Simplified analysis of timber rivet connections

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ABSTRACT

Timber rivets, fasteners for glulam and heavy timber construction, have been used in Canada for about thirty years and recently were adopted by the U.S. National Design Specification for Wood Construction (NDS). Rivet connections can exhibit two failure modes, one of which is fundamentally different from those of other dowel fasteners. Failure can occur when a volume of wood bounded by the perimeter of the closely spaced rivets pulls out from the timber, or via a combination of fastener yielding and localized wood crushing. The code-sanctioned analysis of the wood failure mode for timber rivet connections is so complex that closed form solution is not possible and designers must refer to tabular data for solutions. The code approach to the fastener yield/wood crush failure mode is inconsistent with accepted approaches for other dowel fasteners. The simplified analysis presented here is based on wood failure modes combining shear and tension planes, and is presented in closed form for direct incorporation into design calculations without reference to tables. Results show that the simplified procedure is as accurate as the code-sanctioned procedure for prediction of experimentally measured strengths. Ongoing work will continue the efforts of previous researchers who considered the use of yield theory to predict the strength of connections when wood failure modes do not occur.

INTRODUCTION

Timber rivets, or glulam rivets, were developed in Canada and have been recognized in the Canadian code for engineered wood construction for over twenty years. The rivets are hardened steel nails from 40 to 90 mm long with 3.2 x 6.4 mm oval-rectangular cross section, and are driven with their major cross section dimension parallel to the wood grain. The rivets are installed through predrilled steel side plates (3.2 to 6.4 mm thick) in rectangular arrays with minimum spacings of 15 to 25 mm. These connections have become common in Canadian glulam construction, and the 1994 edition of the O86.1 Canadian code (CSA 1994) included adjustments to the design values for rivets in sawn lumber. Applications can be anywhere that bolts with or without split rings or shear plates are currently used.

Timber rivets were first recognized in the U.S. in the most recent edition of the National Design Specification for Wood Construction (NDS 1997). Provisions in the NDS are based on the same original analysis (Foschi and Longworth 1975) used for the Canadian O86.1, but the NDS treatment is less comprehensive than the Canadian code. The NDS, for example, limits the use of rivets only to Southern Pine and Douglas Fir glulam (see the September 1998 Errata to NDS 1997), ignoring the adjustments for other glulam species and for solid timber that have been added to O86.1. The NDS also does not include the general connection design procedure for non-standard connection geometries that is included with O86.1 as an appendix. Thus the NDS provisions effectively limit the applications for designers in the U.S.

The fasteners' close spacing makes some riveted connections exhibit a brittle failure mode unlike that of other dowel fastener connections, in which the volume of wood defined by the rivet perimeter tears out from the timber. Of course the ductile failure mode combining fastener yield and localized wood crushing, similar to that of other dowel fasteners, is also possible. The analysis procedures in the Canadian and U.S. codes include both types of failures. This paper primarily addresses the wood failure mode.

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Objective

The objective of this study is to enable expanded application of timber rivets in glulam, solid timber, and other lumber products by providing test data to verify the fastener's performance in some wood species and products common in the U.S., and by developing a simplified and consistent analysis of timber rivet connections. Preliminary results presented in this paper refer to the second of these efforts, for loadings parallel to the wood grain. The simplified analysis presented here is based on wood failure on shear and tension planes, and is presented in closed form for direct incorporation into design calculations without reference to tables. Work presented in this paper refers to parallel-to-grain loadings only. The simplified procedure is shown to be as accurate as the code-sanctioned procedure for simulating experimentally measured strengths. Ongoing work will continue the efforts of Karacabeyli et al. (1998) and Buchanan and Lai (1994), who considered the use of yield theory to predict the strength of connections when wood failure modes do not occur. This will bring the design of timber rivet connections more in line with accepted practice for other fasteners. Perpendicular-to-grain loadings will also be considered. Finally, an extensive testing program will form the backbone of the study. Tests on small connections will produce information about the behavior of the fasteners themselves; tests on large connections (to 240 rivets) will permit study of the crossover in failure mode from fastener yield to wood fracture.

Literature Review

The most influential work on timber rivets is certainly that of Foschi and Longworth (1975), which became the basis for timber rivet design procedures in Canadian and U.S. codes. The authors presented rational analyses of the conditions leading to a rivet yield failure mode and to a wood failure mode, and included limited testing to verify and calibrate the analyses. The correlation of their predictions and test results was remarkably good. The equations to predict parallel-to-grain ultimate load controlled by rivet yield (P_y), wood tension (P_t), and wood shear (P_v), respectively, are:

$$P_y = N_R N_C P^*$$

Eq. 1

$$P_t = \frac{\sigma_{ult} \cdot A_t}{K_t \cdot \beta_t \cdot \alpha_t \cdot \gamma_h}$$

Eq. 2

$$P_v = \frac{\tau_{ult} \cdot A_s}{K_s \cdot \beta_s \cdot \gamma_h}$$

Eq. 3

where N_R and N_C are the number of rows and columns in an array of rivets, P^* is the capacity of a single rivet, σ_{ult} and τ_{ult} are the wood ultimate strength in tension and shear, A_t and A_s are the failure areas in tension and shear. The other factors are used to describe the geometry of a connection: K_i is a function of N_R and N_C, β_i is a function of rivet spacing, α_t is a function of wood member thickness and rivet length, and γ_h is a function of rivet embedment. Closed form equations for K_i and β_i are not possible given the complexity of the analysis, so the authors provided tables of values for these factors, based on their finite element analysis of stresses around the fastener group. They concluded that the wood tension failure mode should rarely if ever control, and then only for unusually thin wood members. They also presented analogous developments for perpendicular-to-grain loadings. Their limited experimental work served to show that the analysis gives good predictions. The experimental results supported the conclusion that the wood failure mode produces a brittle failure mode that should be avoided if possible, and that the crossover from wood failure to rivet yield failure can be controlled to some extent by rivet spacing. The work by Foschi and Longworth (1975) has proven to be quite robust - there have been no published alternatives to their basic analysis of concentrically loaded connections.

The first study of timber rivet behavior in solid timber presented promising results with an important caveat. Karacabeyli and Fraser (1990) tested connections parallel and perpendicular to the grain in concentric compression. They reported that the strength, load-displacement response, and failure modes of timber rivet connections in Douglas fir solid timber and Douglas fir glulam were essentially the same. They noted, however, that the absence of major defects such as checks and splits from their solid timber specimens limited the value of their results as an indication of how rivet connections would behave in real solid timber. Karacabeyli et al. (1998) described a large testing program to evaluate the behavior of rivet connections in solid timber (DF-L, SPF, and Hem-Fir). Their solid timber specimens, like those of Karacabeyli and Fraser (1990), were defect free in accordance with testing norms (ASTM 1988). They noted that when rivet yielding is the failure mode, connections in solid timber are 80 to 90 percent as strong as connections in the same species of glulam. For connections with wood failure modes, the authors noted that the failure modes are similar for solid timber and glulam.

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They reasoned that the work of Foschi and Longworth (1975) should, therefore, apply to solid timber. As noted above, the equations developed by Foschi and Longworth use wood tensile and shear strength to determine strength of the riveted connection in wood failure modes. Shear strengths for solid timber are typically 40 to 50 percent of the shear strengths for glulam of the same species group, due to the effects of cracks and checks in solid timber. Karacabeyli et al. (1998) concluded, therefore, that riveted connections with solid timber should have a 50 percent reduction in design strength from connections with glulam of the same species group. The adjustments they suggested were adopted by the Canadian code (CSA 1994).

A SIMPLIFIED RATIONAL ANALYSIS OF TIMBER RIVET CONNECTIONS

The present project addresses three shortcomings of the analysis of timber rivet connections that has been adopted by the Canadian and U.S. wood codes:

1. *Complexity of the wood failure mode analysis results in no closed form design equations.* The analysis of stresses around the fastener group, which leads to prediction of connection strength when wood failure controls (Eqs. 2 and 3), is well reasoned and has been partially verified by comparison with limited test data. Unfortunately, the very complex analysis required numerical solution for several factors that are functions of connection geometry; closed-form solution is not possible. Although codes have traditionally presented tabular data, it is our contention that modern engineering design practices are better served by closed form equations that can be automated in spreadsheets or other computer software. The Canadian code includes a far more comprehensive presentation than the NDS of the original Foschi/Longworth method, but ultimately it, too, relies on tables of constants with no method for verifying or extending the method to other situations.

2. *Some of the results of the wood failure mode analysis are counterintuitive, and have not been adequately verified.* At issue here is the use by Foschi and Longworth (1975) of a Weibull distribution to model the volume effect on shear strength, so connection strength decreases as timber thickness increases if all other things are held constant. Our contention is that the wood shear stresses are highest near the ends of the rivets and decrease with distance from this depth toward the center of the timber, so if a wood failure occurs it will occur near the rivet ends. While a size effect is accepted in several areas of timber design, there does not appear to be sufficient test data reported in the literature to support its inclusion in this analysis.

3. *The rivet failure mode analysis requires the basic rivet capacity as an input, and provides no guidance on how to estimate it.* The widely accepted "yield theory" (as described in Aune and Patton-Mallory 1986 and ASCE 1996, for example), describing failure as a combination of fastener yield and localized wood crushing, has been accepted for use with all other dowel fasteners; it is logical that it should be used for this fastener, too. Karacabeyli et al. (1998) briefly described earlier work in which they applied the yield theory to rivets. A more complete evaluation of yield theory was given by Buchanan and Lai (1994), who showed that it gave good predictions of connection strength when wood failure did not occur.

Block shear wood failure modes

The simplified analysis is based on four possible wood failure modes (the application of yield theory to the rivet failure mode will be addressed in future papers) as shown in Fig. 1. The top image of Fig. 1 indicates the basic statics of the connection: with the end of the timber on the left, the timber tensile force is shown on the right and the force which has been transmitted into the plate is shown on the left. Note that the more common situation is to have rivets driven through plates on each side of the timber, so the images in Fig. 1 can be thought of as showing half the thickness of the timber.

The top image of Fig. 1 shows that the array of rivets defines a volume of wood; the other four images show modes for this volume to be pulled from the timber. The first mode shows the intersection of three failure planes with the edges of the timber. The rightmost plane is in tension, the bottom plane is in shear, and the leftmost plane is in compression. Mode 4 is similar, but the bottom shear plane has extended to the end of the member so the compression plane is not necessary. Mode 2 shows the tear-out of the rivet volume shown in the top image: there is a tension plane on the right, a shear plane on the bottom, a compression plane at the left, and an additional shear plane along each side. Mode 3 is similar, but with the three shear planes extending to the end of the timber so the compression plane is not necessary. In all cases the strength of the compression plane is ignored. Equations for connection capacity based on the four wood failure modes use the connection geometry variables shown in Fig. 2, along with the number of rivet rows, N_R, and the number of rivet columns, N_C (in Fig. 2, $N_R = 3$ and $N_C = 5$). The following equations also refer to wood strengths in shear along the grain, τ_{ult}, and tension parallel to the grain, $\sigma_{t\text{-}ult}$. For mode 1, we have the bottom shear plane plus the tension plane:

$$P_1 = \tau_{ult}(N_C - 1)S_P\left((N_R - 1)S_Q + 2e_p\right) + \sigma_{t-ult}L_p\left((N_R - 1)(S_Q - A) + 2e_p\right)$$
Eq. 4

The constant A is used to reduce the area of the tension plane because the rivets disturb wood grain crossing this plane. Values for this constant and the similar constant B introduced in Eq. 5 will be set empirically to provide the best fit with experimental data. In mode 2, we have the bottom shear plane, the two side shear planes, and the tension plane:

$$P_2 = \tau_{ult}\left((N_C - 1)S_P(N_R - 1)S_Q + 2L_p(N_C - 1)(S_P - B)\right) + \sigma_{t-ult}L_p(N_R - 1)(S_Q - A)$$
Eq. 5

The constant B has been added to reduce the area of the side shear planes for the rivets that perforate these planes. In mode 3, we have the bottom shear plane, two side shear planes, and the tension plane:

$$P_3 = \tau_{ult}\left((N_R - 1)S_Q\left((N_C - 1)S_P + a\right) + 2L_p\left((N_C - 1)(S_P - B) + a\right)\right) + \sigma_{t-ult}L_p(N_R - 1)(S_Q - A)$$
Eq. 6

Finally, in mode 4 we have only the bottom shear plane and the tension plane:

$$P_4 = \tau_{ult}\left((N_R - 1)S_Q + 2e_p\right)\left((N_C - 1)S_P + a\right) + \sigma_{t-ult}L_p\left((N_R - 1)(S_Q - A) + 2e_p\right)$$
Eq. 7

Comparison with code procedures and test data in the literature

In order to evaluate the simplified analysis (referred to below as "new"), its predictions and those of the analysis in Canadian O.86.1-94 (referred to below as "code") were compared to test results from the literature. Three sets of data for tension parallel-to-grain connections were found in the literature; each used a plate on one side of the timber instead of the two plates shown in Fig. 2. Here we must distinguish between tests of rivet arrays that are large enough for a mix of wood failures and rivet failures to be possible on the one hand, and tests of small rivet arrays—usually four rivets per plate—which are meant to avoid wood failures and isolate rivet failures. Foschi and Longworth (1975) tested ten connection types with Douglas Fir-Larch glulam with from 25 to 150 rivets; Buchanan and Lai (1994) tested Radiata Pine glulam connections with 12 and 25 rivets; and Karacabeyli, Fraser, and Deacon (1998) tested Hem-Fir solid timber with 25 to 100 rivets. For each test connection, the new and code analyses used wood tension and shear unit strengths from O86.1: Properties for Douglas Fir-Larch glulam were used for the Foschi and Longworth test simulations and the Buchanan and Lai simulations. Canadian O86.1 does not have strengths for Radiata Pine, the mechanical properties of which are similar to Douglas Fir-Larch. Properties for Hem-Fir *glulam* were used for the Karacabeyli, Fraser, and Deacon simulations. As noted earlier, this set of tests used solid timber that was free of defects in the connection zone. Our

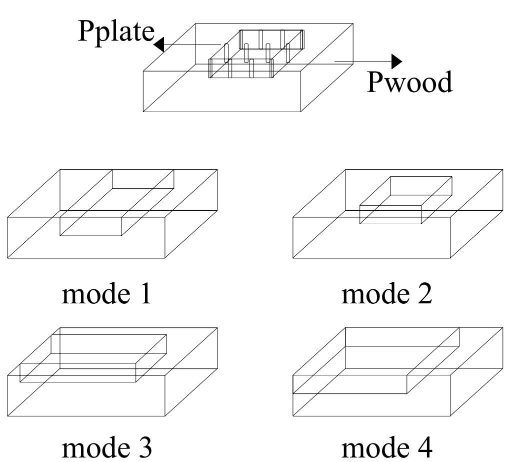

Figure 1. Four wood failure modes.

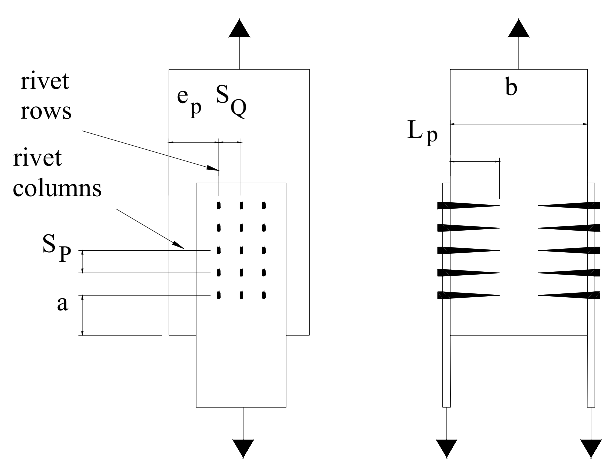

Figure 2. Connection geometry variables.

thinking is that defect free wood is better simulated with the glulam properties than the solid sawn timber properties. The new analysis was augmented with the connection rivet capacity from O86.1 (future work will update this step of the analysis per fastener yield theory).

Table 1. Analysis and test results.

										Canadian O86.1-94				**Simplified analysis**					**Test**
N_R	N_C	S_P (mm)	S_Q (mm)	b (mm)	L_p (mm)	e_p (mm)	a (mm)	f_{tn} (MPa)	f_v (MPa)	P_y (kN)	P_t (kN)	P_v (kN)	$\mathbf{P_{code}}$ (kN)	P_1 (kN)	P_2 (kN)	P_3 (kN)	P_4 (kN)	$\mathbf{P_{new}}$ (kN)	**data** (kN)
tests from Foschi and Longworth (1975)																			
5	5	25	12.5	457	80	25	50.8	20.4	2	111	123	47	**47**	124	53	75	135	**53**	**82**
5	5	37.5	25	457	80	25	50.8	20.4	2	111	220	201	**111**	231	171	197	246	**111**	**155**
5	10	25	12.5	457	80	25	50.8	20.4	2	222	186	72	**72**	149	91	113	160	**91**	**104**
5	10	37.5	25	457	80	25	50.8	20.4	2	222	332	268	**222**	287	254	280	303	**222**	**282**
10	10	25	12.5	457	80	25	50.8	20.4	2	443	313	148	**148**	206	148	176	223	**148**	**178**
10	10	37.5	25	457	80	25	50.8	20.4	2	443	651	431	**431**	502	469	508	530	**443**	**551**
15	10	25	12.5	457	80	25	50.8	20.4	2	665	432	212	**212**	263	205	239	286	**205**	**205**
15	10	37.5	25	457	80	25	50.8	20.4	2	665	938	549	**549**	717	684	736	758	**665**	**729**
15	10	25	12.5	457	80	25	381	20.4	2	665	432	214	**214**	263	205	460	434	**205**	**265**
15	10	37.5	25	457	80	25	381	20.4	2	665	938	947	**665**	717	684	1073	1022	**665**	**1066**
tests from Buchanan and Lai (1994)																			
3	4	25	15	170	40	25	25	20.4	2	43	67	38	**38**	63	22	27	67	**22**	**33**
3	4	25	15	170	40	25	75	20.4	2	43	67	38	**38**	63	22	38	75	**22**	**45**
5	5	25	12.5	170	40	25	50	20.4	2	89	94	45	**45**	72	32	45	82	**32**	**61**
5	5	37.5	25	170	40	25	50	20.4	2	89	161	125	**89**	138	100	118	153	**89**	**101**
tests from Karacabeyli, Fraser, and Deacon (1998)																			
5	5	25	12.5	504	80	25	50.8	20.4	1.75	111	123	41	**41**	122	50	68	131	**50**	**88**
5	5	37.5	25	504	80	25	50.8	20.4	1.75	111	220	176	**111**	225	163	186	239	**111**	**136**
5	10	25	12.5	504	80	25	50.8	20.4	1.75	222	186	63	**63**	144	83	102	153	**83**	**108**
5	10	37.5	25	504	80	25	50.8	20.4	1.75	222	332	233	**222**	275	235	258	288	**222**	**212**
10	10	25	12.5	504	80	25	50.8	20.4	1.75	443	312	130	**130**	197	136	160	211	**136**	**230**

Results in Table 1 show the predictions of the two analyses and the test data from the literature. The first eight columns contain connection geometry data; the edge distance e_p was not reported in any of the cited papers, so a value equal to the code minimum was assumed. The columns titled f_{tn} and f_v are the specified wood strengths in tension parallel to grain and longitudinal shear, respectively, corresponding to τ_{ult} and $\sigma_{t\text{-}ult}$ in equations 4 through 7. Columns P_y, P_t, and P_v are the O86.1 predictions of capacity based on rivet yield, wood tension, and wood shear failures, respectively, as conceptually shown in equations 1 through 3; P_{code} is the minimum of these three, and therefore the code's prediction of connection capacity. The next four columns are the results of equations 4 through 7 for the four simplified failure modes. The constants A and B in equations 4 through 7 were set to 9 mm for the data in Table 1 to create the best fit for the new analysis to the experimental data. The column titled P_{new} is the minimum of P_1 through P_4 along with P_y, so it represents the new procedure's prediction of connection capacity when a wood failure mode occurs. Finally, the last column shows measured connection capacity as reported in the literature. The predictions P_{code} and P_{new} are compared to the test data in Fig. 3.

Several observations are made from the tabular and chart data:

1. The simplified analysis makes predictions that are practically as good as the code analysis. The correlation coefficients (r^2) are 0.96 for the code analysis and 0.94 for the simplified analysis. The standard error in a linear regression is 37 kN for the code analysis and 48 kN for the simplified analysis.

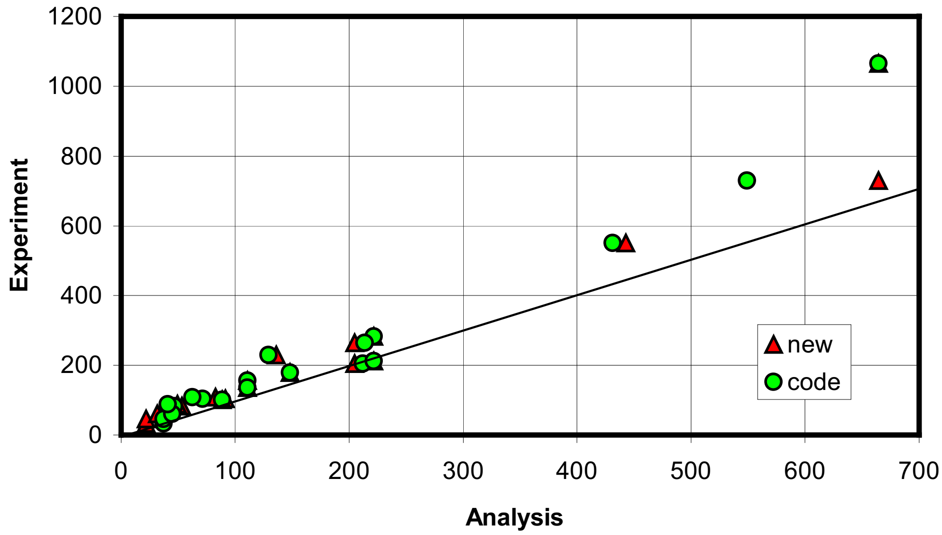

Figure 3. Test data versus new analysis and code analysis.

2. There is insufficient test data to verify or refute the idea of a size effect in the wood failure mode analysis as proposed by Foschi and Longworth. One goal of continuing work in this study is to test connections using timbers with a range of thicknesses to do just that.

3. Modes 1 and 4 do not control the strengths of any connections, even with the code minimum value for edge distance e_p that was assumed for all connections. Likewise, mode 3 does not control the strength of any connections, even thought the code minimum end distance "a" was violated in all but two instances (the code minimum is 75 mm for N_R up to 8, 100 mm for N_R equal to 10, and 175 mm for N_R equal to 15). Additional simulations and tests need to be done, but these results suggest that if the code minimum end and edge distances are maintained, only mode 2 needs to be evaluated. The alternative conclusion here is that it might be possible to reduce the code minimum end and edge distances if additional tests verify the new analysis's ability to make accurate predictions.

CONCLUSIONS

The tight arrays of fasteners in timber rivet connections enable a failure mode not seen with other dowel-type fasteners—in which a block of wood more-or-less bounded by the rivets tears out from the timber. The more common failure mode of combined fastener yield and localized wood crushing is also observed. The analysis of timber rivet connections used in the Canadian O86.1 and the U.S. NDS is based on a common source, which has been proven to be extremely useful and accurate but which has several shortcomings: no closed-form solution is available, there are some counterintuitive predictions, and rivet capacity in a specific species is required as an input. The proposed analysis addresses all three issues, and makes predictions that are for all practical purposes as accurate at the code procedures.

The length of equations 4 through 7 belies that fact that the proposed analysis procedure is truly a simplification of wood failure mode analysis for riveted connections. The simplification is conceptual—wood failure modes consist of a series of failure planes that make sense based on connection geometry and wood behavior—as well as practical—the equations can easily be automated in any spreadsheet or other computer aid for designers. Both of these issues represent significant improvements from a designer's viewpoint.

The proposed analysis currently relies on the code's prediction of the rivet yield failure mode, but on-going work is directed toward adapting the widely used yield theory to that portion of the analysis. This, again, has a conceptual benefit—it is consistent with the treatment of all other dowel type fasteners—as well as a practical benefit—designers can apply the procedure to any species or wood product that has known dowel bearing strength or specific gravity.

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