Is Your Wood Connection All Stressed Out? – It Needn't Be!

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Abstract

Questions from designers periodically arise regarding application of provisions in the *National Design Specification® (NDS®) for Wood Construction* for multiple fastener connections. This article looks at specific provisions in the *NDS* that have been clarified in the *2001 NDS* to address design of multiple fastener joints. A new *NDS* appendix, *Appendix E: Local Stresses in Fastener Groups*, provides one design approach.

Introduction

In a fastener group composed of closely-spaced fasteners loaded parallel to grain, the capacity of the fastener group may be limited by wood failure at the net section or tear-out around the fasteners caused by local stresses. More importantly, wood failures can occur at relatively low capacities when compared to the fastener strength. By increasing the spacing between the fasteners as shown in Figure 1, higher capacity can be achieved, even with fewer fasteners.

The newly released *2001 Edition of the National Design Specification (NDS) for Wood Construction* contains clarified provisions for checking stresses in members at connections. One method for determining these stresses is provided in *NDS* Appendix E. All referenced sections and design values used in sample solutions of the Appendix and this paper are based on information in the *2001 NDS*. However, concepts outlined in *2001 NDS* Appendix E are also applicable when designing connections in accordance with prior editions of the *NDS*.

NDS Appendix E provides detailed examples of allowable stress checks for three failure modes:

- net section tension capacity,
- row tear-out capacity, and
- group tear-out capacity.

Net Section Tension Capacity

Net section tension capacity describes tensile failure through the cross-section of the member (Fig. 2). Bolt holes reduce the member cross-sectional area.

The allowable tension capacity is calculated in accordance with provisions of *2001 NDS* sections 3.1.2 and 3.8:

$$Z_{NT}{}' = F_t{}' A_{net} \qquad \text{[E.2-1]}$$

where:

Z_{NT}' = allowable tension capacity of net section area
F_t' = allowable tension design value parallel to the grain
A_{net} = net section area per NDS 2001 3.1.2

Row Tear-Out Capacity

Row tear-out describes tear-out of fastener rows through the end of the member (Fig. 3). This may occur when fasteners are placed close to the end of the member and fasteners in the row are closely spaced.
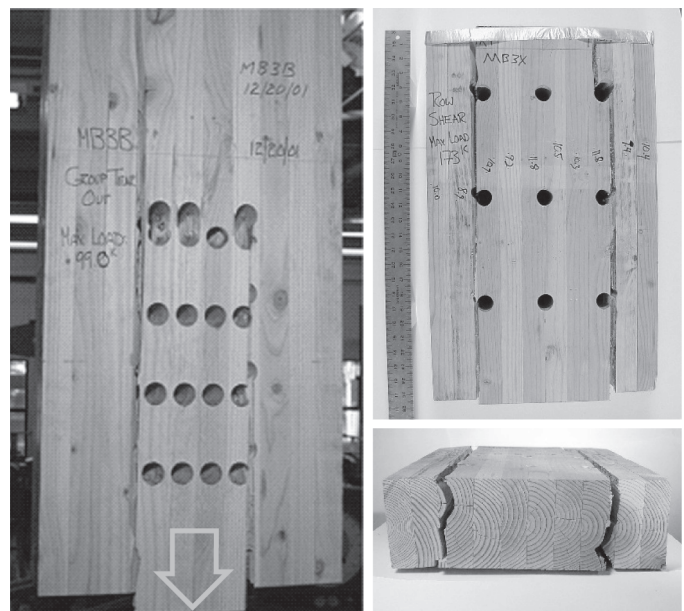

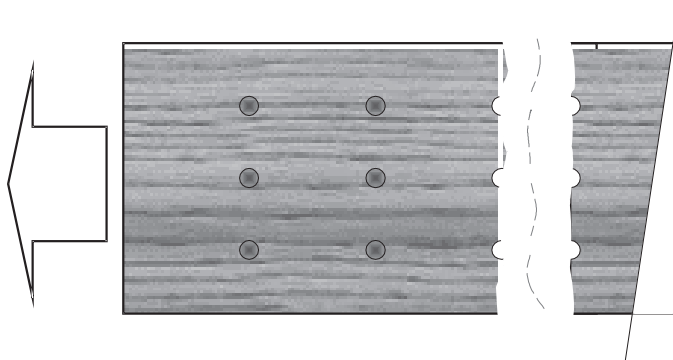**Figure 1.**—Higher connection capacities can be achieved with increased fastener spacings.
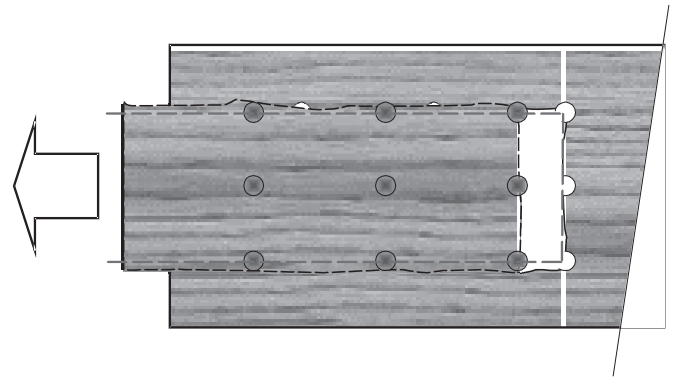
Figure 2.—Net section failure mode.

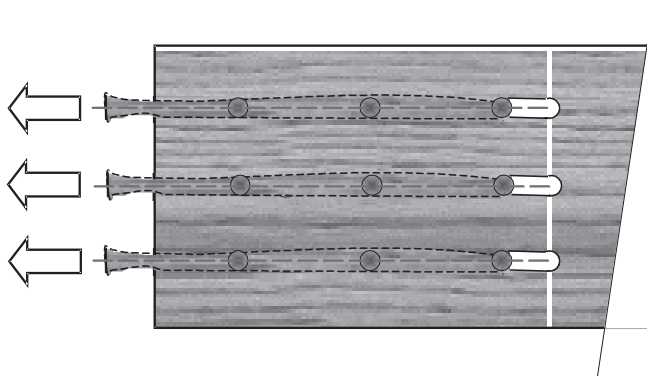**Figure 4.**—Group tear-out failure mode.

Figure 3.—Row tear-out failure mode.

The allowable tear-out capacity of a row of fasteners can be estimated using provisions of *NDS* Appendix E:

$$Z_{RT_i}{'} = n_i \frac{F_v{'} A_{critical}}{2}$$
[E.3-1]

where:

$Z_{RT_i}{'}$ = allowable row tear out capacity of row i

Fv' = allowable shear design value parallel to grain

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

n_i = number of fasteners in row i

Assuming one shear line on each side of bolts in a row (observed in tests of bolted connections and shown in Fig. 2), Equation E.3-1 becomes:

$$Z_{RT_i}{'} = \frac{F_v{'} t}{2} \left[n_i s_{critical} \right] (2\ shear\ lines)$$

$$= n_i F_v{'} t s_{critical}$$
[E3-2]

where:

$s_{critical}$ = minimum spacing in row i taken as the lesser of the end distance or the spacing between fasteners in row i

t = member thickness

The total allowable row tear-out capacity of multiple rows of fasteners can be estimated as:

$$Z_{RT}{'} = \sum_{i=1}^{n_{row}} Z_{RT_i}{'}$$
[E.3-3]

where:

$Z_{RT}{'}$ = allowable row tear out capacity of multiple rows

n_{row} = number of rows

Group Tear-Out Capacity

Group tear-out (Fig. 4) describes the tear-out of a "plug" of wood bounded by the fastener group.

In Appendix E, the allowable tear-out capacity of a group of "*n*" rows of fasteners is estimated as:

$$Z_{GT}{'} = \frac{Z_{RT-1}{'}}{2} + \frac{Z_{RT-n}{'}}{2} + F_t{'} A_{group-net}$$
[E.4-1]

where:

$Z_{GT}{'}$ = allowable group tear-out capacity

$Z_{RT-1}{'}$ = allowable row tear-out capacity of Row 1 of fasteners bounding the critical group area

$Z_{RT-n}{'}$ = allowable row tear-out capacity of Row n of fasteners bounding the critical group area

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

For groups of fasteners with non-uniform spacing between rows of fasteners, various definitions of critical group area should be checked for group tear-out in combination with row tear-out to determine the allowable capacity of the critical section.

Shear Distribution Between Bolts in a Row

In Equation E.3-1 for row tear-out, it is assumed that the induced shear stress varies linearly from a maximum value of $f_v = F_v{'}$ to a minimum value of $f_v = 0$ along each shear line between fasteners in a row. The resulting triangular stress distribution (Fig. 5) between fasteners in a row establishes an apparent shear stress equal to half of the design shear stress, $F_v{'}/2$, as shown in Equation E.3-1. This assumption is combined with use of the minimum shear area of any fastener in a row for evaluating stresses in fastener groups and

Figure 5.—Assumed induced shear distribution between bolts in a row.

provides good agreement with results from tests of bolted connections.

Minimum Shear Area

For calculation of row tear-out capacity and group tear-out capacity, use of the minimum shear area of any fastener in a row is based on the assumption that the smallest shear area between fasteners in a row will limit the capacity of the row of fasteners. Limited verification of this approach is provided from tests of bolted connections.

Allowable Shear Stress

In the *2001 NDS Supplement,* tabulated shear design values for sawn lumber are generally 1.95 times higher than values printed in the 1997 edition in response to revised methods for deriving and adjusting design values in ASTM D 245. Increases in values of tabulated shear stress were coupled with the removal of the shear strength increase factor, C_H, which previously permitted shear design values to be increased by a factor of up to 2.0 based on limited occurrences of splits, checks, and shakes. Design examples in this paper and *NDS* Appendix E use these higher tabulated shear stresses in calculations to evaluate member strength at connections. A more comprehensive review of *2001 NDS* changes related to shear can be found in Line *et al.*

Timber Rivets and Small Diameter Fastener Connections

Tabulated nominal design values for timber rivet connections in *NDS* Chapter 13 account for local stress effects in wood and do not require further modification by procedures outlined in *Appendix E*. Further, limited evaluation of connections with groups of smaller diameter fasteners, such as typical nailed connections in wood-frame construction suggest that these connections may not be limited by wood capacity.

Detailing Tips

Modification of fastener placement within a fastener group can be used to increase row tear-out and group tear-out capacity limited by local stresses around the fastener group. Increased spacing between fasteners in a row is one way to increase row tear-out and group tear-out capacity. Increased spacing between rows of fasteners is one way to increase group tear-out capacity.

In a related issue, footnote 2 to *2001 NDS* Table 11.5.1D limits spacing between outer rows of fasteners paralleling the member on a single splice plate to 5 inches. This requirement is imposed to limit local stresses resulting from shrinkage of wood members. When special detailing is used to address shrinkage, such as the use of slotted holes, the 5-inch limit can be adjusted.

Appendix E Calculation Examples

To show application of the Appendix E provisions, calculation examples follow for various connection types. In each example, the group action factor, C_g, is set to 1.0 for trial design. Note that final design using multiple fastener connections involves calculation of C_g in accordance with *2001 NDS* 10.3-6, in addition to the Appendix E connection member strength calculation. See AWC eCourse DES110 under Outreach/eCourses at www.awc.org for a detailed example of how to perform the C_g calculation.

Example 1: Staggered Bolts

Calculate the net section area tension, row tear-out, and group tear-out allowable design capacities for the double-shear bolted connection in Figure E1.
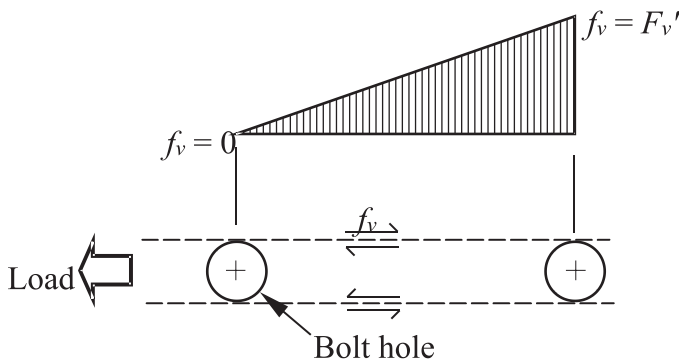

Figure E1.—Staggered bolt example.

Hole diameter $D_h = {}^9/_{16}"$

$t = 1^1/_2"$

$d = 3^1/_2"$

$-7\,D\!-\!\!-4\,D\!-\!\!-4\,D\!-$
(3.5")　(2")　(2")　　$S_{crit} = 2"$

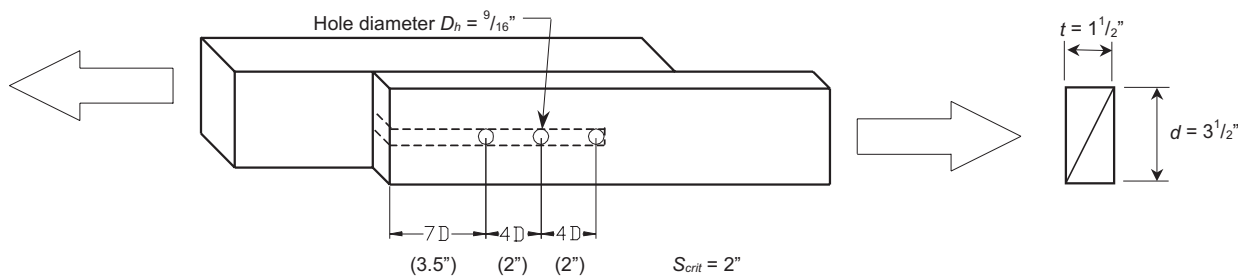**Figure E2.**—Row of bolts example.

Main Member:

Combination 3 Douglas fir 3-1/8 × 12 glued laminated timber member

$F_t' = 1,450$ psi
$F_v' = 240$ psi

Main member thickness, t_m:　　3.125 inches
Main member depth, d:　　12 inches

Side Member:

A36 steel plates on each side
Side plate thickness, t_s:　　0.25 inches

Connection Details:

Bolt diameter, D:　　1 inch
Bolt hole diameter, D_h:　　1.0625 inches
Allowable bolt design value, $Z_\parallel'$: 4,380 lb. (See *NDS* Table 11I. For this trial design, the group action factor, C_g, is taken as 1.0)
Spacing between rows: $s_{row} = 2.5D$

Connection Capacity Limit States:

Allowable Connection Capacity, $nZ_\parallel'$:

$$nZ_\parallel' = (8 \text{ bolts})(4,380 \text{ lb.}) = 35,040 \text{ lb.}$$

Allowable Net Section Tension Capacity, Z_{NT}':

$$Z_{NT}' = F_t' t[d - n_{row}D_h]$$

$$Z_{NT}' = (1,450 \text{ psi})(3.125 \text{ in.})[12 \text{ in.} - 3(1.0625 \text{ in.})]$$
$$= 39,930 \text{ lb.}$$

Allowable Row Tear-out Capacity, Z_{RT}':

$$Z_{RT}' = n_i F_v' ts_{critical}$$

$Z_{RT\text{-}1}' = 3(240 \text{ psi})(3.125 \text{ in.})(4 \text{ in.}) = 9,000 \text{ lb.}$
$Z_{RT\text{-}2}' = 2(240 \text{ psi})(3.125 \text{ in.})(4 \text{ in.}) = 6,000 \text{ lb.}$
$Z_{RT\text{-}3}' = 3(240 \text{ psi})(3.125 \text{ in.})(4 \text{ in.}) = 9,000 \text{ lb.}$

$$Z_{RT}' = \sum_{i=1}^{n_{row}} Z_{RT_i}' = 9,000 + 6,000 + 9,000 = 24,000 \text{ lb.}$$

Allowable Group Tear-out Capacity, Z_{GT}':

$$Z_{GT}' = \frac{Z_{RT-1}'}{2} + \frac{Z_{RT-3}'}{2} + F_t' t\left[(n_{row} - 1)(s_{row} - D_h)\right]$$

$$Z_{GT}' = (9,000 \text{ lb.})/2 + (9,000 \text{ lb.})/2 +$$
$$(1,450 \text{ psi})(3.125 \text{ in.})[(3\text{-}1)(2.5 \text{ in.} - 1.0625 \text{ in.})]$$
$$= 22,030 \text{ lb.}$$

In this sample calculation, the connection capacity is limited to 22,030 lb. by group tear-out, Z_{GT}'. This example uses an allowable shear design value, $F_v' = 240$ psi, to check row tear-out and group tear-out. Shear design values for other conditions such as notched members, non-prismatic members and bending members at connections are to be reduced in accordance with provisions outlined in the *NDS*.

Example 2: Row of Bolts

Calculate the net section area tension and row tear-out allowable design capacities for the single-shear single-row bolted connection represented in Figure E2.

Main and Side Members:

#2 grade Hem-Fir 2×4 lumber
$F_t' = 788$ psi
$F_v' = 145$ psi

Main member thickness, t_m:　　3.5 inches
Side member thickness, t_s:　　1.5 inches
Main and side member depth, d:　3.5 inches

Connection Details:

Bolt diameter, D:　　1/2 inch
Bolt hole diameter, D_h:　　0.5625 inches
Allowable bolt design value, $Z_\parallel'$:
$Z_\parallel' = 550$ lb. (See *2001 NDS* Table 11A. For this trial design, the group action factor, C_g, is taken as 1.0)

Connection Capacity Limit States

Allowable Connection Capacity, $nZ_\parallel'$:

$$nZ_\parallel' = (3 \text{ bolts})(550 \text{ lb.}) = 1,650 \text{ lb.}$$

Allowable Net Section Area Tension Capacity, Z_{NT}':
$$Z_{NT}' = F_t' t[d - n_{row}D_h]$$
$$Z_{NT}' = (788 \text{ psi})(1.5 \text{ in.})[3.5 \text{ in.} - 1(0.5625 \text{ in.})]$$
$$= 3,470 \text{ lb.}$$

Allowable Row Tear-out Capacity, ZRT′:

$$Z_{RT_i}' = n_i F_v' ts_{critical}$$

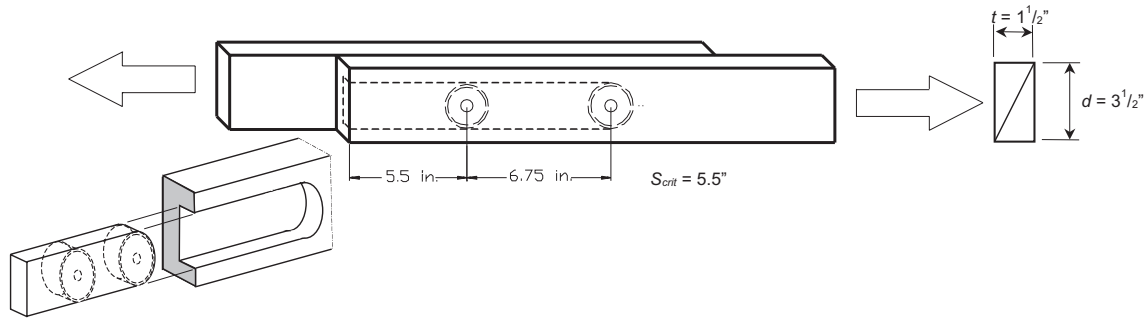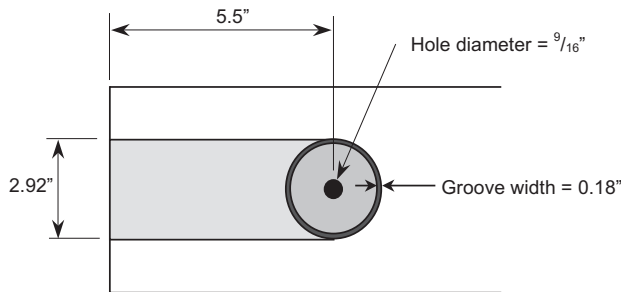$$Z_{RT1}' = 3(145 \text{ psi})(1.5 \text{ in.})(2 \text{ in.}) = 1,310 \text{ lb.}$$

Figure E3.—Row of bolts example.

$$A_{loaded-end} = (5.5")(2.92") + \frac{1}{2}\pi\left(\frac{2.92"}{2}\right)^2 = 19.41$$

$$A_{groove} = \pi\left[\left(\frac{2.92"}{2}\right)^2 - \left(\frac{2.92"-0.18"-0.18"}{2}\right)^2\right] = 1.55$$

$$A_{bolthole} = \pi\left(\frac{0.625"}{2}\right)^2 = 0.2485$$

$$A_{critical} = A_{loaded-end} - A_{groove} - A_{bolthole} = 17.61 \text{ in}^2$$

Figure E4.—Determination of split ring critical shear area.

In this sample calculation, the connection capacity is limited to 1,310 lb. by row tear-out, Z_{RT}'.

Example 3: Row of Split Rings

Calculate the net section area tension and row tear-out allowable design capacities for the single-shear, single-row split ring connection represented in Figure E3.

Main and Side Members:

#2 grade Southern Pine 2×4 lumber
$F_t' = 825$ psi
$F_v' = 175$ psi
Main member thickness, t_m: 1.5 inches
Side member thickness, t_s: 1.5 inches
Main and side member depth, d: 3.5 inches

Connection Details:

Split ring diameter, D: 2.5 inch
(See *NDS Appendix K* for connector dimensions)
Allowable split ring design value, P':

$P' = 2,730$ lb. (See *2001 NDS* Table 12.2A. For this trial design, the group action factor, C_g, is taken as 1.0)

Connection Capacity Limit States

Allowable Connection Capacity, nP':

$$nP' = (2 \text{ split rings})(2,730 \text{ lb.}) = 5,460 \text{ lb.}$$

Allowable Net Section Area Tension Capacity, Z_{NT}':
$$Z_{NT}' = F_t'A_{net}$$
$$Z_{NT}' = F_t'(A_{2x4} - A_{hole} - A_{groove})$$

$$Z_{NT}' = (825 \text{ psi})[5.25 \text{ in.}^2 - 1.5 \text{ in. } (0.5625 \text{ in.}) - 1.1 \text{ in.}^2] = 2,728 \text{ lb.}$$

Allowable Row Tear-out Capacity, Z_{RT}':

$$Z_{RT_i}' = n_i \frac{F_v' A_{critical}}{2}$$

$Z_{RT1}' = [(2 \text{ connectors})(175 \text{ psi})/2] \times [(2 \text{ shear lines})(0.375 \text{ in.})(5.5 \text{ in.}) + (1 \text{ shear line})(17.6 \text{ in.}^2)] = 3,802 \text{ lb.}$

The critical shear area for the split ring is based on assumed failure lines and includes the loaded end shear area, equal to 17.6 in.^{2} (see Fig. E4 for calculation), and the area of 2 shear lines, one on each side of the split ring. Assumed shear areas are calculated based on split ring dimensions provided in *NDS* Appendix K. The loaded end shear area is shown in Figure E4 and is calculated as the total area bounded by the outside of the split ring minus the area of the split ring groove and the bolt hole. For shear lines on each side of the split ring, the shear area is based on half the width of the split ring, or 0.375 in.

In this sample calculation, the connection capacity is limited to 2,728 lb. by net section area tension capacity, Z_{NT}'.

Summary

Detailing a multi-fastener connection in wood can be tricky, especially for large-diameter fasteners that are capable of individually transferring large loads to the wood. Increasing spacing between fasteners in a row or between rows of fasteners are ways to limit overstressing wood members at a connection. More capacity with fewer fasteners can be obtained when increased spacing is provided. New *Appendix E* provisions in the *2001 NDS* gives specific guidance for design of wood members at connections. Three stress checks: net section tension, row tear-out, and

group tear-out can be used to evaluate the viability of the fastener placement pattern designed. These checks are in addition to typical methods for determining the strength of individual fasteners or fastener groups.

References

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AF&PA. 2001. ANSI/AF&PA NDS 2001 National Design Specification (NDS) for Wood Construction. American Forest & Paper Association, Inc., Washington, DC.

Line, P., R.J. Taylor, J.H. Showalter, and B.K. Douglas. 2002. Changes in the 2001 NDS for Wood Construction. Frame Building News. Krause Publications, Inc., Iola, WI (14:4:30-35) [also reprinted in this issue].

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