WCTE 2018
2018 World Conference on Timber Engineering
August 20 - 23, 2018 | Seoul, Republic of Korea

EFFECT OF HOLES ON THE STRUCTURAL CAPACITIES OF LAMINATED VENEER LUMBER

Borjen Yeh[1] and Benjamin Herzog[2]

ABSTRACT: Laminated veneer lumber (LVL) is an engineered wood product manufactured from specially selected veneers with varying strength and stiffness properties. LVL products are often specified where a certain span, strength and/or stiffness is required. As such, LVL products are generally designed for and used in applications where they will be highly stressed under design loads. For this reason, field modifications, such as notching, tapering, or drilling should be avoided and never done without a thorough understanding of the effects on the structural capacities of the LVL. Nonetheless, it is not uncommon for the designer and contractor to find a need to cut holes through LVL members for plumbing pipes, electrical conduits, or air ducts. Therefore, it is usually necessary to determine the residual structural capacities of the LVL member when holes are cut. The objective of this paper is to examine the effect of round holes on the structural capacities of LVL, including bending moment, shear, and bending stiffness. Full-scale LVL bending and shear tests were conducted to provide data for characterization of the hole effect. Based on the test data, design equations that account for single and multiple holes up to 2/3 of the LVL member depth and a clear distance of 15% or more of the LVL depth from the edge of the hole to either tension and compression edge of the LVL member have been developed. To ensure safe implementation of such design recommendations in practice, prescriptive limitations, such as the minimum clear distance between the face of a support and the edge of a hole, and the minimum clear distance between adjacent holes, are also prescribed.

KEYWORDS: Holes, Laminated veneer lumber, Bending moment, Shear strength, Bending stiffness

1 INTRODUCTION

Laminated veneer lumber (LVL) is an engineered wood product manufactured from specially selected veneers with varying strength and stiffness properties. LVL products are often specified where a certain span, strength and/or stiffness is required. As such, LVL products are generally designed for and used in applications where they will be highly stressed under design loads. For this reason, field modifications, such as notching, tapering, or drilling, should be avoided and never done without a thorough understanding of the effects on the structural capacities of the LVL.

The objective of this paper is to examine the effect of round holes on the structural capacities of LVL. Holes in LVL members reduce the net section of the member at the hole location and introduce stress concentrations. This, in turn, causes a reduction in the LVL structural capacities that are related to hole size and location. There are at least two options in addressing allowable holes in an LVL bending member:

a) Prescriptively limit the hole size and location so that the holes will not significantly affect the structural capacities of the LVL, and

b) Develop hole adjustment factors for the published design values on bending moment, shear, and bending stiffness so that the holes can be analyzed for the specific span, loading, and hole size and location.

Option a) is addressed in APA Technical Note G535, *Field Notching and Drilling of Laminated Veneer Lumber* [1]. An example of this prescriptive option is shown in Figure 1.

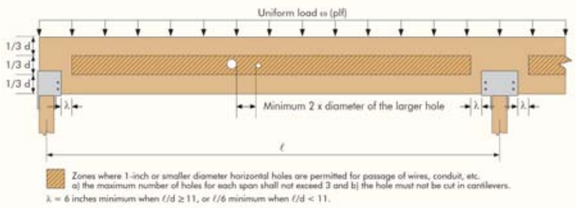

Figure 1. *Prescriptive hole size and location (excerpted from APA G535)*

Option b) is the main purpose of this paper. Along with a previous study on the effect of round holes on LVL shear capacities, as reported in *APA Report T2009L-30* [2], the hole adjustment factors for bending moment and bending stiffness are developed and reported in this paper.

2 OBJECTIVES

The main objective of this study was to examine the effect of round holes on the structural capacities of LVL. Holes

---

[1] Borjen Yeh, APA – The Engineered Wood Association, Tacoma, WA, U.S.A. borjen.yeh@apawood.org,

[2] Benjamin Herzog, University of Maine, Orono, ME, U.S.A. benjamin.herzog@maine.edu

in LVL members reduce the net section of the member at the hole location and introduce stress concentrations. This, in turn, causes a reduction in the LVL structural capacities that are related to hole size and location. Only round holes were investigated in this study.

3 EFFECT OF HOLES ON STRUCTURAL CAPACITIES

3.1 SHEAR STRENGTH

As reported in *APA Report T2009L-30* [2], the hole adjustment factor for shear, $C_{\text{hole,V}}$, can be expressed as the square of the ratio of the depth remaining. Therefore, the net shear strength with a hole can be expressed in Equation 1.

$$V_{net} = C_{hole,V}\, V_{gross} = \left(\frac{d-D}{d}\right)^2 V_{gross} \qquad (1)$$

where d is the LVL depth in mm (or inches), D is the hole diameter in mm (or inches), and V_{gross} is the full allowable shear strength of the LVL without a hole.

Note that the squared term in Equation 1 was derived based on empirical results obtained from single and multiple hole tests, as contained in *APA Report T2009L-30* with the maximum hole size of d/3, and is more conservative than a general engineering equation that is usually based on the ratio of [(d - D) / d] only. A typical shear failure mode from the LVL hole tests is shown in Figure 2. This maximum hole size of 3/d from the shear tests will be considered in the adjustment factor recommendations provided later in this paper, as M and EI data provided in this paper are based on the maximum hole size of 2d/3.

Figure 2. *A shear failure mode of a 406-mm (16-inch) deep LVL specimen with two 135-mm (5-1/3-inch) diameter holes at the neutral axis*

3.2 BENDING MOMENT AND STIFFNESS

A separate study from the shear tests was conducted by APA to evaluate the effect of holes on the LVL bending moment (M) and stiffness (EI) capacities, as described in this section.

3.2.1 Test Methods

Douglas fir LVL members (3100f-2.0E) of 43 mm (1.7 inches) in thickness by 302 mm (11-7/8 inches) in depth were tested at the APA Research Center in Tacoma, Washington, in 2016. The test matrix is presented in Table 1. Specimens were tested with and without holes. Test variables included the number, size, and location of holes. All members were tested at a simple span of 5430 mm (213-3/4 inches) with a span-to-depth ratio of 18:1.

Table 1: *Test Matrix*

Hole Dia. (D)	Hole Location	No. of Holes[a]	Number of Tests
102 mm (4 inches)	Center at the neutral axis	0	5
		1	5
		2	5
		3	5
	Edge of hole 0.15d from tension edge of the LVL	0	5
		1	5
		2	5
		3	5
	Edge of hole 0.15d from compression edge of the LVL	0	5
		1	5
		2	5
		3	5
203 mm (8 inches)	Center on neutral axis	0	5
		1	5
		2	5
		3	5
	Edge of hole 0.15d from tension edge of the LVL	0	5
		1	5
		2	5
		3	5
	Edge of hole 0.15d from compression edge of the LVL	0	5
		1	5
		2	5
		3	5

[a] Control: No holes.
Single hole: One hole centered at mid-span.
Double hole: One hole centered at mid-span and a second hole located 2D clear distance to the left of the center hole.
Triple hole: One hole centered at mid-span, a second hole located 2D clear distance to the left of the center hole, and a third hole located 2D clear distance to the right of the center hole.

Specimens with holes were prepared by removing material with either a hole saw or a plunge router and routing template. Two hole sizes were tested: 102 mm and 203 mm (4 inches and 8 inches), representing approximately d/3 and 2d/3, respectively. For members with multiple holes, the holes were spaced at a clear distance of two hole-diameters.

A third-point load method was applied to all specimens. All holes were located between the applied loads in the area of a constant maximum moment. The test apparatus, including rocker-type reaction supports, reaction bearing plates and rollers, load bearing blocks, and load bearing rollers were set up following Sections 18 to 23 of ASTM D4761 [3] and Figure 2 of ASTM D198 [4]. The reaction bearing plates were 203 mm (8 inches) in length.

The modulus of rupture (MOR) and the modulus of elasticity (MOE) were calculated using Equations 2 and 3 as follows:

$$MOR = \frac{3\,P_{ult}\,a}{b\,d^2} \qquad (2)$$

$$MOE = \frac{\theta\,a\,(3\,L^2 - 4\,a^2)}{4\,b\,d^3} \qquad (3)$$

where:

MOR = modulus of rupture, MPa (or psi)
MOE = apparent modulus of elasticity, MPa (or psi)
P_{ult} = ultimate total load excluding the dead weight of the specimens, N (or lbf)
a = distance between the reaction point to the nearest loading point, mm (or in.)
b = measured member width, mm (or in.)
d = measured member depth, (mm (or in.)
L = test span, mm (or in.), and
θ = slope of load vs. deflection plot below the proportional limit, N/mm (or lbf/in.)

Note that since mid-span deflection at the neutral axis could not be directly measured using point-of-contact methods for specimens having holes, deflection was measured at both the top and bottom edges of the member. The averages of these values were used in the slope determination.

3.2.2 Results

Figure 3 shows the bending failure mode of a specimen with three 203-mm (8-inch) diameter holes at the neutral axis. A summary of the test results is shown in Tables 2a and 2b for bending moment and Tables 3a and 3b for bending stiffness.

Figure 3. *A bending failure mode of a 302-mm (11-7/8-inch) deep LVL specimen with three 203-mm (8-inch) diameter holes at the neutral axis*

3.2.3 Bending Moment

An Analysis of Variance (ANOVA) was performed in order to determine whether significant differences in bending moment exist due to the number of holes in the member (see Table 4). The only test set that showed significant differences ($\alpha \leq 0.05$) in MOR were those members with 203-mm (8-inch)-diameter holes (2d/3) located near the tension edge of the member. Significant differences were shown to exist between members with one hole vs. three holes in both the mean (t-statistic) and coefficient of variation (F-statistic), as shown in Table 4. Nevertheless, in most cases, the data indicate that a clear distance of two hole-diameters between holes is sufficient to ensure the bending stress redistribution around the hole(s).

Table 4*. Statistical analysis of 8-inch hole (tension edge) tests*

1 hole vs. 2 holes	F-statistic	α = 0.0499 (significant)
	t-statistic	α = 0.0544 (insignificant)
2 holes vs. 3 holes	F-statistic	α = 0.9997 (insignificant)
	t-statistic	α = 0.1723 (insignificant)
1 hole vs. 3 holes	F-statistic	α = 0.0499 (significant)
	t-statistic	α = 0.0067 (significant)

The net and gross section moduli (S_{net} and S_{gross}) of each member were calculated, and the S_{net}/S_{gross} ratios were compared to the test data, as shown in Table 5.

Table 5*. Bending strength: Comparison of analytical reduction with test results*[(a)]

Hole Loc.	D (mm)	Clear dis. to tension edge (mm)	S_{net} / S_{gross}	M Ratio = M_{hole} / $M_{control}$		$C_{hole,M}$ = 0.95 x (S_{net} / S_{gross})
				Avg of all hole tests	Worst case: # of holes	
At N.A.	102	100	0.962	0.953	0.942	0.914
	203	49	0.694	0.690	0.667	0.660
0.15d to tension	102	44	0.636	0.711	0.681	0.604
	203	44	0.646	0.702	0.627	0.614
0.15d to comp.	102	156	0.636	0.728	0.719	0.604
	203	54	0.646	0.638	0.625	0.614

[a)] S_{net} and S_{gross} are calculated based on the actual thickness of 43 mm (1.7 inches).

In general, the calculated reduction in bending moment, using the principle of engineering mechanics, agreed well with the test data. This was especially true when the analytical reduction was compared to that of grouped test data. However, when the control bending data was compared to the lowest set of bending data of members having holes, the empirical reduction was slightly greater than predicted. As a result, a conservative approach is to use an additional reduction factor of 0.95 to the calculated ratio of S_{net} / S_{gross} in design, as shown in Equation 4.

$$M_{net} = C_{hole,M}\,M_{gross} = 0.95\left(\frac{S_{net}}{S_{gross}}\right)M_{gross} \qquad (4)$$

The rightmost column in Table 5 shows the calculated ratio of the $C_{hole,M}$ factor. As shown, the use of this factor would provide a conservative adjustment for all cases of single, double, and triple holes regardless of vertical location within the member.

3.2.4 Bending Stiffness

The net and gross moments of inertia (I_{net} and I_{gross}) of each member were calculated. Table 6 compares the ratios of the calculated I_{net}/I_{gross} with the ratios of EI values with holes, $(EI)_{hole}$, and without holes. $(EI)_{gross}$, derived from test data. As shown, the calculated reduction in

***Table 2a**. Summary of **MOR** test results (MPa), 102-mm (4-inch) hole diameter*

Clear distance to tension edge	100 mm (3-15/16 in.) Hole center at the neutral axis				44 mm (1-3/4 in.) Hole center close to the tension (bottom) edge				156 mm (6-1/8 in.) Hole center close to the compression (top) edge			
No. of holes	0	1	2	3	0	1	2	3	0	1	2	3
1	66.3	61.4	54.0	62.6	71.4	49.4	40.8	45.0	61.7	48.0	46.9	45.8
2	64.8	61.4	62.1	64.8	58.7	50.8	44.1	45.2	53.1	48.6	40.1	48.2
3	65.2	59.2	64.3	62.3	65.4	50.8	56.5	42.7	67.6	40.4	43.1	47.1
4	62.7	66.1	66.0	59.0	71.7	50.6	46.4	47.8	58.2	46.5	47.6	45.1
5	66.6	63.1	60.4	64.1	67.6	51.3	45.7	47.0	67.8	45.1	44.3	37.5
Mean	65.1	62.2	61.4	62.6	66.9	50.6	46.7	45.6	61.7	45.7	44.4	44.8
COV (%)	2.4	4.1	7.6	3.6	7.9	1.4	12.7	4.3	10.2	7.1	6.8	9.4
Ratio to Control	Control	0.96	0.94	0.96	Control	0.76	0.70	0.68	Control	0.74	0.72	0.73
Average Ratio		0.95				0.71				0.73		

(a) MOR values with hole(s) are calculated based on the gross sectional dimensions (i.e., gross b and d in Equation 2).

***Table 2b**. Summary of **MOR** test results (MPa), 203-mm (8-inch) hole diameter*

Clear distance to tension edge	49 mm (1-15/16 in.) Hole center at the neutral axis				44 mm (1-3/4 in.) Hole center close to the tension (bottom) edge				156 mm (2-1/8 in.) Hole center close to the compression (top) edge			
No. of holes	0	1	2	3	0	1	2	3	0	1	2	3
1	62.3	36.7	38.6	40.4	61.0	47.9	35.2	33.1	58.1	36.2	41.4	42.2
2	59.9	48.9	44.3	43.7	64.4	44.6	43.9	35.5	71.5	40.6	40.3	39.0
3	64.3	44.6	44.4	45.4	50.0	47.3	44.7	37.2	69.5	46.0	40.4	43.5
4	59.9	47.0	45.0	40.2	65.3	47.6	39.6	44.9	69.1	47.8	39.9	42.3
5	65.3	39.8	48.2	38.1	60.0	48.2	46.0	37.8	62.1	47.3	44.4	41.4
Mean	62.3	43.4	44.1	41.6	60.1	47.1	41.9	37.7	66.1	43.6	41.3	41.7
COV (%)	4.0	11.7	7.9	7.1	10.2	3.0	10.5	11.7	8.6	11.5	4.5	4.0
Ratio to Control	Control	0.70	0.71	0.67	Control	0.78	0.70	0.63	Control	0.66	0.62	0.63
Average Ratio		0.69				0.70				0.64		

(a) MOR values with hole(s) are calculated based on the gross sectional dimensions (i.e., gross b and d in Equation 2).

Table 3a*. Summary of* ***MOE*** *test results (GPa), 102-mm (4-inch) hole diameter*

Clear distance to tension edge	100 mm (3-15/16 in.) Hole center at the neutral axis				44 mm (1-3/4 in.) Hole center close to the tension (bottom) edge				156 mm (6-1/8 in.) Hole center close to the compression (top) edge			
No. of holes	0	1	2	3	0	1	2	3	0	1	2	3
1	16.8	16.5	16.6	16.7	17.6	16.5	16.2	15.4	17.4	17.2	16.3	16.1
2	16.8	17.4	17.2	17.4	16.5	17.9	15.7	16.0	17.2	16.9	15.7	16.2
3	17.4	17.5	18.0	16.6	17.2	16.7	16.5	15.7	16.9	15.7	16.3	15.9
4	17.6	17.5	17.2	16.5	18.1	17.7	15.9	16.4	16.0	17.6	16.9	14.9
5	17.4	16.5	17.0	17.4	18.0	17.2	16.3	15.4	18.4	17.2	15.6	14.4
Mean	17.2	17.1	17.2	16.9	17.5	17.2	16.1	15.8	17.2	16.9	16.1	15.5
COV (%)	2.3	3.0	2.9	2.7	3.8	3.5	2.0	2.6	5.0	4.3	3.3	5.2
Ratio to Control	Control	0.99	1.00	0.98	Control	0.98	0.92	0.90	Control	0.98	0.94	0.90
Average Ratio		0.99				0.93				0.94		

(a) MOE values with hole(s) are calculated based on the gross sectional dimensions (i.e., gross b and d in Equation 3).

Table 3b*. Summary of* ***MOE*** *test results (GPa), 203-mm (8-inch) hole diameter*

Clear distance to tension edge	49 mm (1-15/16 in.) Hole center at the neutral axis				44 mm (1-3/4 in.) Hole center close to the tension (bottom) edge				54 mm (2-1/8 in.) Hole center close to the compression (top) edge			
No. of holes	0	1	2	3	0	1	2	3	0	1	2	3
1	16.5	15.3	15.0	14.5	16.5	15.3	14.7	13.3	15.9	16.3	15.4	14.2
2	17.0	15.9	14.9	14.5	16.8	16.2	15.4	13.4	17.9	14.9	15.7	14.6
3	17.2	15.5	14.5	14.1	15.7	15.8	14.5	14.5	16.6	16.5	15.6	15.0
4	17.0	15.3	14.7	14.6	17.2	16.3	15.3	14.9	16.9	16.8	15.7	14.8
5	16.8	15.2	15.2	14.8	17.3	16.4	15.7	14.5	17.4	16.5	15.9	15.3
Mean	16.9	15.4	14.9	14.5	16.7	16.0	15.1	14.1	17.0	16.2	15.7	14.8
COV (%)	1.6	1.9	1.8	1.7	3.8	2.8	3.2	5.2	4.6	4.7	1.1	2.8
Ratio to Control	Control	0.91	0.88	0.86	Control	0.96	0.90	0.85	Control	0.96	0.92	0.87
Average Ratio		0.88				0.91				0.92		

(a) MOE values with hole(s) are calculated based on the gross sectional dimensions (i.e., gross b and d in Equation 3).

bending stiffness (I_{net}/I_{gross}) is much greater than the test results. This suggests that the bending stiffness adjustment factor due to holes is unnecessarily conservative if based simply on the I_{net}/I_{gross} ratio.

***Table 6**. Bending stiffness: Comparison of analytical reduction with test results*$^{(a)}$

Hole Loc.	D (mm)	Clear dis. to tension edge (mm)	I_{net} / I_{gross}	EI Ratio = $(EI)_{hole}$ / $(EI)_{control}$	
				Avg of all hole tests	Worst case: # of holes
At N.A.	102	100	0.962	0.992	0.983
	203	49	0.694	0.885	0.860
0.15d to tension	102	44	0.755	0.936	0.903
	203	44	0.688	0.903	0.846
0.15d to comp.	102	156	0.755	0.943	0.904
	203	54	0.688	0.917	0.872

[a] I_{net} and I_{gross} are calculated based on the actual thickness of 43 mm (1.7 inches).

There are at least three variables that affect EI: the size, number, and vertical location of holes. As shown in Table 7, EI decreases as the size and number of holes increases. As shown in Figures 4 through 9, EI decreases linearly for each additional hole at a rate that can reasonably be approximated as 6% in the worst-case – 203-mm (8-inch) diameter holes with a clear distance of 49 mm (1-5/16 inches), as shown in Figure 4.

***Table 7**. Analysis of EI data with reduction factors*

D (mm)	Clear dis. to tension edge (mm)	No. of holes	Average $(EI)_{gross}$ (10^6 kN-mm^2)	EI Ratio
102	100	0	7.15 x I_{gross}	1.000
		1	7.12 x I_{gross}	0.994
		2	7.15 x I_{gross}	1.000 $^{(a)}$
		3	7.03 x I_{gross}	0.983
203	49	0	7.03 x I_{gross}	1.000
		1	6.43 x I_{gross}	0.915
		2	6.20 x I_{gross}	0.881
		3	6.06 x I_{gross}	0.860
102	44	0	7.59 x I_{gross}	1.000
		1	7.17 x I_{gross}	0.985
		2	6.72 x I_{gross}	0.921
		3	6.57 x I_{gross}	0.903
203	44	0	6.94 x I_{gross}	1.000
		1	6.66 x I_{gross}	0.957
		2	6.28 x I_{gross}	0.905
		3	5.88 x I_{gross}	0.846
102	156	0	7.15 x I_{gross}	1.000
		1	7.03 x I_{gross}	0.985
		2	6.72 x I_{gross}	0.941
		3	6.46 x I_{gross}	0.904
203	54	0	7.06 x I_{gross}	1.000
		1	6.74 x I_{gross}	0.956
		2	6.51 x I_{gross}	0.924
		3	6.14 x I_{gross}	0.872

(a) This result is not included in the regression analysis, as shown in Figure 3.

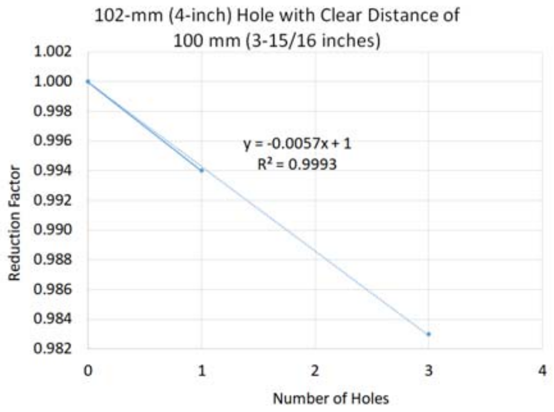

***Figure 4**. Number of holes vs. EI reduction factor for 102-mm (4-inch) holes (hole center at the neutral axis)*

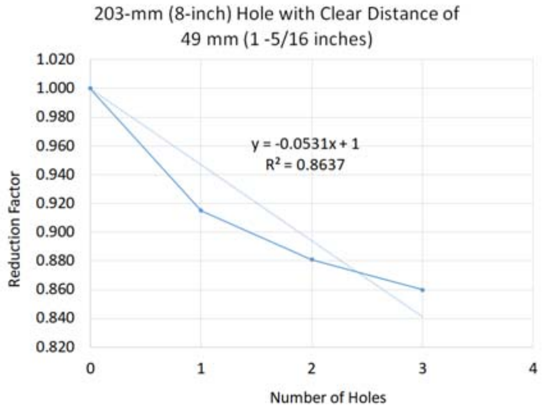

***Figure 5**. Number of holes vs. EI reduction factor for 203-mm (8-inch) holes (hole center at the neutral axis)*

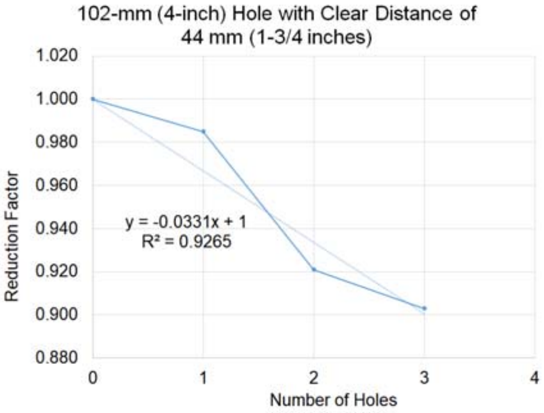

***Figure 6**. Number of holes vs. EI reduction factor for 102-mm (4-inch) holes (hole center closer to the tension edge)*

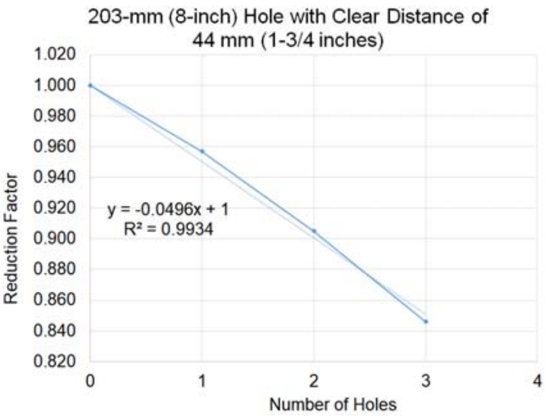

Figure 7*. Number of holes vs. EI reduction factor for 203-mm (8-inch) holes (hole center closer to the tension edge)*

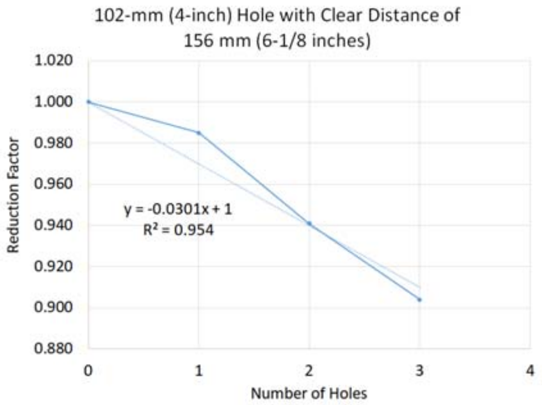

Figure 8*. Number of holes vs. EI reduction factor for 102-mm (4-inch) holes (hole center closer to the compression edge)*

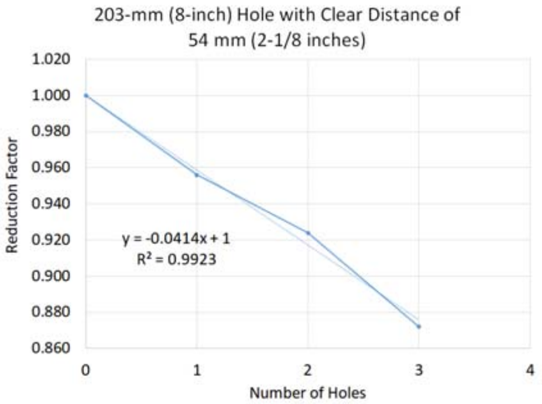

Figure 9*. Number of holes vs. EI reduction factor for 203-mm (8-inch) holes (hole center closer to the compression edge)*

Note that the intercepts of the linear regression lines shown in Figures 4 through 9 were set to 1.0. Also, as indicated in Table 7, the result for the double 102-mm (4-inch) diameter holes with a clear distance of 100 mm (3-5/16 inches), i.e., hole center at the neutral axis, was ignored in the linear regression analysis shown in Figure 4 due to an unusually high EI ratio. If the result is included, the liner regression equation will be $Y = -0.041X + 1$ with R^2 of 0.5197, which will show a less effect of the number of holes on the EI. This does not affect the estimate that EI decreases linearly at 6% for each additional hole.

An EI adjustment factor due to holes should consider the ratio of the proposed hole diameter to the maximum permissible hole diameter, $D/(2d/3) = 3D/2d$, as well as the location and number (N) of holes (0.06N as determined to be a conservative approximation based on Figure 5). It is reasonable to assume that there will also be a volume effect in which a given size hole will have a greater effect on shorter member spans. Therefore, an adjustment based on the ratio of the tested span to the design span (18d/L) should be considered as well.

Combining all effects considered above, the hole adjustment factor for EI, $C_{hole,EI}$, can be expressed as shown in Equation 5, provided that the clear distance between the edge of the hole and either edge of the member is at least 0.15d.

$$C_{hole,EI} = 1 - \left(\frac{18d}{L}\right)(0.06N)\left(\frac{3D}{2d}\right) = 1 - \left(\frac{1.6ND}{L}\right) \le 1.0 \qquad (5)$$

where:

N = number of holes ≤ 3,
d = member depth, mm (or inches),
L = member span, mm (or inches), and
D = hole diameter (the largest diameter for multiple holes) ≤ 2d/3, mm (or inches).

Therefore, the net EI for holes can be expressed as shown in Equation 6.

$$(EI)_{net} = C_{hole,EI}(EI)_{gross} = \left(1 - \frac{1.6\,N\,D}{L}\right)(EI)_{gross} \le (EI)_{gross} \qquad (6)$$

Comparison of Equation 5 and test results are shown in Table 8 and Figure 10. As shown, Equation 5 is generally more conservative than test results with only 4 cases that were off by 1 to 3%. Given that EI is a serviceability property that is based on the mean, these results are considered acceptable in practice. The overall ratio between test results and Equation 5 is 1.02 on average, suggesting that Equations 5 and 6 are reasonable.

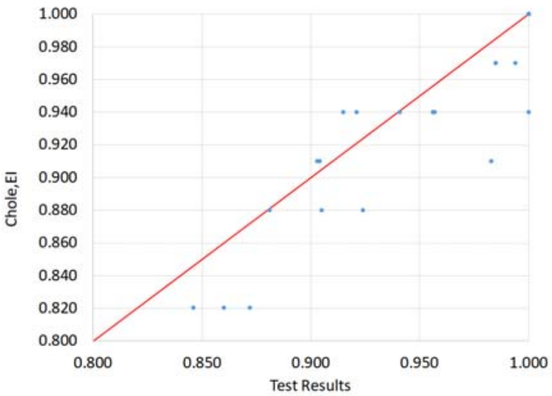

Figure 10*. Comparison of Equation 5 and test results*

***Table 8**. Comparisons of Equation 5 and test results*

N	D (mm)	L (mm)	$C_{hole,EI}$	Test Results[(a)]	Test Results / $C_{hole,EI}$
0	102	5436	1.000	1.000	1.00
1			0.970	0.994	1.02
2			0.940	1.000	1.06
3			0.910	0.983	1.08
0	203	5436	1.000	1.000	1.00
1			0.940	0.915	0.97
2			0.880	0.881	1.00
3			0.820	0.860	1.05
0	102	5436	1.000	1.000	1.00
1			0.970	0.985	1.02
2			0.940	0.921	0.98
3			0.910	0.903	0.99
0	203	5436	1.000	1.000	1.00
1			0.940	0.957	1.02
2			0.880	0.905	1.03
3			0.820	0.846	1.03
0	102	5436	1.000	1.000	1.00
1			0.970	0.985	1.02
2			0.940	0.941	1.00
3			0.910	0.904	0.99
0	203	5436	1.000	1.000	1.00
1			0.940	0.956	1.02
2			0.880	0.924	1.05
3			0.820	0.872	1.06
		Average =			1.02

[(a)] From Table 7.

4 CONCLUSIONS

a) The effect of holes on LVL shear capacity is described in *APA Report T2009L-30*. The adjustment factor for shear, $C_{hole,V}$, is provided in Equation 1.

b) The data suggest that a clear distance of two hole-diameters between holes is sufficient to ensure bending stress redistribution around the holes. The calculated reduction in bending strength, using the principle of engineering mechanics, agrees well with the test data. A slightly conservative approach is to combine a factor of 0.95 with the calculated ratio of S_{net} / S_{gross} in design. The resulting adjustment factor for bending moment, $C_{hole,M}$, is provided in Equation 4.

c) The data suggest that hole size, number, and vertical location all affect member stiffness. An empirical factor, $C_{hole,EI}$, which accounts for these effects as well as an assumed volume effect that varies with the member span, was developed and is provided in Equation 6.

d) The adjustment factors apply to simple-span or multiple-span members that carry uniform and/or concentrated loads.

e) For the application of these adjustment factors, the following restrictions apply:

   1) Holes shall be round and neatly cut with a hole saw or a router and template. Holes cut by other means, such as a reciprocating saw, are prohibited. Rectangular holes are outside the scope of this paper.

   2) A cluster of small holes may be analyzed as a single round hole that circumscribes the cluster and meets all other requirements prescribed in Item (e).

   3) The number of holes in a given span shall be limited to 3 or less.

   4) Holes shall not be cut in cantilevers.

   5) The minimum distance along the length of the member between the face of a support and the edge of a hole shall be 152 mm (6 inches).

   6) For taper or notch cuts at the end of the member, the minimum distance along the length of the beam to the nearest edge of a hole shall be 305 mm (12 inches).

   7) For adjacent holes, the clear distance between holes shall be 2 hole-diameters or larger based on the diameter of the larger hole. The clear distance shall be measured along the member length, as opposed to diagonally across the member depth if holes are staggered.

   8) Where the design shear exceeds 1/3 of the published allowable shear, hole diameter shall not exceed d/3 and the clear distance between the edge of the hole and either edge of the member shall be at least d/3 (i.e., the hole shall be located at the neutral axis). Otherwise, hole diameter shall not exceed 2d/3 and the clear distance between the edge of the hole and either edge of the beam shall be at least 0.15d or 44 mm (1-3/4 inches), whichever is greater.

   9) At concentrated loads, the minimum distance along the length of the member between the face of a top-load object (e.g. column above) or the edge of a side-load object (e.g. beam or girder hanger) shall be 152 mm (6 inches).

   10) When calculating $C_{hole,EI}$ for a span containing holes of different diameters, use the diameter of the largest hole.

ACKNOWLEDGEMENT

The extensive input from the LVL manufacturers through the APA Technical Advisory Committee during the course of this study is greatly appreciated.

REFERENCES

[1] APA – The Engineered Wood Association: *Field Notching and Drilling of Laminated Veneer Lumber*. APA Technical Note G535, Tacoma, WA, 2010.

[2] APA – The Engineered Wood Association: Allowable Holes in LVL. APA Report T2009L-30, Tacoma, WA, 2009.

[3] ASTM International: Standard Test Methods for Mechanical Properties of Lumber and Wood-Base Structural Material, ASTM D4761. West Conshohocken, PA, 2013.

[4] ASTM International: Standard Test Methods of Static Tests of Lumber in Structural Sizes, ASTM D198. West Conshohocken, PA, 2015.