

Shear Design Values for Glulam Member Design at Connections

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Introduction

In recent years, published design values for shear in structural glued laminated timber (glulam) have increased. While research justifies these increased design values in normal beam applications (Yeh et. al. 2001), the use of these increased design values for other applications has not been confirmed and therefore design provisions require use of shear values reduced approximately to historical levels for design of non-prismatic members, notched beams, connections, and members subject to impact or cyclic loading (AITC 117-2004, NDS[®] 2005).

Scope

This paper reviews the recent history of glulam shear values and compares current design provisions to available research related to member failure modes at connections.

Historical Shear Values

Since its initial publication in 1978, ASTM D3737 has prescribed that shear values for glulam be based on 5% exclusion limit green clear wood stresses from ASTM D2555 divided by 4.1 and multiplied by 1.13. The factor of 4.1 was intended to account for: (a) differences in duration of load between the test and normal design conditions (16/10), (b) a factor of safety (9/8), and (c) stress concentrations due to drying (9/4). The 13% increase was intended to account for a shear strength increase due to drying. The same adjustment factors were applied to solid-sawn lumber as early as 1969 (ASTM D245-69). Lumber design values were further reduced by 50% to account for the possibility of a split at the end of the piece reducing the shear capacity to half.

ASTM D3737-78 prescriptively limited shear values of Douglas Fir-Larch and Southern Pine to 165 psi and 200 psi, respectively, to be consistent with previously published values for those species. The

value of 200 psi for Southern Pine glulam was rationalized through elimination of coarse grain lumber from the laminating material (AITC “Brown Book” 1979, AITC 500-91). The value of 165 psi for Douglas Fir-Larch glulam was reached by reducing the calculated value of 194 psi by 15% based on experience and to allow for some in-service checking (AITC “Brown Book” 1979, AITC 500-91, AITC Technical Note 18, 1991). Similar reductions were not applied to other species.

Current Shear Values

Uncertainty in the 1/4.1 adjustment factor used in small shear block tests led to development of a full-scale beam shear test method (Yeh et. al. 2001, ASTM D3737-2000a). Tests of Douglas Fir-Larch, Southern Pine, and Spruce-Pine-Fir glulam beams justified publication of shear design values of 265 psi, 300 psi, and 235 psi respectively, for beam applications.

The judgment of the glulam industry was to apply increased shear values based on full-scale beam tests only to situations similar to those tested. Consequently, a 28% reduction in design values is currently applied for non-prismatic members, notched members, and all members subject to impact or cyclic loading. The reduced design value is also applied for design of members at connections (AITC 117-2004, NDS 2005). This provision reduces shear values approximately to historical levels for cases other than the static beam shear case tested.

Connection Tests for Row and Group Tear-out

Recent connection tests conducted at the USDA Forest Service Forest Products Laboratory (FPL) in conjunction with the American Wood Council (AWC) indicated that connections with closely spaced dowel fasteners could result in member failure modes not explicitly checked in the calculation of fastener yield

capacities previously required by the *National Design Specification® (NDS) for Wood Construction*. Preliminary analysis of the data led to development of equations for prediction of localized member failure modes of row and group tear-out, which were included in Appendix E of the 2001 and 2005 NDS.

The connection tests were performed on glulam members made with all L1 DF-L laminating lumber. After the connection testing, small, clear specimens were cut from undamaged portions of the members and tested to determine shear and tensile strengths of the lumber.

Connection Test Results

Test results were reported to the AWC in the final report for CRADA 01-RD-11111132-093 by Douglas Rammer of the Forest Products Laboratory. Four connection configurations were tested. Three configurations (A, B, and C, Figures 1, 2, and 3) were fabricated with tightly grouped bolts at the minimum spacing permitted by the NDS, and the fourth configuration (Configuration D, Figure 4) was fabricated with more reasonable bolt spacing.

The three connection configurations with minimum fastener spacing (A, B, and C) resulted in a group tear-out failure mode prior to fastener yielding. The fourth configuration (D) resulted in fastener yielding as predicted by NDS behavioral equations. The average failure load and coefficient of variation for each configuration are shown in Table 1.

Material Shear Strength

Average shear strength from 30 tests of small shear blocks taken from the tested specimens was 1,331 psi with a coefficient of variation (CoV) of 12.0%. The 5% tolerance limit with 75% confidence for shear parallel-to-grain strength was calculated as 1,033 psi (based on an assumed normal distribution).

Because currently published design values for glulam shear are based on full-scale beam tests, it would be useful to estimate beam-shear strength from block-shear strength data. Beam-shear tests were not conducted for this study; however, for purposes of analysis used in this paper it is approximated by comparison of published block-shear data for dry Coastal Douglas fir from ASTM D2555 ($f_{v,avg,dry,block} = 1,130$ psi, $f_{v05,dry,block} = 679$ psi) with beam-shear test data from Yeh et al. ($f_{v,avg,dry,beam} = 640$ psi, $f_{v05,dry,beam} = 555$ psi). This comparison indicates that the ratio of beam-shear strength to block-shear strength is $640/1,130 = 0.57$ on average. The ratio of fifth percentile beam-shear strength to average block-shear strength can be estimated as $555/1,130 = 0.49$.

Material Tensile Strength

Full-scale tension tests were not conducted on the material, so tensile strength cannot be precisely estimated. For purposes of analysis used in this paper, a range of design tensile strengths is approximated based on prior research and judgment. Full-scale tension tests of L1 Douglas Fir laminated timbers conducted at Oregon State University in the early 1970s (Brassell) indicated an average tensile strength of about 4,500 psi and a coefficient of variation of approximately 20% for L1 grade laminated timbers. (The tests were conducted on full-size tension specimens of laminated timbers.) A fifth percentile strength estimate for the data is approximately 3,000 psi. This value gives a design stress of $3,000/2.1$ or 1,450 psi, which is slightly lower than the current design stress of 1,600 psi for the lay-up. This data (4,500 psi on average) was judged to be a reasonable lower limit of tensile strength to analyze connection group-tear-out data. An upper limit of 6,000 psi (average tensile strength) was chosen as the maximum expected tensile strength for the material. A

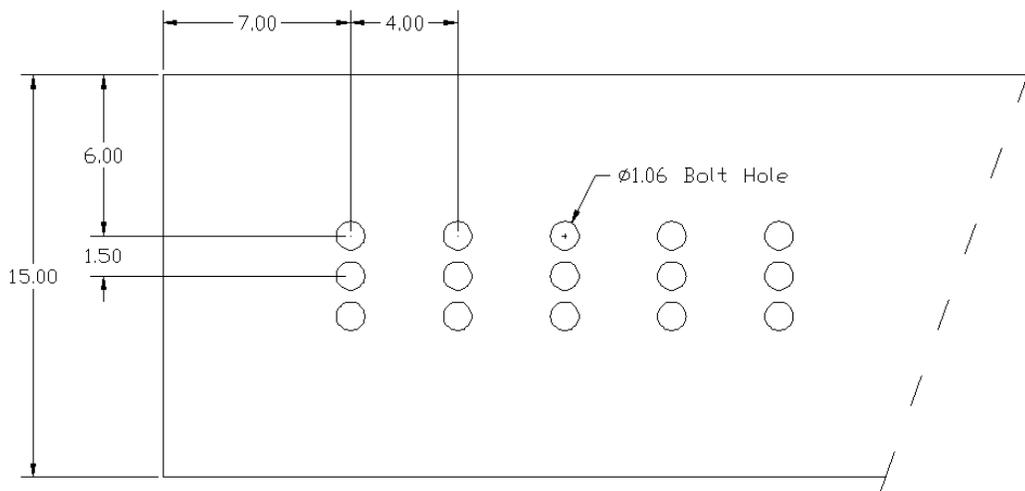


Figure 1. Configuration A: Three rows of bolts, five bolts per row.

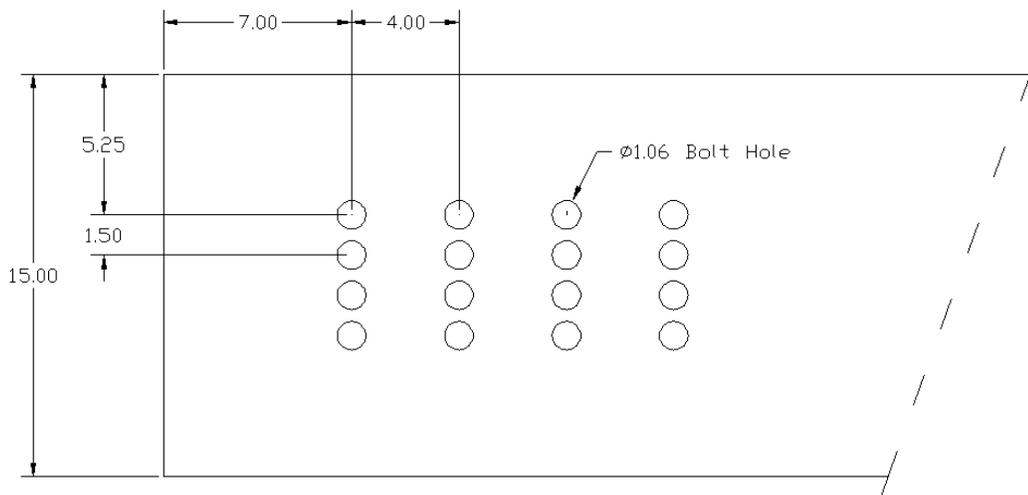


Figure 2. Configuration B: Four rows of bolts, four bolts per row.

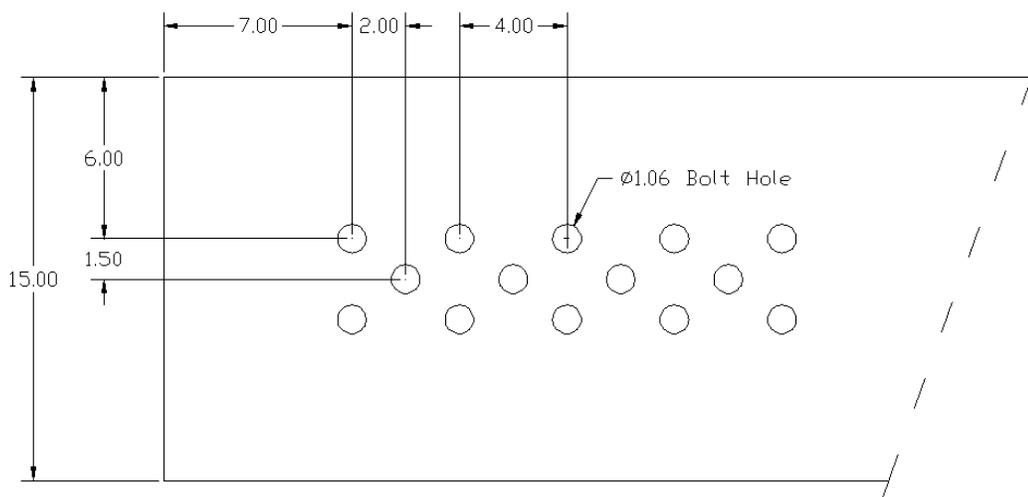


Figure 3. Configuration C: Two rows of five bolts and one row of four bolts, bolts staggered.

corresponding fifth percentile strength assuming a CoV of 20% is 4,000 psi (equivalent to a design stress of $4,000/2.1$ or 1,900 psi).

The average tensile strength of small, clear specimens taken from the tested timbers was 11,485 psi with a CoV of 28.0%. The 5% tolerance limit for clear wood strength in tension parallel to grain can be calculated as 2,607 psi (based on an assumed normal distribution). This value is 18.5% higher than the 2,200 psi clear wood strength assumed by the ASTM D3737 model for dense Douglas Fir lumber. It is unclear if this difference is due to conservatism in the D3737 model for tension or due to real differences in the strength of this material compared to published design values. Increasing published tension design value (1,600 psi) by 18.5% gives a value of 1,900 psi, which compares very well with the upper bound on tensile strength assumed for the material. Estimates for the range of tension are intentionally established to be consistent with methods for establishing the published design tensile strength of glulam to coincide with use of published design values in NDS cal-

culations for group tear-out (see Equation 1). The analysis in this paper, which concludes with a review of safety levels where allowable stresses are used in group tear-out calculations, does not attempt to model or replicate complex stress distributions in the wood at time of connection failure.

Analysis of Connection Data

Within established average tensile strength bounds for the material, the effective average shear strength of the material to resist group tear-out can be calculated by solving for the NDS group tear-out formula shear term:

$$f_{v\,avg} = \frac{P_{avg} - h_{gt}t(F_{t\,avg})}{n_t s} \quad \text{Equation 1.}$$

where:

- $f_{v\,avg}$ = average shear strength
- $f_{t\,avg}$ = average tensile strength

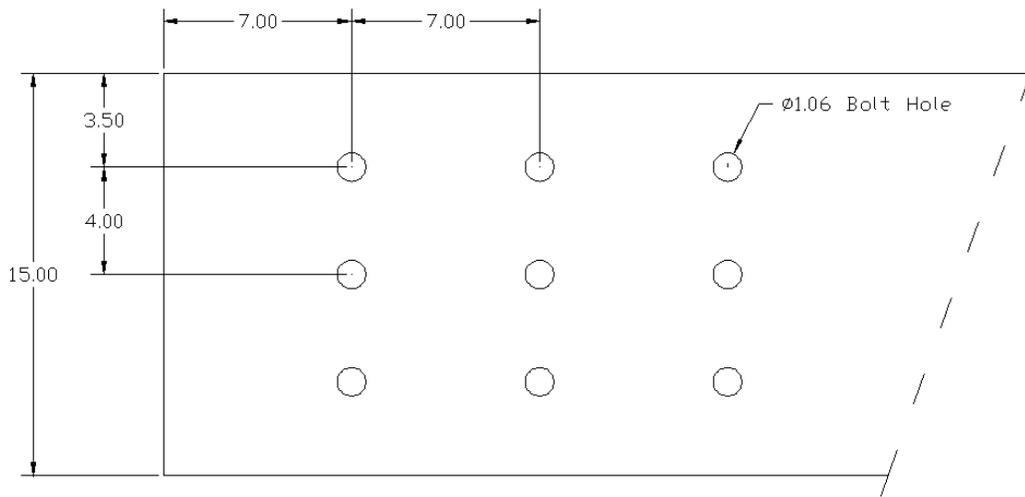


Figure 4. Configuration D: Three rows of bolts, three bolts per row.

Configuration	Number of Specimens	Average Failure Load (lb)	CoV (%)
A	5	85,600	8.0
B	5	86,700	15.8
C	5	84,500	13.0
D	1	173,000	--

Table 1. Summary of connection test results.

- P_{avg} = average connection capacity
- h_{gt} = net height of section resisting tension in group tear-out equation
- n_i = number of bolts in each outer row
- t = thickness of member
- s = spacing between bolts in a row

Using average tensile strength bounds of 4,500-6,000 psi as previously established, the required average shear strength to satisfy the NDS group tear-out equation was calculated using Equation 1. Results for each connection configuration are shown in Table 2.

These calculations indicate that the effective average shear strength for the group tear-out failure mode in the material tested is expected to be within a range of 565-650 psi (42-49% of the material's average block shear strength of 1,331 psi). Estimating that the fifth percentile beam shear strength will be 49% of the average block shear strength (as calculated previously) and the fifth percentile of connection shear will be 77% of the average connection shear strength (CoV = 14%, Wood Handbook), a factor to

adjust from beam-shear strength to effective connection shear strength can be calculated as shown below.

This calculation indicates that the effective shear strength for group tear-out is in the range of 66-77% of the shear strength established from full-scale beam tests. Applying the same calculation except using average values of strength produces values of shear strength for group tear-out in the range of 73-86% of the shear strength from full-scale beam tests. The current factor of 0.72 recommended by the glulam industry for this design case is within the range of results considering the fifth percentile estimate and conservative relative to the average estimate and appears to be reasonable.

Factor of Safety

The previous analysis does not include any factors of safety. For timber design, it is customary to further adjust the characteristic material strength value from testing by a factor of 1/2.1. The shear design value

$$(0.42) \left(\frac{1}{0.49} \right) (0.77) \leq \left(\frac{f_{v, avg, tear-out}}{f_{v, avg, block}} \right) \left(\frac{f_{v, avg, block}}{f_{v, 05, beam}} \right) \left(\frac{f_{v, 05, tear-out}}{f_{v, avg, tear-out}} \right) \leq (0.49) \left(\frac{1}{0.49} \right) (0.77)$$

$$0.66 \leq \left(\frac{f_{v, 05, tear-out}}{f_{v, 05, beam}} \right) \leq 0.77$$

Assigned Average Tensile Strength, f_t avg (psi)	Connection Configuration	Load, P_{avg} (lb)	Calculated Average Shear Strength, f_v avg (psi)
4,500	A	85,600	637
	B	86,700	686
	C	84,500	626
	Avg.	--	650
6,000	A	85,600	571
	B	86,700	562
	C	84,500	560
	Avg.	--	565

Table 2. Shear strengths calculated by Equation 1.

Connection Configuration	Load, P_{avg} (lb)	Group Tear-out Design Capacity (lb)	Factor of Safety
A	85,600	47,600	1.77
B	86,700	46,200	1.86
C	84,500	47,600	1.75
Avg.	--	--	1.79

Table 3. Group tear-out design capacities and safety factors.

for tear-out calculations in glulam can be expressed as:

$$\frac{0.66f_{v05 \text{ beam}}}{2.1} \leq F_{v \text{ tear-out}} \leq \frac{0.77f_{v05 \text{ beam}}}{2.1}$$

where:

$F_{v \text{ tear-out}}$ = shear design value for tear-out calculations

$f_{v05 \text{ beam}}$ = fifth percentile shear strength estimate from beam shear tests

A factor of safety for group tear-out failure modes in this study can be estimated by dividing measured strength of the connections by the design capacity. For this calculation, the published design tensile value of 1,600 psi was used and the design value for shear tear-out was estimated as 72% of the beam shear design value, which was estimated as 0.49/2.1 times the average value from block shear tests, yielding a value of 224 psi. With these design values, the design capacity for group tear-out was calculated and is shown in Table 3 with corresponding safety factors. The average safety factor in Table 3 increases from 1.79 to 2.11 where the published design shear value of 190 psi is used in lieu of 224 psi.

The factors of safety for estimated group tear-out capacities in this study compare favorably to the factor of safety for glulam beams in flexure. The average strength of glulam beams when tested in flexure is approximately 2.95 times published design values (Hernandez et. al., 1995). Dividing by the 10-minute load duration factor of 1.6 yields a factor of safety of 1.84 based on average flexure strength.

Summary

Based on results of full-scale connection tests and an estimated range of material tensile strengths, the effective shear strength of the material to resist group tear-out of the fasteners was determined. Ratios were calculated to relate effective shear strength for tear-out to tests of shear blocks and full-scale beams. Results indicate that shear design values for tear-out failure modes should be limited to 65-75% of the 5% tolerance limit shear design value from full-scale beam tests. The glulam industry currently recommends a factor of 0.72, which appears to be reasonable. Design values established this way are expected to provide a factor of safety for group tear-out similar to the factor of safety for glulam beams in flexure.

Shear design values for solid-sawn lumber are currently determined following different procedures

than glulam. The values are generally lower than those published for beam design in glulam and are similar to reduced values used for glulam connection design. Based on this relationship, published shear values for lumber appear to be reasonable for calculation of tear-out failure modes, provided that splits are not present at the connection.

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