference of bolt heads for Configurations A and C, as shown in Figure 2. Also, for Configurations A through C, the minimum bolt spacing requirement of 3d for steel construction was violated. However, since one of the objectives of the study was to investigate the possibility of wood failure mechanisms, the bolt head interference was accommodated using bushing under the bolt heads, and the minimum connection bolt spacing requirement for steel construction was ignored.

***Figure 2**: Interference of bolt heads*

Configuration D was designed with the minimum end spacing but had increased row and bolt spacing to 4d and 7d, respectively. The final test configuration that had the row spaced further apart was conducted to validate the NDS Appendix E expression and show the benefit of larger row and bolt spacing.

3.3 TEST METHODS

All connection tests were conducted at the FPL with the test setup shown in Figure 3. A total of 20 specimens was tested by application of a monotonic tensile loading until failure at a speed to cause failure between 5 and 10 minutes.

Load and joint slip readings were acquired at a rate of 2 Hz until the test was concluded. Tests were concluded when the load dropped by more than 50% of the maximum load. Displacement of the steel side plate, which was referenced to the main member, was measured by linear voltage displacement transformers (LVDT's) located at each side of the joint. For all four LVDT's used for measurements, the center of the LVDT was located 50.8 mm (2 in.) from the center at the end of the steel side plate. Five replicates were tested for each configuration, as shown in Table 1.

***Figure 3**: Multiple bolted connection test setup*

***Table 1:** Test Matrix*

ID	Total No. of bolts	End spa-cing	Bolt spa-cing	Row spa-cing	No. of rows	No. of bolts in a row	No. of tests
A	15	7d	4d	1.5d	3	5	5
B[(a)]	14	7d / 9d	4d	1.5d	2 / 1	5	5
C	16	7d	4d	1.5d	4	4	5
D	9	7d	7d	4d	3	3	5

[(a)] Configuration B consisted of 3 rows total with the middle row being staggered.

To accommodate the placement of bolts and loading pins, holes were 1.6 mm (1/16 in.) oversized. At the beginning of a test, all the bolts might not be in bearing contact with the wood and could slip up to 1.6 mm (1/16 in.) before recording any increase of load. On the other hand, all bolts might be in bearing contact and an increase of load could be immediate. For determination of a consistent slip value, the beginning point of the connection contact slip was defined by the lesser of 1.6 mm (1/16 in.) and the deformation corresponding to an applied load of 4.5 kN (1 kip). Maximum connection slip was defined as the difference between the displacement at the maximum load and the initial contact displacement as defined by the criteria mentioned above.

Supplemental bolt bending yield strength was also determined at the FPL using three-point bending tests. One bolt from each source box was tested for a total of 10 bolt bending tests. Bolts were loaded at the center of a 127-mm (5-in.) span and at a rate of 1.27 mm/min (0.05 in./min) until the head displacement reached 5 mm (0.2 in.) of movement. A load-deformation curve was obtained using the movement of the head of the testing machine as a measure of deflection.

A total of 20 LVL specimens that were end-matched with the specimens used for the connection tests was used for testing the tensile strength and block shear strength at the APA Research Center in Tacoma, WA, after moisture conditioning. Tension tests were conducted with a 1219-mm (4-ft) gauge length in accordance with ASTM D5456 [6] on 2 specimens of 191 mm (7-1/2 in) in width prepared from each matched 381-mm (15-in.) wide specimen used for the connection test. Two block shear tests were conducted in the through-the-thickness shear orientation, as shown in Figure 4, in accordance with ASTM D5456 [6] on each matched LVL used for the connection test. This resulted in 40 tensile strength data and 40 block shear strength data for the LVL materials.

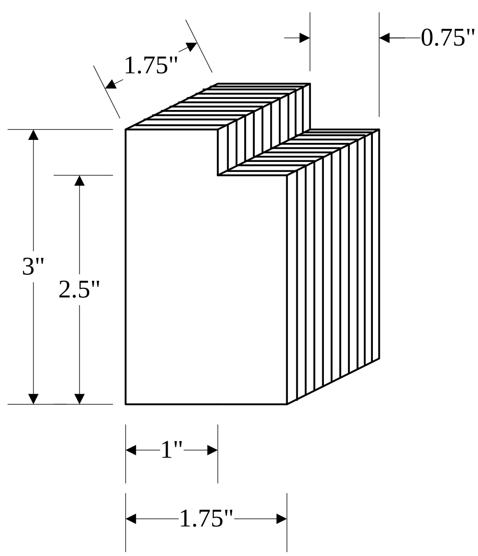


***Figure 4**: Orientation and dimensions of block shear test specimen (for SI: 1 inch = 25.4 mm)*

4 RESULTS

4.1 LVL Block Shear and Tensile Strengths

Test results for LVL block shear and tensile strengths are summarized in Table 2. The average moisture content and specific gravity (based on oven-dry weight and as-tested volume) of all specimens was 9.1% and 0.55, respectively.

***Table 2:** LVL Shear and Tensile Strengths*

Joint Group	LVL Board ID	Average Shear Strength[a] (psi)	Average Tensile Strength[a, b] (psi)
A	1	960	7148
	2	945	5367
	3	1002	5667
	4	960	5693
	5	988	6227
B	6	940	6311
	7	1025	6404
	8	985	6417
	9	1011	6301
	10	920	5370
C	11	940	6311
	12	1025	6404
	13	985	6417
	14	1011	6301
	15	920	5370
D	16	976	5629
	17	949	5691
	18	975	6000
	19	973	6456
	20	909	5668
N		20	20
Mean		975	6079
COV		0.034	0.080
Minimum		909	5367

For SI: 1 psi = 6895 Pa
(a) Average of 2 specimens from the same LVL board.
(b) Test values have been adjusted to an LVL length of 2591 mm (8.5 ft) by the length effect factor of $(4/8.5)^{1/10}$, as published by the manufacturer to reflect the actual LVL length used in the connection tests.

It is important to note that since the mechanics-based model used by the NDS to predict the connection performance is based on the allowable tensile stress and allowable shear stress of the substrate LVL, the test results are required to be analyzed based on the allowable properties of the LVL. Based on ASTM D5456 [6], the allowable shear stress is the characteristic (5^{th} percentile with 75% confidence) shear strength divided by an adjustment factor of 3.15 and the allowable tensile stress is the characteristic tensile strength divided by an adjustment factor of 2.1. However, since the test duration for connection tests was about 10 minutes, the load duration factor of 1.6 based on the NDS is applicable. Therefore, the allowable shear and tensile stresses at the test duration should be the characteristic shear and tensile strengths divided by 3.15/1.6 or 1.97, and 2.1/1.6 or 1.31, respectively.

For the purpose of this study, the characteristic shear and tensile strengths based on the 5th percentile with 75% confidence were estimated as the minimum value from 40 tests for each property based on non-parametric statistics. Therefore, the allowable shear and tensile stresses for the LVL on the load duration of 10 minutes were estimated as 3.2 MPa (458 psi) and 26.4 MPa (3828 psi), respectively. These LVL properties were used to estimate the connection strengths for comparison to connection test results provided below.

It should be noted that the allowable shear and tensile stresses published by the LVL manufacturer on the load duration of 10 minutes are 3.1 MPa (456 psi) and 21.5 MPa (3116 psi), respectively. If these values were used in design, the connection design strength will be lower than the calculated values based on the slightly higher LVL properties obtained from this study.

4.2 Connection Test Results

Results for individual connection tests are provided in Table 3.

Table 3: *LVL Connection Test Results*

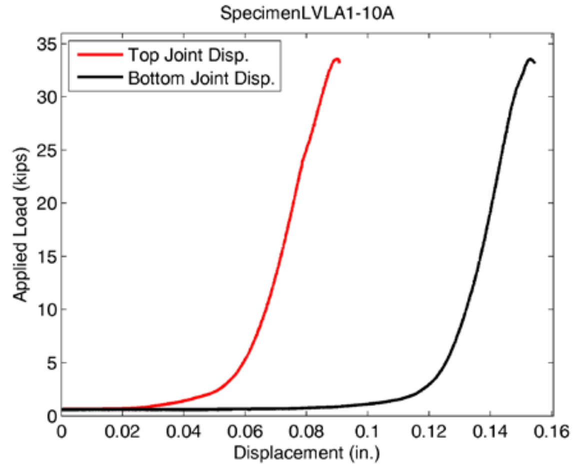
Joint Group	LVL Board ID	Ultimate load, P_{ult} (kips)	Group Mean P_{ult} (kips) and [COV]	Failure joint
	1	36.06		Top
	2	31.90		Bottom
A	3	33.58	33.59 [0.055]	Bottom
	4	34.70		Top
	5	31.71		Bottom
	6	36.45		Top
	7	37.03		Bottom
B	8	33.05	36.47 [0.062]	Bottom
	9	36.43		Bottom
	10	39.39		Top
	11	37.96		Bottom
	12	39.46		Bottom
C	13	35.35	38.49 [0.067]	Bottom
	14	37.42		Top
	15	42.26		Bottom
	16	60.56		Bottom
	17	71.30		Bottom
D	18	63.22	66.24 [0.065]	Bottom
	19	68.62		Bottom
	20	67.49		Top

For SI: 1 kip = 1000 lbf = 4448 N

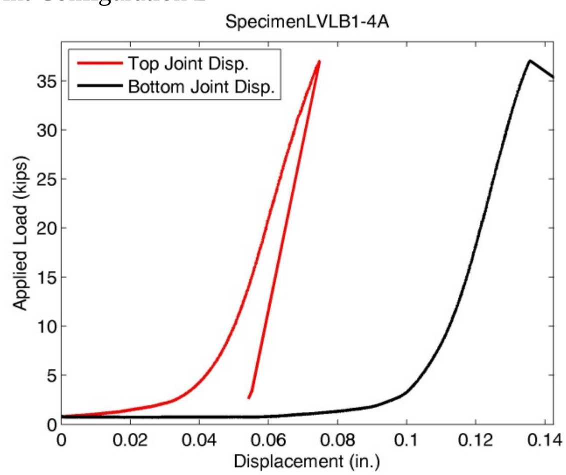
4.3 Joint Slips

Figure 5 shows the typical joint slips from selected specimens for each joint configuration. Overall, there was a non-linearity at the beginning of the test, followed by a generally linear behavior, and ended with a slight plasticity prior to failure. This applies to all joints tested in this study, irrespective of the ultimate failure mode (see discussion below).

Joint Configuration A



Joint Configuration B



Joint Configuration C

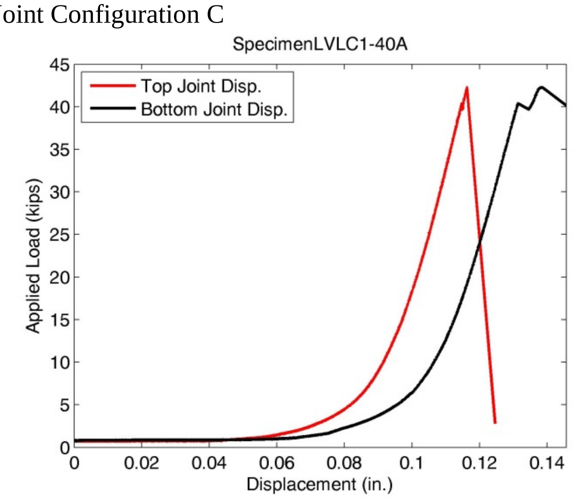


***Figure 5**: Typical joint slips (for SI: 1 inch = 25.4 mm; 1 kip = 1000 lbf = 4448 N)*

Joint Configuration D

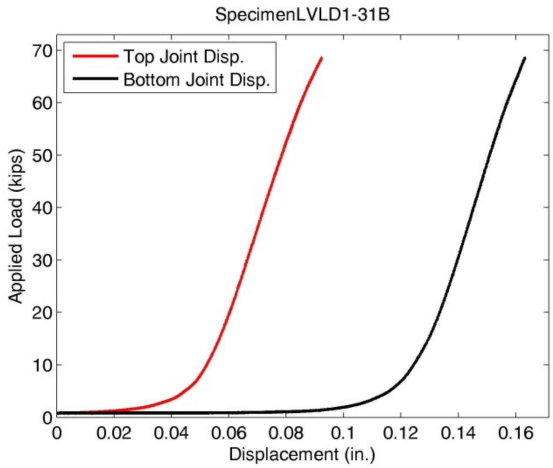


***Figure 5 (Continued)**: Typical joint slips (for SI: 1 inch = 25.4 mm; 1 kip = 1000 lbf = 4448 N)*

4.4 Censored Data Analysis

For each specimen, 2 multiple bolted configurations were tested. However, the maximum test load was limited by the weaker connection. To determine the capacity for the ten tested connections for each joint configuration, censored statistic approaches are applied.

The maximum likelihood estimate (MLE) procedure is implemented using the following expression and techniques as described in Lawless [7], exploiting the relationship that if joint strength is lognormal, the logarithm of joint strength is normally distributed. The likelihood function[1] is expressed as follows:

$$L(\mu,\sigma)=\prod_{i\in D}\frac{1}{\sigma}\phi\left(\frac{y_i-\mu}{\sigma}\right)\prod_{i\in C}Q\left(\frac{y_i-\mu}{\sigma}\right) \qquad (1)$$

where:

$\prod$ = at the range of products and

$$\prod_{i=n} a_i = a_1 \bullet a_2 \bullet a_3 \bullet \ldots \bullet a_n$$

μ = true population mean of the normal distribution,

σ = true population standard deviation of the normal distribution,

φ = the standard normal probability density,

Q = the survivor functions (one minus the cumulative distribution function),

D = the set of specimens for which y_i is the observed log joint strength, and

C = the set of specimens for which y_i is the observed log censored joint strength.

Substituting φ and Q into Equation 1 and taking the logarithm of the expression results in the log likelihood function:

$$\log L(\mu,\sigma) = -r\log\sigma - \frac{1}{2\sigma^2}\sum_{i\in D}(y_i-\mu)^2 + \sum_{i\in C}\log Q\left(\frac{y_i-\mu}{\sigma}\right) + \frac{r}{2}\log(2\pi) \qquad (2)$$

where:

r = the number of observed joint failure.

Estimates of the mean and standard deviation are determined by maximizing the log likelihood function. Maximize Equation 2 by taking derivatives with respect to both σ and μ and setting each expression to zero. This leads to the following system of equations:

$$\sum_{i\in D} z_i + \sum_{i\in C} V(z_i) = 0 \qquad (3)$$

$$-r + \sum_{i\in D} z_i^2 + \sum_{i\in C} z_i V(z_i) = 0 \qquad (4)$$

where:

$V(z_i)=\dfrac{\phi(z_i)}{Q(z_i)}$ = the hazard function of the normal distribution, and

$z_i = \dfrac{y_i-\mu}{\sigma}$

Estimates of the mean and standard deviation, $\hat{\mu}$ and $\hat{\sigma}$, are determined by an iterative process using Equations 3 and 4. Approximate standard errors of the estimated mean and variance are determined by inverting the Fisher information matrix, I_o, as shown in Equation 5.

$$I_o = \begin{bmatrix} \dfrac{-\partial \log L}{\partial \mu^2} & \dfrac{-\partial^2 \log L}{\partial\mu\partial\sigma} \\ \dfrac{-\partial^2 \log L}{\partial\mu\partial\sigma} & \dfrac{-\partial \log L}{\partial\sigma^2} \end{bmatrix}_{(\hat{\mu},\hat{\sigma})} \qquad (5)$$

where log L is the log likelihood function in Equation 2. The square root of the diagonal entries of the inverted matrix are approximate standard errors for $\hat{\mu}$ and $\hat{\sigma}$. This procedure determines the maximum likelihood estimates of mean and standard deviation of the normal distributed logarithms of joint strength, $\hat{\mu}$ and $\hat{\sigma}$. For comparison with experimental observations the following expressions were used to estimate the lognormal mean and standard deviations, $\hat{\mu}_\ell$ and $\hat{\sigma}_\ell$, which are one-to-one functions of the estimates $\hat{\mu}$ and $\hat{\sigma}$.

$$\hat{\mu}_\ell = \tilde{\mu}\, e^{\frac{\hat{\sigma}^2}{2}} \qquad (6)$$

$$\hat{\sigma}_{\ell} = \tilde{\mu}\,(e^{2\hat{\sigma}^2} - e^{\hat{\sigma}^2})^{\frac{1}{2}} \quad (7)$$

where $\hat{\mu} = e^{\hat{\mu}}$ (estimated median value of the joint strength). The above expressions are used to estimate censored data set means and standard deviations.

Table 4 provides summary statistics for the connection test results, including the mean time to failure, joint slips, and ultimate loads based on a censored data analysis. Note that the censored data analysis based on the MLE gives a higher mean and higher coefficient of variation (COV), as compared to the test mean and COV (see Table 3). For example, for Configuration A (three rows, five bolts in each row), the test mean ultimate load from Table 3 was 149 kN (33.59 kips) with a COV of 0.055, and the estimated censored mean from Table 4 was 155 kN (34.77 kips) and COV of 0.060. The same is true for Configurations B, C, and D. It should be noted that the average moisture content and specific gravity (oven-dry weight and volume) for all specimens was 8.4% and 0.61, respectively.

***Table 4:** Summary Statistics[(a)] for Connection Tests*

Joint Group	Time to failure (mm:ss)	Joint slip (in.)	Censored Mean P_{ult} (kips)	COV
A	07:41	0.077	34.77	0.060
B	07:00	0.064	37.92	0.067
C	09:15	0.081	40.14	0.073
D	09:25	0.104	69.01	0.070

For SI: 1 kip = 1000 lbf = 4448 N; 1 in. = 25.4 mm
[(a)] Mean of 5 specimens (10 connections).

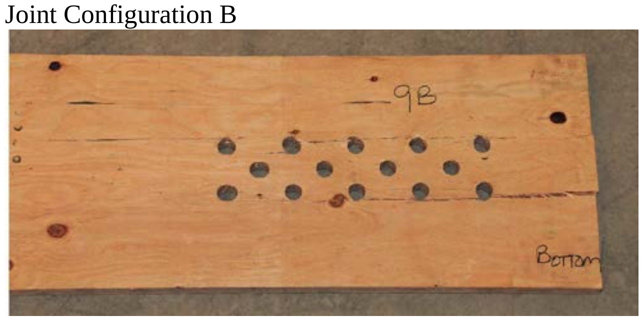
4.5 Failure Modes

Specimens from Joint Configurations A, B, and C all failed by group tear-out, while specimens from Joint Configuration D failed in all cases by one of the outer row and surrounding wood material splitting away from the specimen and the formation of the split progressed to the opposite connection. Representative failures for each test configuration are shown in Figure 6. These failure modes are similar to those previously reported for glulam [3].

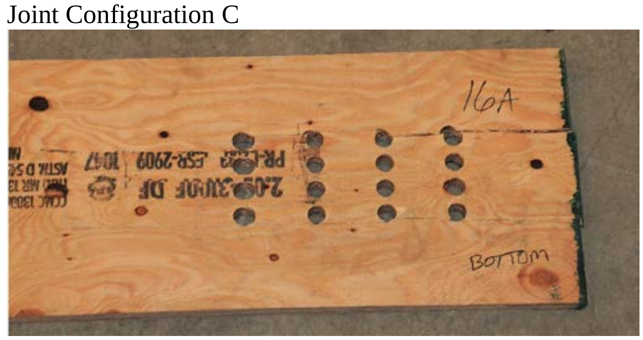
A visual inspection of the bolts showed no permanent bolt bending after the connection test or any bearing wear on the steel side plates. Inspection of the steel side plate hole with a center punch device showed no visible permanent deformation of the steel plate holes, indicating the failures were attributed exclusively to the limit states of LVL. These results validated the failure modes predicted by the NDS Appendix E with multiple bolted connections made of LVL.

Joint Configuration A

Joint Configuration B



Joint Configuration C



Joint Configuration D

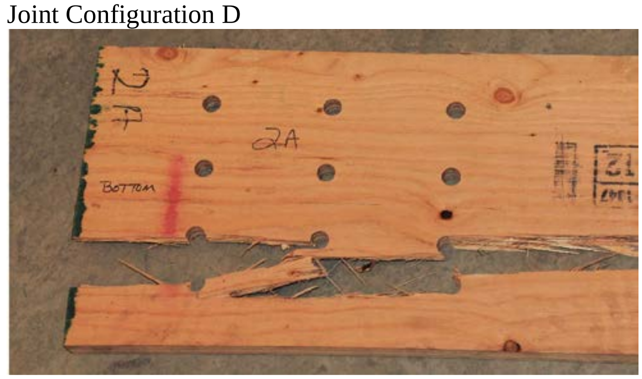


***Figure 6**: Typical failure modes*

4.6 Estimated Design Connection Strengths

The NDS Appendix E provides equations for determining the design capacity for wood failure mechanisms in multiple bolted connections. Expression for net tension, row tear-out, and group tear-out are as follows:

Net Tension:

$$Z_{NT}' = F_t' A_{net} \quad (8)$$

where:

Z_{NT}' = adjusted tension capacity of net section area,

F_t' = adjusted tension design value parallel to grain, and

A_{net} = net section area.

Row Tear-Out:

$$Z_{RTi}' = n_i \frac{F_v' A_{critical}}{2} \quad (9)$$

where:

Z_{RTi}' = adjusted row tear out capacity of row i,

F_v' = adjusted shear design value parallel to grain,

$A_{critical}$ = minimum shear area of any fastener in row i, and

n_i = number of fasteners in row.

$$Z_{RT}' = \sum_{i=1}^{n_{row}} Z_{RTi}' \quad (10)$$

where:

Z_{RT}' = adjusted row tear out capacity of multiple rows, and

n_{row} = number of rows.

Group Tear-Out:

$$Z_{GT}' = \frac{Z_{RT-1}'}{2} + \frac{Z_{RT-n}'}{2} + F_t' A_{group-net} \quad (11)$$

where:

Z_{GT}' = adjusted group tear-out capacity,

Z_{RT-1}' = adjusted row tear-out capacity of row 1 of fasteners bounding the critical group area,

Z_{RT-n}' = adjusted row tear-out capacity of row n of fasteners bounding the critical group area, and

$A_{group-net}$ = critical group net section area between row 1 and row n.

For the data analysis, the mean LVL thickness for all specimens of 42 mm (1.657 in.) was used with the width of 381 mm (15 in.) and the allowable shear and tensile stresses of 3.2 MPa (458 psi) and 26.4 MPa (3828 psi), respectively (load duration of 10 minutes), as mentioned above. The multiple bolted connection design strengths were calculated based on Equations 8 through 11 above for each possible failure mode, as shown in Table 5.

It should be noted that for Joint Configuration D, while the connection capacity based on row tear-out governs all 3 failure modes considered in the NDS Appendix E, the design lateral resistance of all 9 bolts, which is 17.4 kN (3.92 kips) for each bolt (load duration of 10 minutes and the "equivalent specific gravity" of 0.5, as published by the LVL manufacturer) actually governs the design, i.e., 3.92 kips/bolt x 9 bolts = 35.3 kips. This is consistent with the failure mode observed from all 5 Joint Configuration D specimens tested in this study. As noted in Table 5, the group tear-out failure mode governs Joint Configurations A, B, and C, as also supported by the failure mode observed from the experiment conducted in this study.

Table 5: *Calculated Design Strengths for Multiple Bolted Connection (kips)*

Joint Group	Net Section	Row Tear-Out	Group Tear-Out	Control
A	74.9	45.5	20.7	20.7
B	74.9	42.5	20.7	20.7
C	68.2	48.6	20.5	20.5
D	74.9	47.8	53.2	35.3[(a)]

For SI: 1 kip = 1000 lbf = 4448 N

(a) This value has taken the the lateral resistance of bolts into account (see explanation below).

4.7 Load Factors for LVL Multiple Bolted Connections

Table 6 provides the ratios of connection strengths between the mean test results and the NDS calculations. The mean test results include the as-tested data from Table 3 and the results based on the censored data analysis from Table 4. The NDS values have been adjusted to the as-tested load duration, as shown in Table 5, so that the comparisons are made on the same load duration basis.

Table 6: *Ratios of Mean Connection Strength between Test Results and NDS*

Joint Group	Test (kips)	Censored (kips)	NDS (kips)	Test/ NDS	Cen-sored/ NDS
A	33.59	34.77	20.7	1.62	1.68
B	36.47	37.92	20.7	1.76	1.83
C	38.49	40.14	20.5	1.88	1.96
D	66.24	69.01	35.3	1.88	1.95

For SI: 1 kip = 1000 lbf = 4448 N

As can be seen from Table 6, the test results for Joint Configurations A through C, which are governed by the group tear-out failure mode, are in a range of 1.68 to 1.96 times the calculated NDS design values based on the censored data analysis. This multiplier is an indication of the "load factor" for LVL multiple bolted connections when the group tear-out is the controlling failure mode. Interestingly, test results for Joint Configuration D, which is governed by the lateral resistance of bolts without the involvement of group tear-out or row tear-out failure mode, are 1.95 times the calculated NDS design value based also on the censored data analysis.

It is important to note that there is no clear requirement in the national codes or standards on the minimum load factor for the group or row tear-out failure mode. As can be seen from Table 6, the mean load factor for each joint configuration is in the range of 1.68 to 1.96. When

Configurations A through C are combined (due to the same failure mode of group tear-out), the mean load factor is 1.82 based on the censored data analysis. As a comparison, the mean load factor for glulam multiple bolted connections, as previously reported by the authors [3], was 1.79, approximately the same, with the reduced allowable glulam shear value.

To establish the minimum load factor for the group or row tear-out failure mode, the following approach is considered and proposed. It has been standardized that the allowable mechanical properties, such as bending and tension, for engineered wood products should be derived based on a factor of safety of 1.3 and an adjustment between test duration and standard design load duration over the characteristic test value (5th percentile with 75% confidence) of such mechanical properties [6], as shown in Equation 12.

$$P_{10-yr} = \frac{CV}{C_D \times FS} \tag{12}$$

where:

$P_{10\text{-}yr}$ = allowable property based on a standard design load duration of 10 years,

CV = characteristic value (5th percentile with 75% confidence) from test results of approximately 10-minute load duration,

C_D = load duration factor = 1.6 and 1.0 for 10-minute and 10-year load duration, respectively, and

FS = factor of safety, which is typically 1.3 for wood products.

The relationship between characteristic and mean values can be expressed in accordance with Equation 13.

$$CV = \overline{X}\,(1 - K \times COV) \tag{13}$$

where:

$\overline{X}$ = mean value from test results with approximate 10-minute load duration,

K = statistic for a specified confidence level at a specified percentile = 1.645 for a large data population at 5th percentile with 75% confidence [8], and

COV = sample coefficient of variation.

Table 4 shows that the COV for the LVL multiple bolted connections is in a range of 6.0 to 7.3%. It is understood that the test COV obtained from this study may not represent all grades of LVL from various manufacturers. However, it would seem reasonable that a COV of 10 to 15% can be applied to LVL multiple bolted connections in the group or row tear-out failure mode. With these COV's, it can be shown from Equation 13 that the characteristic value (CV) is equal to 0.8355 and 0.7533 times the test mean ($\overline{X}$), respectively. Substituting these CV values and the factor of safety (FS) of 1.3 into Equation 12,

$$\text{When COV = 10\%,}\ P_{10-yr}\ C_D = \frac{\overline{X}}{1.56} \tag{14}$$

$$\text{When COV = 15\%,}\ P_{10-yr}\ C_D = \frac{\overline{X}}{1.73} \tag{15}$$

As a result, a load factor of 1.56 to 1.73 over the mean test value could be considered appropriate for the LVL multiple bolted connections with a coefficient of variation between 10 to 15%. Note that the load duration of 1.6 that adjusts the 10-minute test duration to the standard 10-year design load duration is separated from this load factor, as shown in Equations 14 and 15.

On the basis of the consideration mentioned above, it seems reasonable to conclude that the load factor of 1.82 for LVL multiple bolted connections obtained from this study meets the minimum load factor requirements. As a result, the LVL allowable shear value is not required to be reduced when designing LVL multiple bolted connections that may involve a row or group tear-out failure mode in accordance with Appendix E of the NDS.

5 SUMMARY AND CONCLUSION

The design of multiple bolted connections in accordance with Appendix E of the NDS has incorporated provisions for evaluating localized member failure modes of row and group tear-out when the connections are closely spaced. Originally based on glulam members made with all L1 Douglas fir-Larch laminating lumber, the NDS provisions were confirmed by additional analysis, which indicates the applicability of the provisions to glulam with reduced design shear values. Due to the similarity to glulam in the grain orientation and layup strategy, LVL is subject to similar failure modes. As a result, a study was initiated by APA – The Engineered Wood Association and the LVL industry, in collaboration with the FPL, to evaluate if a reduced design shear stress is necessary for LVL under similar multiple bolted connection configurations.

A total of 20 full-scale LVL multiple bolted connection specimens were tested in 4 different joint configurations. As 2 connections were tested in each specimen, this study covered a total of 40 connections. A censored data analysis was performed to estimate the mean and COV of the connection performance. End-matched specimens were also tested to determine the characteristic shear and tensile strengths of the LVL, which were used to predict the connection strengths based on the provisions specified in Appendix E of the NDS.

The failure modes from test results obtained from this study match very well with the NDS predictions. In addition, the test results demonstrate that the mean load factor for each joint configuration tested in this study is in the range of 1.68 to 1.96, which meets the minimum load factor of 1.56 and 1.73 for the COV of 10 and 15%, respectively. Therefore, it is concluded that an adequate load factor exists for LVL multiple bolted connections without a reduction in the LVL design shear stress when designed in accordance with Appendix E of the NDS.

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