Development of Failure Mechanisms for Fasteners in the United States

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Summary

In the 2001 National Design Specifications® for Wood Construction (NDS), Appendix E was added to explicitly address wood failure mechanisms that may occur in fasteners. One approach to estimate design capacities for net section, row tear out, and group tear failure mechanisms is presented in Appendix E of the 2001 NDS. Since the 2001 NDS, efforts are being untaken to further develop the specification to include a possible splitting mechanism and to address the possible failure mechanisms for connections loaded perpendicular to the wood grain.

This paper will discuss efforts to further develop the Appendix E expressions to include the splitting failure mechanisms and evaluate the effectiveness of Appendix E expressions to establish reliable design capacities for single and multiple bolted connections loaded parallel to the grain. This will be accomplished by comparing design expressions to select fastener research conducted worldwide over the last 70 years.

1. Introduction

Since 1991, multiple-bolted connections have been designed based on the yield model for a single bolt along with a group action factor. Prescriptive spacing requirements such as end distance and spacing between bolts and row limited permissible connection geometries. Testing, using the largest diameter bolts and minimum spacing requirement permitted by the NDS, indicated that use of prescriptive spacing requirements alone, without wood limit states checks, are inadequate to assure a yield mode before wood failure (Rammer 2002).

In the 2001 NDS, Appendix E provides a method to calculate three possible failure modes for a connection loaded in tension parallel to grain to address this concern. The possible failure modes discussed include net tension, row shear out, and group tear out. In an effort to evaluate the effectiveness of these expressions, the paper will compare the experimental results of select connection parallel to grain research results to values calculated by both Appendix E and yield model expressions.

2. Fastener Design Criteria

Specifications for wood construction are constantly being modified and updated. One significant area under revision is the design criteria dealing with fasteners. A brief discussion of the current design approach, based on Chapter 10 and 11 of the 2005 NDS (2005), for multiple fasteners followed by Appendix E expressions for net tension, row shear-out, and group tear-out capacity is presented

2.1 Fastener Design Criteria

The adjusted allowable stress design capacity of a multiple bolted connection loaded parallel to grain (Z') is determined using the single fastener yield connection value (Z), duration of load factor (C_D), wet service factor (C_M), group action factor (C_g), and number of bolts within the connection (n) in the following expression:

$$Z' = nC_D C_M C_g Z \qquad [1]$$

In general the design of the multiple bolted connection focuses on the single –fastener yield performance, group action or load distribution factor, and the prescriptive spacing requirement. Separate calculations evaluate the limit states of net section tension, row tear-out, and group tear-out.

2.1.1 Single-fastener yield performance- The nominal single-fastener yield connection value is dependent on the joint geometry (thickness of main and side members), bolt diameter, dowel bending-yield strength, dowel-bearing strength, and direction of load to the grain. Yield expressions relating these parameters were developed by Johansen (1949) using a static analysis that assumes the wood and the bolt are both perfectly plastic. The yield model theory selects the worst case of yield modes based on different possibilities of wood bearing and dowel bending. Mode I is a wood-bearing failure in either the main or side member; mode II is a rotation of the fastener in the joint without bending; modes III and IV are a combination of wood-bearing failure and one or more plastic hinge yield formations in the fastener. Illustrations of these modes for a single shear and double shear connection is shown in Figure 1.

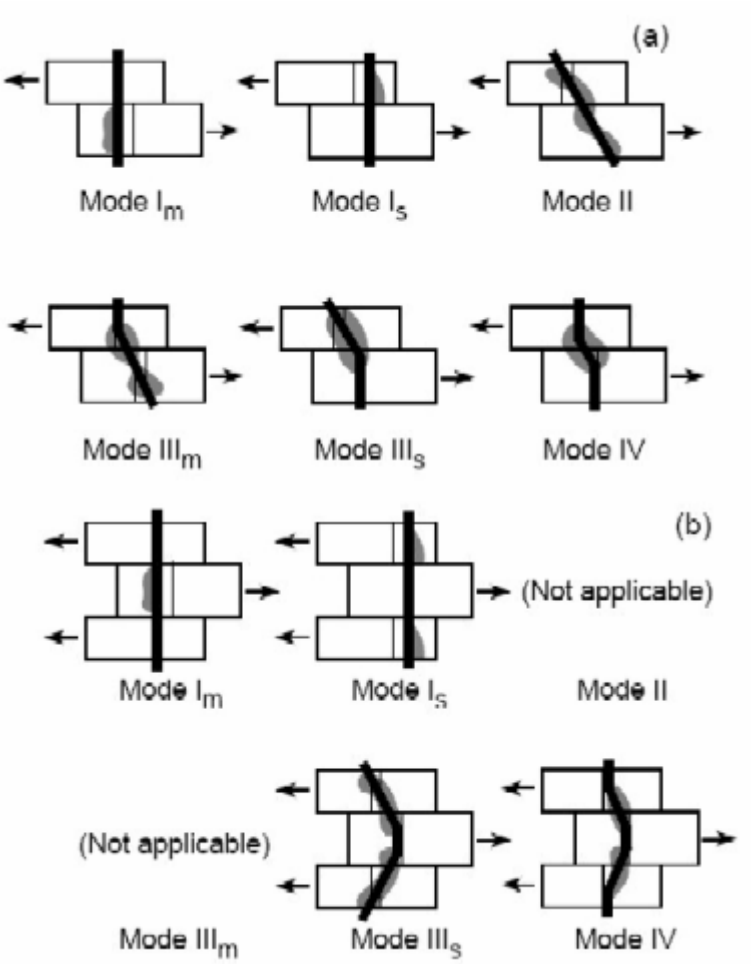

Figure 1. Possible yield modes for (a) single and (b) double shear connections.

2.1.2 Load distribution factor-When fasteners are used in rows parallel to the direction of loading, total joint load is unequally distributed among fasteners in the row. Simplified methods of analysis have been developed to predict the load distribution among the fasteners in a row. These analyses indicate that the load distribution is a function of (a) the extensional stiffness of the joint members, (b) the fastener spacing, (c) the number of fasteners, and (d) the single-fastener load deformation characteristics. Specific details of the load distribution factor (C_g) can be found in Chapter 10 of the

NDS. Note, the elastic assumptions of the load distribution factor are not applicable when trying to predict wood limit states. At the wood limit stress, localize crushing should result in a more even distribution of the loads to the fasteners.

2.2 Failure Mechanisms

Test results that probed the lower limits of the prescriptive spacing requirements led to explicit language to require calculation of the wood failure limit states for dowel fasteners loaded parallel to grain. Expressions for net tension, row tear-out, and group tear-out are as follows:

$$Net\ tension: \quad Z_{NT}' = F_t' A_{net} \qquad [2]$$

$$Row\ tear-out: \quad Z_{RT_i}' = n_i \frac{F_v' A_{critical}}{2} \qquad [3]$$

$$Z_{RT}' = \sum_{i=1}^{n_{row}} Z_{RT_i}' \qquad [4]$$

$$Group\ tear-out: \quad Z_{GT}' = \frac{Z_{RT-1}'}{2} + \frac{Z_{RT-n}'}{2} + F_t' A_{group-net} \qquad [5]$$

where Z_{NT}' = adjusted tension net section capacity, Z_{RT}'= adjusted row tear out capacity of multiple rows, Z_{GT}'= adjusted group tear-out capacity, F_t'= adjusted tension parallel to grain design value, A_{net}= net section area, Z_{RT_i}' = adjusted row tear out capacity of row i, n_i = number of fasteners in row i, F_v'= adjusted shear parallel to grain design value, $A_{critical}$= minimum shear area of any fastener in row i, Z_{RT-1}'= adjusted row tear-capacity of row 1 of fasteners bounding the critical group area, Z_{RT-n}'= adjusted row tear-capacity of row n of fasteners bounding the critical group area net section area, and $A_{group-net}$ = critical group net section area between row 1 and row n. Note adjusted shear values from the 2005 NDS Supplement for glued laminated timber must be modified by 0.72 when used in connection design since these shear values are applicable to design of prismatic beams. This adjustment brings glued-laminated shear values for connection design to levels comparable to those for dimension lumber. Expressions assume the stress through the depth of the member is uniform, and the shear stress (row tear-out and group tear-out) between bolts in a row is a triangular distribution. The maximum shear stress occurs on the bearing side of the bolt hole.

3. Fasteners Studies – Tension Parallel to Grain

For evaluation of the effectiveness of the Appendix E expression, previous research studies on both single and multiple fasteners are used. For this evaluation, 16 documented studies generated from various research institutions since 1921 are used. This is not a complete listed of all tension parallel to grain tests conducted since 1921 but, it represents studies for which all the significant material properties and geometrical connection parameters of both the main and side members are available. This information is needed for the determination of both the yield loads and wood failure mechanisms. In some cases, the ultimate connection wood failure mode was identified in the studies, but this documentation did not restrict the use of any data set.

Table 1 lists a reference to the publication, material, bolt diameters, row spacing, bolt spacing, end spacing, and the total number of connection patterns for all of the selected studies. For row, bolt, and end spacing, the value in the table is the ratio of the actual spacing to the bolt diameter for the given configuration.

The types of joints varied from single bolted to multiple bolt connections. Six studies contained single bolts in tension (Wilson, 1921; McLain, 1981; Wilkinson 1992; Windorski and others 1997, Daudeville and others 1999, and Sawata and Yasumura 2003). Three studies focused specifically on a single row of bolts with different bolt spacing, end spacing and member thickness (McLeod 1951, Ely and McLeod 1943, and Jorissen 1998). Finally, the remaining eight studies investigated mostly bolted connections having multiple rows of bolts (Soltis and Font 1997, Rammer 2002, Quenneville and Mohammad 2000, Massé and others, 1988, Doyle 1964, Vermeydem 1963, and Scholten 1958).

Ref. No.	Material	Bolt dia. (mm)	Ratio of spacing to bolt dia. Row	Bolt	End	No. of joint patterns
[18]	So. Pine	25.4	—	—	3, 4, 5, 6	12
[11]	S-P-F	12.7	—	3, 4.5, 6, 7.5	3, 4.5, 6, 7.5	13
[7]	S-P-F	12.7	—	4.5, 6, 7.5	4.5, 6, 7.5	10
[14]	D.F.	19.1	1.6, 2, 2.9	4, 8, 12	7, 8, 12.7	9
[16]	Norway Spruce	12.7 19.1	4	7	7	10
[6]	D. Fir Glulam	12.7 19.1	4, 6	4, 6, 9	7, 10.5	6
[10]	So. Pine	12.7	—	—	12	8
[9]	D. Fir & S-P-F Glulam	19.1	2, 3	4, 6.7	7, 10	10
[17]	D. Fir Glulam	12.7 19.1 25.4	—	—	7.5	12
[13]	D. Fir	19.1	2.5, 4	4	7	6
[19]	S-P-F	25.4	—	—	7	1
[8]	Norway Spruce	10.6 11.3 11.8	—	3.1, 5.1, 5.3, 7.2, 7.5, 7.9, 11.2, 12.4	5.1, 5.3, 7.2, 7.5, 7.9	31
[5]	Spruce	8.3 12.4, 15.9 19.1	—	—	2.5, 4, 7, 10	19
[15]	D. Fir & S-P-F Glulam	12.4, 19.1	3, 4.5, 5, 7.5	4, 5, 7, 7.5, 10, 15	3, 7, 10, 15	39
[2]	D. Fir	25.4	1.5, 4	4, 7	7	4
[12]	S-P-F	15.9	—	—	7	7

Table 1. Summary of joints used in analysis of the NDS fastener design criteria using Appendix E Expressions

Information not included in Table 1 but documented in the original reports was the side and main member size along with the specific gravity of the wood material. For example, Wilkinson (1992) joints varied in main member thickness to achieve specific L/D ratios.

In summary, 197 total connection patterns consisting of 64 single fasteners connections, 65 connection patterns with one row of bolts, and 68 connection patterns with multiple row of bolts were used in this comparison.

5. Comparison Fastener Design Criteria with Experimental Results

Average experimental loads were compared with 2005 NDS adjusted bolted connection design values (Z'), and average experimental loads were compared the minimum of the adjusted bolted connection or the wood limit states design values (Z', Z_{NT}, Z_{RT}, Z_{GT}).

Adjusted bolted connection design values, (Z'), were calculated using provisions of NDS Chapter 11 including the application of the group action factor. Calculations used an assumed bolt bending yield strength of 310 MPa (45,000 lbf/in^2), dowel bearing strengths obtained through the specific gravity-dowel bearing relationships in the NDS, and a 1.6 duration of load factor to adjusted 10 year design values to 10-minute loading predictions.

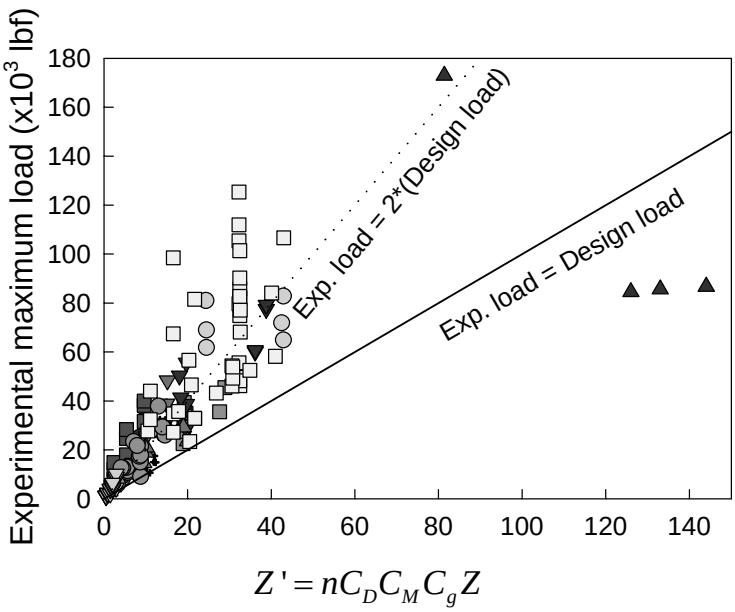

Figure 2. Comparison of experimental failure loads to minimum of the design load calculated by Chapter 11 of the 2005 National Design Specification.

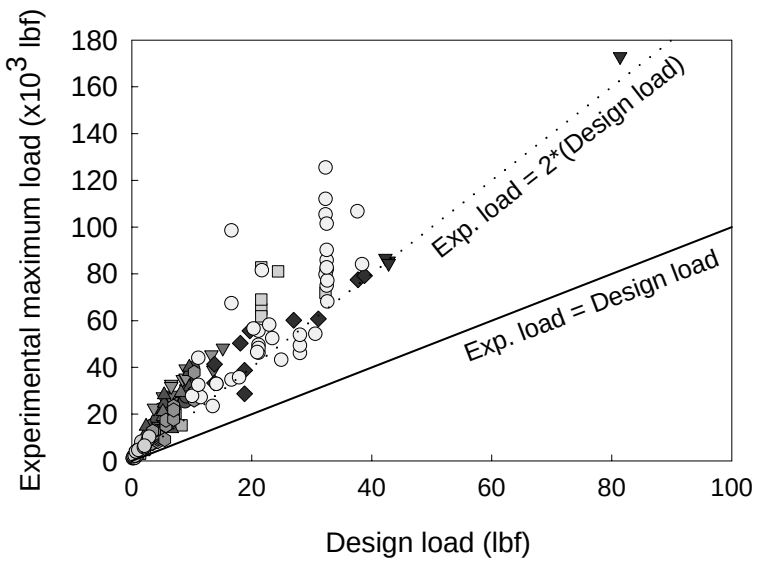

Figure 3. Comparison of experimental failure loads to minimum of the design load calculated by Chapter 11 or Appendix E equations of the 2005 National Design Specification.

Figure 2 shows a plot of the adjusted design values calculated by Chapter 11 expression versus maximum experimental joint loads for all 197 joints. These design loads lead to a ratio of maximum joint load to design load that ranged between 0.60 and 6.17 with an average ratio of 2.39.

Four joints did not have a ratio greater than 1, indicating the tested joints did not achieve the adjusted design load level (Z'). Three of the joints that did not achieved Z' had the minimum row spacing allowed by the NDS, 1.5D. The other joint was a single row of four bolts with both an end and bolt spacing of 3D. A spacing lower than the NDS minimum for full design load

Approximately 36% of the joints had a ratio lower than 2 indicating a relatively low margin of safety for many test configuration.

To compare the effectiveness of using the minimum design connection loads, obtained by Chapter 11 or Appendix E expressions, the minimum design load versus maximum joint load is plotted in Figure 3. Shear (F_v) and tension parallel to grain (F_t) design values were taken from the 2005 NDS Supplement for the specific lumber species or glued laminated timber combination under consideration. If the material did not have a species grouping in the NDS the nearest species grouping based on specific gravity was used. For glued-laminated timber combinations, equivalent stress class design values were used.

In general these design loads lead to a ratio of maximum joint load to design load that ranged between 1.52 and 6.33 with an average ratio of 3.17. Based on the average ratios, use of Appendix

E expression increase the margin of safety by 32% while not significantly increasing maximum joint failure load to design load ratio. Approximately 7% of the joints had a ratio lower than 2 and 7% of the joints had a ratio of greater the 6. The four experimental joints that did not achieved the design Z' value in Figure 2 all had ratios of maximum load to design load of 2 or greater after application of the Appendix E expressions.

For the 7% of joints that did not exceed a ratio of 2, application of the Appendix E expression did on average increase the margin of safety by 21%. All these same joints, expect one, failed by row shear/ splitting while the remaining joint failed by group tear-out. It is expected that further investigation development of the Appendix E expressions to include a splitting mode will assist in achieving more consistent safety levels without penalizing connection with relatively high levels of safety.

5. Possible Modifications of Appendix E Expressions

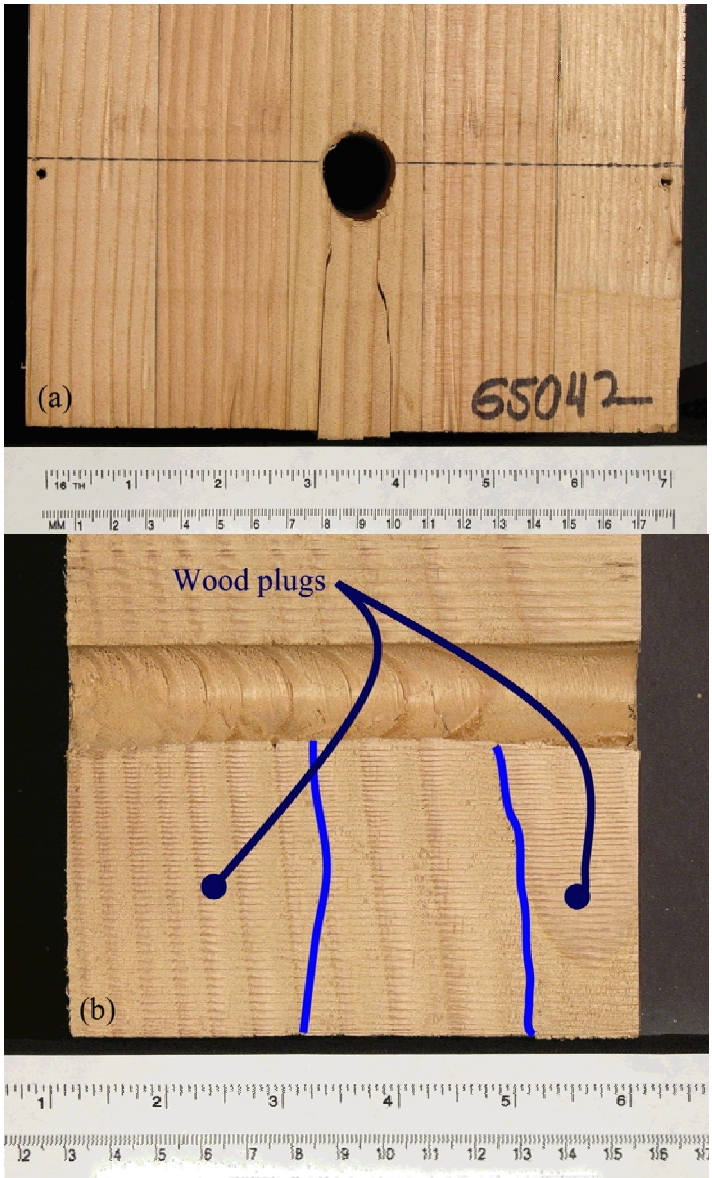

Figure 4. Post mortem pictures of the (a) side and (b) of 19.1mm bolted connection showing wood failure plugs.

A recent study investigating the affects of end spacing and L/D ratio highlighted some fasteners issues that should be considered in the development of wood failure mechanisms expression for connections.

This study experimentally determined the maximum fastener capacity for single bolt connections with the following parameters: four end distances; 2D, 4D, 7D, and 10D where D is the diameter of the fasteners being tested, four fastener diameters; D = 6.35 cm, 12.7 mm, 19.1 mm, 25.4 mm and three main member thicknesses; L = 38 mm, 127 mm, 222 mm are considered. Most of the 123 tensile loaded bolted joints ultimately failed in a splitting mode.

When the L/D ratio increased or end distance decreased, failures occurred by a split moving toward the middle of the member and maximum load was achieved when the splits from both side met. In many cases, after the initial split occurred a parallel split would develop upon continued loading so that at the end of the test the failure resembles a row tear out.

For fasteners with larger L/D ratios, the flexibility of the fastener causes the main member edges to become significantly loaded. In these cases, the effective wood area resisting the applied load should be reduced.

Figure 4 shows the both the effect of fastener flexibility on the wood failure planes. It in seen that the wood at the ends of the main wood member fail first and splitting progressively moved towards the middle of the main member. One possible approach is to create a reduced stress distribution or effective depth for the calculation of row shear-out or group tear-out. Instead of assuming a uniform through thickness stress distribution, assume only the wood stresses that resist the applied load are those stress generated from the bending of the fasteners. Therefore, the effective depth of the stress distribution is the distance from the edge of the main member to the plastic hinge that is developed as determined by the yield theory.

6. Concluding Remarks

In the 2001 National Design Specifications for Wood Construction, Appendix E provisions were added to address possible wood failure mechanisms that may occur in connections. One approach to estimate design capacities for net section, row tear out, and group tear failure mechanisms was presented in Appendix E of that 2001 NDS.

Approximately 200 joint connections considering of single and multiple bolted connections from sixteen different studies were used to compare the effectiveness of the current fastener design methods in the United States. A comparison of a yield theory based approach revealed that in four cases the design load was not achieved in experiments and in 36% of the tests the ratio of experimental to design load was less than 2.

When using an approach that chooses the minimum of both the yield theory based or wood limit states expressions the experimental load never eclipsed the design load. Furthermore, the overall margin of safety increased by 32% through the use of the wood failure expressions. More significantly the inclusion of wood limit states checks increased margin of safety for connection below twice the design load, reduced the variability of the design predictions, and, at the same time, did not penalize connection with relatively high levels of safety.

Finally additional development of a wood splitting criteria and inclusions of the dowel flexibility on the wood failure behavior of the connection should be considered for future development of Appendix E expressions.

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