Effect of drilled holes on the bending strength of large dimension Douglas-fir lumber

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Abstract

In this study, experimental bending tests were performed on nominal 4- by 8-inch (actual 89-mm by 191-mm) lumber members to determine how a notch and holes drilled in the wide face affect edgewise bending strength. Holes were drilled at the midspan in three locations relative to the edge. The results appear to justify an allowable hole one-half the allowable knot size that is currently permitted for cedar in No. 1 Beams & Stringer grade. Furthermore, the data indicate that hole location may be as important as hole size. A 1-inch (25.4-mm) hole had about the same effect on strength as a 1-3/4-inch (44-mm) hole when the holes were 1 inch (25.4 mm) from the tension edge.

Over the past several years, there has been a growing interest in reusing lumber from building dismantlement (also known as building deconstruction). This interest is driven by several factors, which include a desire to utilize building materials that otherwise might be destined for a landfill, a demand for dry stable lumber for construction, and the aesthetics that wood members offer in exposed timber-framed construction. Over the last 100 years, more than 3 trillion board feet of lumber and timber have been sawn in the United States; much of this wood was used to construct our existing building infrastructure (Steer 1948, Howard 1999,Urlich 1999). As this infrastructure ages and is repaired or replaced, a large volume of lumber could be available for reuse in construction (Falk 2002). Unlike lumber fresh from the sawmill, reclaimed lumber exhibits characteristics resulting from a lifetime of use as well as damage from the deconstruction process, such as bolt and nail holes, mechanical damage, and drying checks. The extent to which these defects affect engineering properties and potential reuse options has not been fully determined.

Traditionally, when grading reclaimed lumber, the wood products industry has applied existing grading rules through the certificate process; no individual grade stamp specific to reclaimed lumber currently exists. Existing grading criteria focus on naturally occurring wood characteristics such as slope of grain and knot size. In addition, the allowable hole limits for western species is limited to pin holes (≤ 1/16 in.) in Select Structural and No. 1 timber (5 in. and thicker). An exception to this limit is in No. 1 cedar timbers where holes are permitted up to one-half of the allowable knot size. Grading agencies allow for the use of plugs and fillers: "In dimension and other lumber and other lumber graded for strength, inserts are limited to the same size and location as knots." (WCLIB 2000).

Existing literature

No technical references could be found on the effect of bolt and nail holes on lumber bending strength. Recent testing and analysis of lumber from military buildings have helped define residual engineering properties for reclaimed nominal 2- by 10-inch (standard 38- by 235-mm) joists (Falk et al. 1999a) as well as the effect of drying checks on the residual strength of timber column members (Falk et al. 2000) and beams

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Table 1. — Drilled hole location for tested specimen groups.[a]

Test group[b]	Hole size	Hole location
A	1 in. (25.4 mm)	1 in. (25.4 mm) from top
B	1 in. (25.4 mm)	1 in. (25.4 mm) from bottom
C (control)	NA	No holes
D	1 in. (25.4 mm)	1/4 in. (6 mm) from bottom
E	1 in. (25.4 mm)	Half-circle notch at bottom
H	1-3/4 in. (44 mm)	1 in. (25.4 mm) from top
I	1-3/4 in. (44 mm)	1 in. (25.4 mm) from bottom

[a]See Figures 1 to 7 for hole layouts.
[b]Each group consisted of 22 specimens.

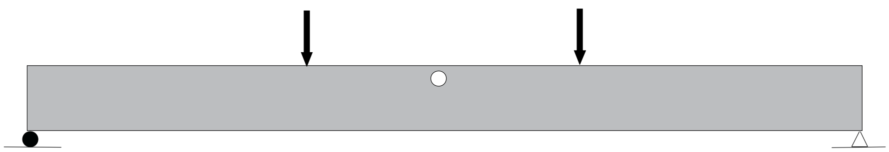

Figure 1. — Test configuration and hole layout for group A beams.

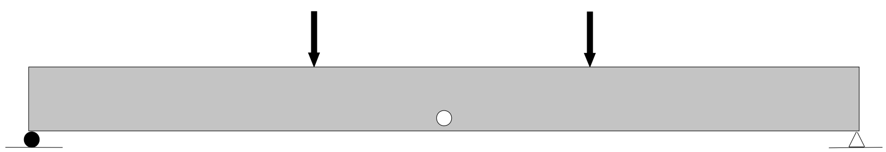

Figure 2. — Test configuration and hole layout for group B beams.

Figure 3. — Test configuration and hole layout for group C (control) beams.

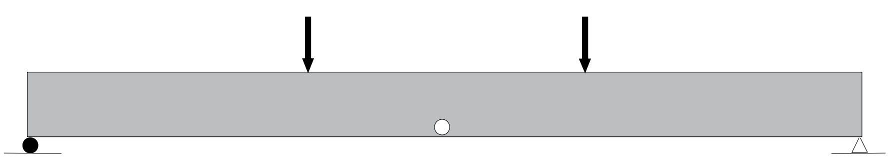

Figure 4. — Test configuration and hole layout for group D beams.

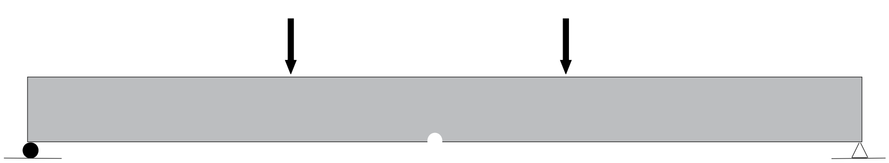

Figure 5. — Test configuration and hole layout for group E beams.

(Green et al. 2001). In addition, the effects of damage on grade yield were identified in an evaluation of lumber from residential military buildings (Falk et al. 1999b); Williams et al. (2000) used the experimental results described in this paper to verify a finite element model developed to predict the failure of lumber with midspan holes.

The continued load-carrying capacity of reclaimed wood members has been investigated in old wood structures. Wood (1954) tested two old floor beams (white pine) from St. Raphael's Church in Madison, Wisconsin, and determined that a large horizontal check in one beam had resulted in horizontal shear that initiated failure. McAlister (1930) found that shear had initiated failure in a significant number of old Douglas-fir beams. He attributed these shear failures to horizontal checks in the old timbers. Bending tests of old bridge members by the Santa Fe Railroad (1921) indicated that most beams failed in horizontal shear and failure was initiated in the seasoning checks. Tests of small clear specimens cut from the timbers indicated that no substantial strength loss had occurred during the building's service life.

Objective

This study was initiated to meet three objectives: 1) evaluate if the industry rule on allowable hole size for cedar applies to Douglas-fir; 2) empirically determine to what extent drilled holes and a notch affect lumber bending strength; and 3) validate a finite element computer model developed to evaluate the effect of holes in timber (Williams et al. 2000). Only the results of objectives 2 and 3 are presented. Two hole sizes, three hole locations, and one notch size/location were evaluated.

Materials and methods

Materials

Initially, it was intended to test only reclaimed members. However, it was not possible to locate and purchase the sizes and number of reclaimed lumber specimens desired. For this reason, lumber fresh from a sawmill was purchased and it was assumed that the effects of drilled holes and the notch could be applied to reclaimed lumber. It was also felt that testing "new" lumber would highlight the effect of the drilled holes on beam strength by eliminating the aforemen-

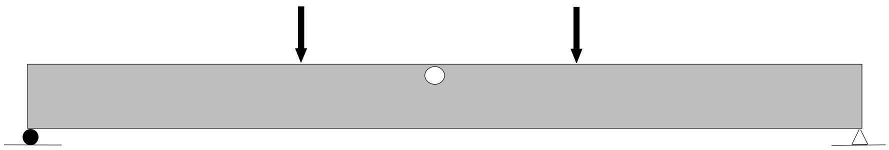

Figure 6. — Test configuration and hole layout for group H beams.

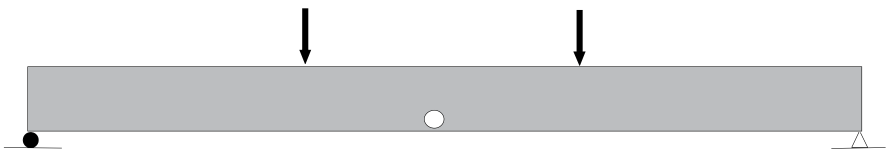

Figure 7. — Test configuration and hole layout for group I beams.

Figure 8. — Local buckling around hole in group A beam.

tioned characteristics found in reclaimed lumber (uncontrolled nail holes, drying checks, damage) that might confound test results.

To maximize the number of test specimens for the budget available, it was decided to test nominal 4- by 8-inch (actual 89- by 184-mm) Douglas-fir lumber. The lumber was purchased in Oregon and graded by West Coast Lumber Inspection Bureau (WCLIB) staff using the criteria for Select Structural grade dimension lumber (Structural Joists & Planks) to minimize the number of naturally occurring defects. After the lumber was graded, it was shipped to Bellingham, Washington, for kiln-drying. The lumber was dried to an average moisture content (MC) of 19 percent.

Tests

Before drilling holes, the lumber was segregated in seven treatment groups of like modulus of elasticity (MOE) in edgewise bending on a portable bending test machine by WCLIB staff. Forest Products Laboratory (FPL) statistical staff used this MOE data to create the seven treatment groups (22 specimens each). This resulted in an average MOE of 2.0×10^6 psi (14 GPa) for each group. Five of the groups were then drilled with 1- or 1-3/4-in. (25.4- or 44-mm) holes at mid-span in the wide face. A sixth treatment was notched, the remaining treatment was the control group. The hole layout for each beam group is given in **Table 1** and **Figures 1** through **7**.

The 1-inch (25.4-mm) hole was chosen to reflect a size of hole frequently found in reclaimed lumber. The larger 1-3/4-inch (44-mm) hole reflects the described industry rule of thumb for No.1 cedar that limits hole size to 50 percent of the maximum knot size for a given beam size and grade. For the tested lumber, a hole size reflecting a No. 2 allowable knot was used, in accordance with the knot-size limits for Douglas-fir structural joists and planks (**Table 2**).

After drilling, the lumber was shipped to FPL for laboratory testing. Bending tests to failure were performed in the FPL Engineering Mechanics Laboratory on a 1-million-pound (45,400-kg) capacity universal twin-screw testing machine under third-point edgewise bending according to ASTM D 198 (ASTM 1999). A span-to-depth ratio of approximately 21 was used. For each beam, modulus of rupture (MOR) was determined according to standard procedures. MOR data for the tested specimens were based on the ultimate load capacity, not the first failure local buckling load. Failure patterns were recorded for each beam.

Results

Failures

Failures exhibited by the lumber varied depending on the location and size of the drilled hole. **Table 3** indicates the type and frequency of failures for the beam groups. If the hole was on the compression side of the beam (Groups A and H), local buckling most often occurred above the hole (**Fig. 8**), typically followed by a load increase and general tension-side failure in the beam. When the drilled hole was on the tension side of the beam, failure typically initiated at the hole (Groups B, D, and I). Group B lumber (1 in. (25.4mm) hole, 1 in. (25.4 mm) from tension edge) exhibited a variety of failures including tension at the hole, normal wood tension, compression failure, and slope-of-grain failure. Interestingly, Group E lumber (half cir-

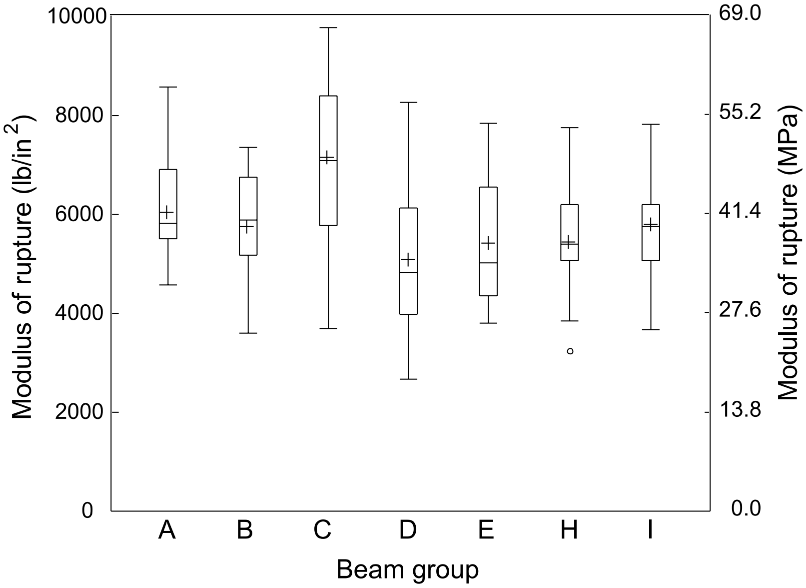

Figure 9. — Box plot of MOR data.

Table 2. — Knot limits for Douglas-fir Structural Joists & Planks per WCLIB Grade Rules No. 17.

Nominal wide-face dimension	Knot limit			
	Select Structural		No. 2	
	Wide-face	Edge	Wide-face	Edge
	(in.(mm))			
6 (140)	1-7/8 (48)	1-1/8 (29)	2-7/8 (73)	1-7/8 (48)
8 (184)	2-1/4 (57)	1-1/2 (38)	3-1/2 (89)	2-1/2 (64)
10 (235)	2-5/8 (67)	1-7/8 (48)	4-1/4 (108)	3-1/4 (83)
12 (286)	3 (76)	2-1/4 (57)	4-3/4 (121)	3-3/4 (95)

Table 3. — Failure types (% of total).

Group	Tension at hole	Compression at hole	Normal tension	Normal compression	Slope-of-grain
	(%)				
A	0	73	18	9	0
B	45	0	36	14	5
C	NA	NA	73	27	0
D	73	0	9	0	18
E	32	0	59	0	9
H	0	73	9	0	18
I	86	0	5	9	0

cle notch on tension side) only failed at the notch in 32 percent of the lumber.

Mean and ranked MOR

Ideally, the sample size would have been large enough to empirically predict the fifth percentile MOR for all the beam groups. However, the large number of specimens required to calculate this percentile with confidence was not practical within the budget allocated. For this reason, a *mean* MOR was calculated and used for part of the analysis. At the mean level, the control (group C) lumber exhibited the highest MOR, with all other groups exhibiting lower strengths (71.5% to 86.8% of control) (**Table 4**, **Fig. 9**). The weakest beam group was group D, a 1-inch (25.4-mm) hole 1/4 inch (6 mm) from the tension face, suggesting that holes closer to the tension edge reduce strength more than those further away. An analysis of variance followed by a Tukey Studentized range test indicated that the mean MOR of group C is different from all groups except group A. This analysis also indicated that the mean MOR of group A is different from group D.

The MOR values of each group were ranked to determine how the whole distribution compared to the control group (**Fig. 10**). To generate **Figure 10**, the MOR values of each group were ranked highest to lowest. The MOR of each group (ranked 1 to 22) was divided by the group C MOR values (ranked 1 to 22). As shown in **Figure 10**, all ratios of ranked MOR values that were less than 1.00 indicate lumber with strengths lower than that of the control. Overall, this figure indicates that with the exception of a few specimens at the lower end of the distributions, all specimens with holes were weaker than the control group of the same rank (in the worst case, strength was about 70% that of the control).

MOR tolerance limit

In addition to evaluating the mean and ranked MOR values, the 5th percentile Tolerance Limit (TL) value (75% confidence) of each group was estimated using the curve fitting procedures of ASTM D 5055 (ASTM 2000), Appendix X4. The estimates were based on Normal, 2-parameter Weibull, and 2-parameter Log-Normal distributions fit to the group strength values. The lowest Standard Error was obtained from the 2-parameter Log-Normal distribution (**Table 5**). The estimated 5th percentile TL values in **Table 6** indicate that two of the groups, A and B, had predicted values greater than the control group C. These results differ from those using ranking. This may be due to the influence of fluctuations in the lower tail of the distribution that can occur with smaller sample sizes or differences in the variability between the sample groups.

Significance of results

The knots in groups H and I (1-3/4-in. [45-mm] holes, 1 in. [25.4 mm] from the edge) are half the allowable size of a 4 by 8 centerline knot for Douglas-fir No. 2 grade. Both the normal and estimated 5th percentile values for these groups suggest that the 1/2-knot limit used for cedar is appropriate as grading criteria for Douglas-fir

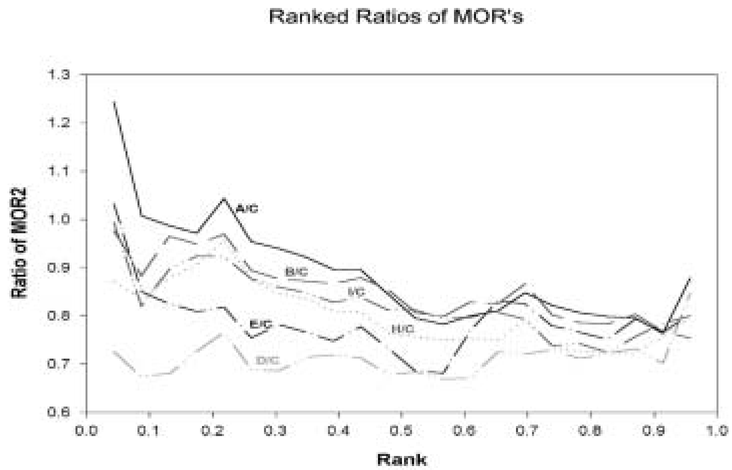

Figure 10. — Ranked ratios of MOR values.

Table 4. — Comparison of properties of specimen groups.[a]

Group	SG	RPI	MC	Mean MOR	Percentage of group C	Mean MOE
			(%)	(psi (MPa))		(10^6 psi (MPa))
A	0.47	5	20	6,060 (41.8)	86.8	2.05 (14,100)
B	0.46	5	20	5,870 (40.5)	84.1	2.02 (13,900)
C	0.48	6	18	6,980 (48.1)	100	2.04 (14,100)
D	0.48	6	19	4,990 (34.4)	71.5	2.05 (14,100)
E	0.45	5	19	5,450 (37.6)	78.1	2.05 (14,100)
H	0.46	6	19	5,510 (38.0)	78.9	2.03 (14,000)
I	0.46	6	21	5,670 (39.1)	81.2	2.04 (14,070)

[a]Each group consisted of 22 specimens. SG = specific gravity; RPI = rings per inch (25.4 mm); MC = moisture content; MOR = modulus of rupture.

Table 5. — Estimated 5th percentile TL (75% confidence) Per ASTM D 5055, Appendix X4.

Distribution group	Normal 5th percentile TL	Standard error	2P Log-Normal 5th percentile TL	Standard error	2P Weibull 5th percentile TL	Standard error
	(psi)		(psi)		(psi)	
A	5,050	0.041	5,210	0.035	5,030	0.058
B	4,740	0.037	4,850	0.036	4,570	0.046
C	4,370	0.033	4,750	0.025	4,400	0.042
D	2,760	0.039	3,180	0.023	2,940	0.043
E	3,400	0.073	3,810	0.054	3,640	0.091
H	4,170	0.050	4,320	0.057	4,070	0.052
I	4,480	0.044	4,680	0.040	4,420	0.054
Average		0.045		0.038		0.055

In groups D and E, the 1-inch (25.4-mm) holes were drilled at, or very close to, the maximum tensile stress zone. In addition to being a very common hole size in reclaimed timbers, the 1-inch (25.4-mm) hole corresponds to half the 2-inch (50.8-mm) allowable edge knot requirement for 8-inch-wide No. 1 grade lumber. The Group D/Group C and Group E/Group C ratios of the estimated mean and 5th TL equal or exceed the ratio of No. 1 F_b/ Select Structural F_b values (**Table 7**).

While Group E (1/2-in. notch in the tension face) may meet the grade requirement for Select Structural grade, under Section 3.2.3 of the National Design Specification for Wood Construction (AFPA 2001), such a notch is not permitted in the middle third of the tension face of a bending member.

Conclusions

Bending tests of 4 by 8 Douglas-fir lumber with 1- or 1-3/4-inch (25.4- or 44-mm) holes drilled in three locations at the mid-span appear to justify an allowable hole one-half the allowable knot size that is currently permitted for cedar in No. 1 Beams & Stringer grade. However, these results should be viewed with some caution due to the limited sample size, hole diameters, and hole locations evaluated. Furthermore, hole location may be more important than hole size. A 1-inch (25.4-mm) hole had about the same effect on strength as a 1-3/4-inch (44-mm) hole when the holes were 1 inch (25.4 mm) from the tension edge.-

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Table 6. — Comparison of estimated 5th percentile TL (75% confidence) values.

Group	Mean MOR,	Ratio to Group C	5th percentile TL 2P Log-Normal	Ratio to Group C
	(psi (MPa))		(psi (MPa))	
A	6,060 (41.8)	0.87	5,210 (35.9)	1.10
B	5,870 (40.5)	0.84	4,850 (33.5)	1.02
C	6,980 (48.1)	1.00	4,750 (32.7)	1.00
D[a]	4,990 (34.4)	0.71	3,180 (21.9)	0.67
E[a]	5,450 (37.6)	0.78	3,810 (26.3)	0.80
H[b]	5,510 (38.0)	0.79	4,320 (29.8)	0.91
I[b]	5,670 (39.1)	0.81	4,690 (32.4)	0.99

[a]1/2 of allowable edge knot for No. 1 grade.
[b]1/2 of allowable centerline knot for No. 2 grade.

Table 7. — Design values for bending.

Grade	Assigned F_b[a]	Ratio to SS Grade
	(psi (MPa))	
Select Structural	1,950 (13.4)	1.00
No. 1	1,300 (9.0)	0.67
No. 2	1,170 (8.1)	0.60

[a]Size-adjusted values rounded to nearest 5 psi (0.03 MPa).

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