STRUCTURAL PERFORMANCE OF TIMBER RIVETS IN ENGINEERED WOOD PRODUCTS

by

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Abstract

Timber Rivets are oval-shaped nails made from high-strength steel that allow for strong and ductile timber connections. Timber Rivets have been successfully used in the construction industry for over 40 years. Both the Canadian design code (CSA-O86) and the American design code (NDS), however, only specify Timber Rivets to be used with Glulam and solid sawn timber of certain species. In recent years, significant research has been conducted in New Zealand regarding the application of Timber Rivets to Laminated Veneer Lumber. As a result, the Johansen Yield Model, which is verified as a valid approach to predict the ductile failure of Timber Rivet connections, has been complemented with new failure models and design equations that predict brittle failure modes.

The objective of the research was to evaluate the feasibility of using the novel models to predict the failure modes and capacities of Timber Rivet connections in Laminated Veneer Lumber and Cross Laminated Timber. The experimental investigations carried out as part of this thesis consisted of 29 test series (with three or five replicates each) of Timber Rivet connections in these structural composites made from North American species. Quasi-static monotonic and cyclic tests with loading parallel and perpendicular to the grain were conducted in the Wood Mechanics Laboratory at the University of British Columbia Vancouver. The quasi static tests were used to validate the prediction models; the cyclic tests were used to assess the seismic performance of the connections.

The results showed that the recent New Zealand model provides good predictions for Timber Rivet connections in Laminated Veneer Lumber. Furthermore, it was shown that cyclic loading does not severely weaken the performance of Timber Rivet connections. The existing models, however, do not provide accurate predictions for Timber Rivet connections in Cross Laminated Timber and more research is deemed necessary before such connections can be safely designed.
Preface

This thesis is original, unpublished, independent work by the author, Tianyi Wu, under supervision of Dr. Thomas Tannert.
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Latin upper case

$E_0 = \text{Modulus of elasticity in bending parallel to the major strength direction [MPa]}$

$E_{90} = \text{Modulus of elasticity in bending perpendicular to the major strength direction [MPa]}$

$A_t = \text{Area in tension [mm}^2\text{]}$

$A_s = \text{Area in shear [mm}^2\text{]}$

$D = \text{Distance from unloaded edge to the group of nails [mm]}$

$F_{em} = \text{Dowel bearing strength per unit area in the main member [MPa]}$

$H = \text{Material factor [-]}$

$P_r = \text{Factored connection resistance parallel to grain [N]}$

$P_u = \text{Lateral resistance parallel to grain [N]}$

$P_w = \text{Wood Capacity [N]}$

$P_y = \text{Rivet yielding capacity [N]}$

$K_b = \text{Average bottom shear plane stiffness [N/mm]}$

$K_l = \text{Average lateral shear plane stiffness [N/mm]}$

$M_{r,p} = \text{Perpendicular-to-grain moment capacity of rivet [N*mm]}$

$M_{r,l} = \text{Parallel to grain moment capacity of rivet [N*mm]}$

$N_R = \text{Number of rivet rows [-]}$

$N_C = \text{Number of rivet columns [-]}$

$P^* = \text{Ultimate carrying capacities of a single rivet [N]}$

$Q_r = \text{Factored connection resistance perpendicular to grain [N]}$

$Q_u = \text{Lateral resistance perpendicular to grain [N]}$

$W = \text{Connection width [mm]}$

$X_p = \text{Adjustment factor for tension perpendicular to grain [-]}$

$L_p = \text{Length of penetration [mm]}$
**Latin lowercase**

\( a_q = \) End distance in perpendicular to grain loading [mm]

\( a_p = \) Bearing end distance in parallel to grain loading [mm]

\( b = \) Member thickness [mm]

\( d = \) Fastener’s diameter [mm]

\( d_{a.l.} = \) End distance on the left end [mm]

\( d_{a.r.} = \) End distance on the right end [mm]

\( d_l = \) Rivet cross section dimension bearing on the wood parallel to grain [mm]

\( d_p = \) Rivet cross section dimension bearing on the wood perpendicular to grain [mm]

\( e_p = \) Edge distance in parallel to grain loading [mm]

\( e_q = \) Bearing edge distance in perpendicular to grain loading [mm]

\( e_x = \) Rivet spacing parallel to grain [mm]

\( e_y = \) Rivet spacing perpendicular to grain [mm]

\( d_s = \) End distance [mm]

\( d_e = \) Edge distance [mm]

\( e_s = \) Row spacing [mm]

\( f_{ax} = \) Withdrawal resistance [N/mm]

\( f_{b,0} = \) Characteristic bending strength parallel to the major strength direction [MPa]

\( f_{b,90} = \) Characteristic bending strength perpendicular to the major strength direction [MPa]

\( f_{c,0} = \) Characteristic compressive strength parallel to the major strength direction [MPa]

\( f_{c,90} = \) Characteristic compressive strength perpendicular to the major strength direction [MPa];

\( f_{h,90} = \) Embedment strength for rivets bearing perpendicular to grain [MPa]

\( f_{s,0} = \) Characteristic rolling shear strength parallel to the major strength direction [MPa]

\( f_{s,90} = \) Characteristic rolling shear strength perpendicular to the major strength direction [MPa]

\( f_{t,0} = \) Characteristic tension strength parallel to the major strength direction [MPa]

\( f_{t,90} = \) Characteristic tension strength perpendicular to the major strength direction [MPa]
\( f_{t, m} \) = Mean strength of wood in tension parallel to grain [MPa]
\( f_{t, p} \) = Mean strength of wood in tension perpendicular to grain [MPa]
\( f_{v, m} \) = Mean strength of wood in shear parallel to grain [MPa]
\( f_w \) = Characteristic embedment stress of wood member [MPa]
\( f_{v, 0} \) = Characteristic shear strength parallel to the major strength direction [MPa]
\( f_{v, 90} \) = Characteristic shear strength perpendicular to the major strength direction [MPa]
\( f_s \) = Fastener yield stress [MPa]
\( J_y \) = Side plate factor [-]
\( n_C \) = Number of rivet columns [-]
\( n_R \) = Number of rivet rows [-]
\( n_p \) = Number of plates [-]
\( p_w \) = Lateral resistance parallel to grain [N]
\( q_w \) = Lateral resistance perpendicular to grain [N]
\( s_p \) = Rivet spacing parallel to grain [mm]
\( s_q \) = Rivet spacing perpendicular to grain [mm]

Greek lower case
\( \sigma \) = Tension strength parallel to grain [MPa]
\( \tau \) = Shear strength parallel to grain [MPa]
\( \sigma_{t, \text{ult-perp}} \) = Tension strength perpendicular to grain [MPa]
\( \beta \) = effective crack length coefficient for partial width splitting [mm]
\( \gamma \) = effective crack length coefficient for full width splitting [-]
\( \zeta \) = factor depending on unloaded edge distance and joint length [-]
\( \eta \) = factor depending on end distances and joint width [-]
\( \rho \) = wood mean density [kg/m\(^3\)]
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- NSERC (Natural Science and Engineering Research Council of Canada) for financial support for this project.
1. Introduction

1.1. Background

Timber Rivets are nails made from high-strength steel with an oval-shaped cross section in its shank. The head of Timber Rivets is forged into a wedge shape. Three rivet lengths: 40 mm, 65 mm, and 90 mm are available on the market. Timber Rivets have to be installed with predrilled mild steel plate as connectors and can be used in applications such as heavy timber trusses, beam to column joints, and hold-downs. Figure 1 shows a close up of Timber Rivet connections in the Forest Science Center at UBC. Timber Rivets are also known as Glulam Rivets, which were originally developed for Glulam applications only. Since the first appearance of Timber Rivet connections, scientists and engineers have been devoted to generating a more accurate estimation of connection capacity and failure mode. Currently, there is an increase in the demand for the application of Timber Rivet application into a larger scope of engineered timber products along with better predictions of connection capacities.

![Figure 1 – Timber Rivets truss application in Forest Science Center, UBC](image_url)
1.2. Research need

Timber Rivet connections can be designed following either National Design Specification® (NDS®) for Wood Construction (American Wood Council 2012) or CSA O86 (Canadian Standard Association 2009). Most of the prediction models in the literature (Foschi 1973); (Buchanan & Lai 1994); (Stahl et al. 2004); (Zarnani 2013) use the European Yield Model to predict connection capacity under ductile failure. Nevertheless, no consensus has been reached in predicting connection capacities under brittle failure modes. Moreover, the design of Timber Rivet connections has been restricted to Douglas-fir-larch or southern pine Glulam by the US code (NDS). While the Canadian code, CSA O86, allows the application of Timber Rivets with a reduction factor on different species, the materials are still restricted to Glulam and sawn lumber.

With more structural composite lumber (SCL) expanding into the building materials market, Timber Rivet design needs to be adapted to current products. Therefore, tests on SCL from different species are needed. The newly proposed New Zealand design model (Zarnani 2013) needs to be verified with North American species. Furthermore, tests under cyclic loading were also deemed to be of interest.

1.3. Objectives

The primary objective of this research is to assess the feasibility of applying current models for Timber Rivet connection to predict the performance of such connections in Laminated Veneer Lumber (LVL). As a secondary objective, the performance of Timber Rivet connections in Cross Laminated Timber (CLT) is studied.
2. State of the art

2.1. Materials used for Timber Rivet connections

2.1.1. Timber Rivets

Timber Rivets were developed in Canada by Madsen to reduce the high probability of brittle failure caused by traditional connection methods in Glulam applications (McGowan & Madsen 1965). Traditional timber connectors at the time did not provide adequate stiffness and easily moved when subjected to reversal of the forces (Madsen 1998). As shown in Figure 2, Timber Rivets are nails made from heat-treated steel that has an oval shaped cross section and a tapered head. They are hot-dip galvanized and have Rockwell hardness from 32 to 39 (Popovski et al. 2002). Commonly available lengths for Timber Rivets are 40, 65, and 90 mm.

As a complete load carrying system, Timber Rivets are required to be installed with steel side plates, whose thickness should at least be 3.2 mm. Steel plates should be made according to CAN3-G40.21 or ASTM standard A36 (Canadian Wood Council 2010). Timber Rivets’ flat faces should always be installed parallel to the grain direction to lower the possibility of cracking of wood around rivets. Timber Rivets act like a cantilevered beam in the wood while the shear forces and bending moments are carried through its shank (Madsen 1998). The ring tension created at the tapered rivet head with steel plate offers extra fixity for the rivet so that the rivet will not rotate during loading. The oval cross section of rivet improves the efficiency in using material to get large enough section modulus. When driven into the wood member, the rivet is designed to push wood fibers aside instead of damaging them. This mechanism also increases the wood member density between two rivets across the grain direction by 25%. Thus, the force from timber can be transferred in two ways (Madsen 1998):

- Through the bearing between timber and rivets
- Through the friction along two 6.4 mm sides of the rivet shank
Timber Rivets were originally developed for Glulam only. However, the common applications of Timber Rivets gradually extended to members made from sawn lumber and some other products such as Parallel Strand Lumber (PSL) and Laminated Strand Lumber (LSL) (Wolfe et al. 2004). Timber Rivets are designed to resist in-plane compression and tension and work best when they are loaded in one direction as a group (Taylor & Moses 2008). The traits of Timber Rivets include:

- Provision of strong, stiff and ductile connection.
- Reduction in fabrication time by eliminating predrilling processes.
- Installation can be done with an ordinary hammer.
- Reducing the size of members due to elimination of wood removal.

*Figure 2 – Close-up of Timber Rivets (65 mm and 90 mm)*
2.1.2. Glulam

Glulam is a material glued up from selected wood in a straight or curved form with the grain of all pieces essentially parallel to the longitudinal axis of the member (ASTM International 2012b). Visually graded or machine stress rated Douglas fir-Larch, Southern Pine, Hem-Fir, and SPF lumber are commonly used as feedstock for Glulam in North America. Radial grain orientation through the thickness of feedstock is commonly systematically varied during lay-up process to minimize the effects of changing moisture nevertheless the outermost laminations are always turned with the core side outwards. To use materials efficiently, it is accepted to use higher quality timber panels at the outer lamination through the cross section of a Glulam panel because stress at the outer layer is normally the highest (Nordic Innovation 2003). Due to the fact that Glulam is made from pieces of lumber joined end to end, edge to edge, and face to face, the size of Glulam is limited only by the capabilities of the manufacturer and transportation method (Forest Products Laboratory 1987). Finger joints are typically used in Glulam. The most common adhesive used in Glulam is phenol resorcinol formaldehyde, which is water-proof and able to cure at room temperature. Glulam strength classification, material strength, and modulus of elasticity (MOE) for common Canadian products are summarized in Table 1. On the building construction side, Glulam is used as a bending member, axial members, curved members, and tapered straight members (Forest Products Laboratory 1987). The manufacturing process of Glulam is summarized as a flow chart in Figure 3.

Table 1 – Specified strength and modulus of elasticity for Douglas-fir-Larch Glulam (MPa) (Canadian Standard Association 2009)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>24f-E</th>
<th>24f-EX</th>
<th>20f-E</th>
<th>20f-EX</th>
<th>16c-E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending Moment (pos.) $f_b$</td>
<td>30.6</td>
<td>30.6</td>
<td>25.6</td>
<td>25.6</td>
<td>14.0</td>
</tr>
<tr>
<td>Bending Moment (neg.) $f_b$</td>
<td>23.0</td>
<td>30.6</td>
<td>19.2</td>
<td>25.6</td>
<td>14.0</td>
</tr>
<tr>
<td>Longitudinal Shear $f_{0,0}$</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Compression Parallel $f_{c,0}$</td>
<td>30.2</td>
<td>30.2</td>
<td>30.2</td>
<td>30.2</td>
<td>30.2</td>
</tr>
<tr>
<td>Compression Perpendicular $f_{c,90}$</td>
<td>7.0</td>
<td>7.0</td>
<td>7.0</td>
<td>7.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Tension Parallel $f_{t,0}$</td>
<td>20.4</td>
<td>20.4</td>
<td>20.4</td>
<td>20.4</td>
<td>20.4</td>
</tr>
<tr>
<td>Tension Perpendicular $f_{t,90}$</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Modulus of Elasticity $E_0$</td>
<td>13,100</td>
<td>13,100</td>
<td>12,400</td>
<td>12,400</td>
<td>12,400</td>
</tr>
</tbody>
</table>
The traits of Glulam consist of:

- Architectural effects: a lot of architectural effects are expressed by curving lumber during manufacturing process
- Seasoning advantages: checking and other drying defects are minimized due to using seasoned lumber only
- Efficient material use: grades are varied among laminations by using highest grade lumber at highly stressed laminations (bottom and top edges)
2.1.3. Laminated Veneer Lumber (LVL)

LVL is a high-strength engineered wood product made by gluing rotary-peeled veneers of soft wood together with water proof adhesive (Çolak et al. 2007). As a composite material, this product is more uniform and less likely to warp, twist, bow or shrink than conventional lumber (Wang & Dai 2013). The different grain layouts separate LVL products into two categories, one in which all layers run longitudinally and another where some layers run crosswise (Figure 5). The veneer thickness ranges from 2.5mm to 4.8mm and common species of veneer in Canada include Douglas-fir, larch, southern yellow pine, and poplar (Canadian Wood Council 2012). Phenolic resin is used for LVL lamination. Recently, thick laminated LVL has been introduced to the market (Figure 6).

The manufacturing process of LVL depends on the source of veneer. Based on the costs of raw materials and energy, manufacturers have the option to buy pre-dried veneers, buy green veneers or even peel veneers on site. The general process of producing LVL consists of veneer drying, grading, resin application, billet layup, hot pressing, sawing, and final finishing process (Duprey 1995). Sheets of LVL are usually produced with width from 0.6 to 1.2 m and thickness of 38 mm (Forest Products Laboratory 1987). Figure 4 shows the entire process flow of LVL manufacture.

![Process flow diagram for LVL manufacture](image)

LVL is widely used in wood structural framing for both residential and commercial constructions. In addition, it can be combined with designs containing open web steel joists and light steel beams (Canadian Wood Council 2012). Applications of LVL generally include header, beams, flange on wood I-joists, rafters, columns, studs, truss chords, and rim board in residential floor and roof system. Common bending moduli of LVL range between 12,000 MPa and 15000 MPa (Wang & Dai 2013).
The traits of LVL include:

- Possibility of utilizing small diameter trees to produce large wood composite members.
- Natural defects in the trees could be removed during manufacture.
- More uniform than sawn lumber in material strength.

*Figure 5 – KERTO-Q (Cross bonded LVL) (Metsawood 2014)*

*Figure 6 – Secondary laminated Douglas fir LVL*
2.1.4. Cross Laminated Timber (CLT)

CLT panels commonly consist of an odd number of board layers stacked perpendicular to adjacent layers. Each layer is again made up of several narrow panels having glue on their wide surfaces. Two close-up pictures of 3-ply and 9-ply CLT are shown in Figure 8 and Figure 9. The minimum of specific gravity of sawn lumber used to build CLT is regulated at 0.35. Common species used to build CLT include Spruce-pine-fir, Douglas fir-Larch, Southern pine, Eastern softwoods, Northern species, and Western woods.

CLT panels are usually fabricated products with 3 to 7 layers, in some cases, more layers as well. ANSI/APA PRG 320 “Standard for Performance-rated Cross Laminated Timber”, jointly developed by the Engineered Wood Association in the U.S. and FPInnovation in Canada (APA-The Engineered Wood Association 2012) regulates that 1200f-2.0E MSR or visually graded No.2 lumber as the minimum material requirement for parallel layers in CLT. Visually graded No.3 lumber is the minimum requirement for perpendicular layers. Table 2 summarizes the product specifications of CLT in different grades.

Table 2 – Specified Strength and Modulus of Elasticity for PRG 320 CLT (MPa) (APA-The Engineered Wood Association 2012)

<table>
<thead>
<tr>
<th>CLT Grades</th>
<th>$f_{b0}$</th>
<th>$E_0$</th>
<th>$f_{t0}$</th>
<th>$f_{c0}$</th>
<th>$f_{c90}$</th>
<th>$f_{s0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>28.2</td>
<td>11700</td>
<td>15.4</td>
<td>19.3</td>
<td>1.5</td>
<td>0.50</td>
</tr>
<tr>
<td>E2</td>
<td>23.9</td>
<td>10300</td>
<td>11.4</td>
<td>18.1</td>
<td>1.9</td>
<td>0.63</td>
</tr>
<tr>
<td>E3</td>
<td>17.4</td>
<td>8300</td>
<td>6.7</td>
<td>15.1</td>
<td>1.3</td>
<td>0.43</td>
</tr>
<tr>
<td>V1</td>
<td>10.0</td>
<td>11000</td>
<td>5.8</td>
<td>14.0</td>
<td>1.9</td>
<td>0.63</td>
</tr>
<tr>
<td>V2</td>
<td>11.8</td>
<td>9500</td>
<td>5.5</td>
<td>11.5</td>
<td>1.5</td>
<td>0.50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CLT Grades</th>
<th>$f_{b90}$</th>
<th>$E_{90}$</th>
<th>$f_{t90}$</th>
<th>$f_{c90}$</th>
<th>$f_{c90}$</th>
<th>$f_{s90}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>7.0</td>
<td>9000</td>
<td>3.2</td>
<td>9.0</td>
<td>1.5</td>
<td>0.50</td>
</tr>
<tr>
<td>E2</td>
<td>4.6</td>
<td>10000</td>
<td>2.1</td>
<td>7.3</td>
<td>1.9</td>
<td>0.63</td>
</tr>
<tr>
<td>E3</td>
<td>4.5</td>
<td>6500</td>
<td>2.0</td>
<td>5.2</td>
<td>1.3</td>
<td>0.43</td>
</tr>
<tr>
<td>V1</td>
<td>4.6</td>
<td>10000</td>
<td>2.1</td>
<td>7.3</td>
<td>1.9</td>
<td>0.63</td>
</tr>
<tr>
<td>V2</td>
<td>7.0</td>
<td>9000</td>
<td>3.2</td>
<td>9.0</td>
<td>1.5</td>
<td>0.50</td>
</tr>
</tbody>
</table>
The manufacturing process of CLT consists of strength grading, finger jointing, trimming, edge planning, surface planning, edge bonding, and surface bonding. The flow chart is summarized in Figure 7.

**Figure 7 – Flow chart of CLT manufacturing process** (Brandner 2013)

CLT is a strong wood composite competitor against concrete in terms of wall and floor applications. It also retains the advantages of lighter carbon footprint as a product based on sustainable materials.

The traits of CLT include (Structurlam 2013):

- Up to 6 times lighter than concrete.
- Dimensional stability and static strength due to cross lamination.
- Short assembly time and less skill required due to capability of prefabrication.
Figure 8 – Close Up of 3-ply Cross Laminated Timber

Figure 9 – Close Up of 9-ply Cross Laminated Timber
2.2. Performance of Timber Rivet Connections

2.2.1. Load bearing capacity and failure modes

The connection capacity is determined by the interaction between the steel plates, timber, and rivets. The failure mode varies depending on which part fails first. For Timber Rivet connections, there are two major failure modes: ductile failure and brittle failure.

Ductile failure refers to the failure modes involving the yielding of Timber Rivets along with crushing of wood around the fasteners or the failure of metal plates (Figure 10 and Figure 11). It is the most desirable failure mode for connections since it is more predictable and does not lead to immediate structural collapse. The analysis of rivet ductile failure modes is derived from Johansen’s yielding theory where a rigid-plastic behavior for wood under bearing and dowels in bending is shown (Johansen 1949). Timber Rivets ductile failure modes in wood members can be narrowed down to three modes due to the fact that Timber Rivets are only subjected to single shear in designed connections and the rivet heads can be considered as rotationally fixed in the holes on steel plates (Zarnani 2013). The three possible ductile failure modes of a single rivet are shown in Figure 10.

Brittle failure refers to the failure of wood material in shear or tension. The most common brittle failure mode results in a block of wood material being pulled out from the main member, see Figure 12. The boundary of pulled out block are the peripheral rivets in the rivet group. Brittle failure is greatly affected by the anomalies of the wood member and hard to predict. Also, Timber Rivets act as a group in a single connection; thus, the inner configurations such as end distance, spacing parallel to grain or perpendicular to grain affect the potential failure mode.

2.2.2. Ductility, stiffness, and over strength factor

In addition to the capacity and an indication of the failure modes, the stiffness, ductility, and over strength factor can be deduced from a load-slip curve as shown in Figure 13 and Figure 14. Since wood is inherently brittle when loaded in tension or shear, ductility in a timber structure is provided by designing...
ductile steel connections. The ductility of a connection hinges on its type, geometry, and the level of displacement capacity relative to yield displacement and is defined as the ratio of its maximum displacement to yield displacement (New Zealand Timber Design Federation 2007).

Figure 11 – Ductile rivet failure mode

Figure 12 – Brittle rivet failure mode
**Figure 13** – Idealized load-slip curve for a nailed connection (New Zealand Timber Design Federation 2007)

**Figure 14** – Idealized load-slip curve for a bolted connection (New Zealand Timber Design Federation 2007)
It is also accepted to use 40% of the ultimate strength of a connection to define its yielding strength (ASTM International 2011) (New Zealand Timber Design Federation 2007). Therefore, in a load slip curve under monotonic loading, the part from original point to 0.4 $F_{max}$ is called initial linear elastic section whose slope is known as connection stiffness. As can be seen in Figure 14, bolted connections tend to have some initial alignment thereby causing low initial stiffness.

Another connection property is over strength factor, the amount by which the actual strength of yielding component could pass the designed capacity. The over strength factor depends on following factors (New Zealand Timber Design Federation 2007):

- The strength reduction factor used in the initial design.
- Strain-hardening in the steel of the yielding components due to large displacement.
- Any other unintentional over-design of the weakest components.
2.3. Design approaches for Timber Rivet Connections

The first comprehensive design approach for Timber Rivets was developed by Foschi (1973). Foschi used finite element modeling method to perform a stress analysis on the behavior of Timber Rivet connections loaded both parallel and perpendicular to grain on Glulam. This research leads to the constants used in CSA O86 code (Marjerrison 2007). Foschi’s research on the load slip behavior of Timber Rivets is considered the basis of the current Canadian design procedure.

Karacabeyli et al. (1990) performed tests on short term strength of riveted connections with Douglas fir solid wood and Glulam made from white spruce and Douglas fir. They suggested a species factor of 0.80 be used with spruce Glulam to calculate connection capacities compared with a connection assembled with Douglas fir Glulam. Few differences were discovered between connections assembled with Douglas fir Glulam and check-free Douglas fir solid wood. However, these results were not encouraged to be applied with designing cases since solid timber components could have defects.

Karacabeyli et al. (1998) also extended the member material range to the Douglas fir-larch, spruce-pine-fir (SPF), and Western Hemlock-amabilis fir sawn lumber. This study consisted of 715 lateral resistance tests and 440 rivet withdrawal tests and in the end provides material factor, $H$, for sawn lumber in different species, along with a factor for 3.2 mm side plate applications. These factors and withdrawal design values were incorporated into the 1994 version of CSA O86 (CSA 1994).

Based on previous work, Begel et al. (2004) continued to use the yield theory to fit equations for Timber Rivets loaded parallel to grain and performed tests on American domestic species. The National Code Specification (NDS) for wood construction finally included the Timber Rivets design in the code in 1997 (Marjerrison 2007).

Buchanan and Lai (1994) tested the performance of Timber Rivets in Radiata Pine (Pinus radiata) sawn lumber and found that the Timber Rivet connections in Radiata Pine have 70-90% strength compared with the connections assembled with Canadian Douglas fir. They confirmed that the European Yield Model (EYM) gives an accurate estimate of rivets strength.

Wolfe et al. (2004) conducted tests on Timber Rivets applied with Parallel Strand Lumber (PSL) and Laminated Strand Lumber (LSL) to find viable options for Timber Rivet connections. They found that Timber Rivets performed better in LSL than in PSL and better in yellow poplar PSL than in Douglas fir or Southern Pine PSL. Length of Timber Rivets did not contribute to the difference between yellow poplar LSL and yellow poplar PSL.
Popovski et al. (2002) assessed Timber Rivets’ seismic performance by quasi-static cyclic tests and found that the Timber Rivets failed in the ductile mode and showed superior performance compared with bolted connections. Besides, Timber Rivet connections dissipated a higher amount of energy before failing.

Hampson et al. (2003) tested Timber Rivet connections in terms of the effect on moment resistance brought by varying end distance. The tests were performed on Glulam, LVL and PSL, showing that splits are very common both in installations and tests even though the end distance has satisfied the requirements in the code. Splits do not necessarily drive failure mode into total brittle failure. However, greater end distance helps distribute failure between wood crushing and rivets yielding.

Stahl et al. conceptualized the brittle failure of riveted connection as the failure of the wood block surfaces around rivet array. Shear strength, tension strength parallel to grain direction were used along with the subjected area to determine the resistance in brittle wood failure (Stahl et al. 2004).

The most recent research on rivets was conducted at the University of Auckland, New Zealand by Zarnani and Quenneville (2012a). They improved prediction of capacity based on EYM by considering additional withdrawal and frictional contribution and point out there would only be 3 models in EYM needing to be tested for Timber Rivets (2012a). Moreover, they proposed a stiffness-based elastic spring model to improve the prediction of brittle failure mode (2012b).

In the following, the existing design approaches for connections with Timber Rivets are summarized:
2.3.1. Model by Foschi and Longworth

Foschi and Longworth (1975) provided a potential design approach for Timber Rivet connections which is considered the basis of the Canadian wood design code, CSA O86. Figure 15 shows the schematic geometry of a Timber Rivet connection.

![Figure 15 – Connection geometry for loading parallel to grain (Foschi & Longworth 1975)](image)

Failure caused by yield of rivets:

\[ P_R = N_R N_C P^* \]

Equation 1

Failure caused by tension in wood:

\[ P_T = \frac{\sigma A_t}{K B_t} \]

Equation 2

Failure caused by shear in the wood:

\[ P_S = \frac{\tau A_v}{K \beta_v} \frac{(N_v - 1) e_v + 50.8}{(N_v - 1) e_v + d_v} \]

Equation 3

Failure in connections loaded perpendicular to grain:
\[ P_{uw} = \frac{f_{tp}A_t}{K_i \beta_y \beta_d} \]

\[ \sigma_{uw} = \frac{5}{\sqrt[5]{2DWL_\sigma}} \]

Equation 4

Equation 5

Where:

- \( \sigma \) = Wood ultimate tensile strength parallel to grain (MPa)
- \( \tau \) = Wood ultimate tensile strength parallel to grain (MPa)
- \( f_{tp} \) = Tension strength perpendicular to grain (MPa)
- \( P^* \) = Ultimate carrying capacities of a single rivet (N)
- \( e_s \) = Row spacing (mm)
- \( d_s \) = End distance (mm)
- \( A_t \) = Area in tension (mm\(^2\))
- \( A_s \) = Area in shear (mm\(^2\))
- \( D \) = The distance from unloaded edge to the group of nails (mm)
- \( W \) = Connection width (mm)
- \( L_\sigma \) = Nail penetration length (mm)
- \( K_i, K_\tau, \beta_y, \beta_s, \beta_d \) = Tabular constants
2.3.2. Model by Buchanan and Lai

Buchanan and Lai (1994) explained the behavior of Timber Rivet connections by using the EYM. In addition to using New Zealand domestic species, they compared the different predictions generated by Canadian, American, and European codes and performed embedment tests on Chilean wood species to get input parameters for the connection capacity prediction model shown as Equation 6. This model is based on a modification of the EYM from Eurocode 5 (EC 5) (European Committee for Standardization 2004) where only three failure modes (Figure 16) are retained since rivets are only subjected to single shear. It is also assumed that as long as the minimum required thickness (3.2 mm) of the steel plates is met, these plates should not deform during loading.

\[
R_b = \min \left( \frac{f_w L_d}{d}, \frac{1.25 f_w L_d}{3} \left[ \sqrt{4 + \frac{12 M_y}{f_w d L_d^2}} - 1 \right], \frac{1.40 \sqrt{2 M_y} f_w d}{d} \right)
\]

Equation 6

Where,

- \( f_w \) = Characteristic embedment stress of wood member (MPa)
- \( d \) = Fastener’s diameter (mm)
- \( L_d \) = Penetration of the dowel in the wood member (mm)

\[
M_y = \frac{f_y d^3}{6} \quad (N \times mm)
\]

Equation 7

Where,

- \( f_y \) = Fastener yield stress (MPa)

![Mode b', mode e', mode f'](image)

Figure 16 – Mode of failure for steel to wood connections (Buchanan, Lai 1994)

Buchanan and Lai (1994) reported that the connections made with New Zealand radiate pine Glulam have lower capacity than the same connections made with Canadian Douglas Fir. They also pointed out that the Canadian Code produces some discrepancies between predicted loads and failure modes. Tested
result/prediction ratios range from 0.81 to 1.25. Overestimations on short rivets and underestimations on long rivets are attributed to the overlook of the friction between steel plates and wood and imprecise assumptions on the deformation behavior of rivets. It was concluded that further research should be conducted on configurations that cause wood tension failure (e.g. large groups of rivets with close spacing).

2.3.3. Model by Stahl et al.

Stahl et al. (2004) proposed improved models based on three potential wood failure modes shown in Figure 20.

![Figure 17](image)

**Figure 17 – Connection geometry variables: parallel-to-grain connection at left; perpendicular-to-grain connection at center; through-thickness view at right** (Stahl et al. 2004)

For brittle wood failure mode parallel-to-grain, the capacity of the rivet group in the timber is:

\[ P_w = \min(p_1, p_2, p_3) \]

Equation 8

Where, the load causing each failure mode is given by the same general formula

\[ P_1, P_2, P_3 = \tau_{ult}A_v + \sigma_{ult}A_t \]

Equation 9

Here, \( \tau_{ult} \) = wood’s ultimate strength in shear along the grain; \( \sigma_{ult} \) = wood’s ultimate strength in tension parallel to the grain; \( A_v \) = area subject to shear stress; \( A_t \) = area subjected to tensile stress. For mode 1, the shear area includes the bottom plane and two side planes

\[ A_v = (nr - 1)s_q(n - 1)s_y + 2Lp[(nc - 1)s_y + 6.4nc] \]

Equation 10

\[ A_t = Lp[(nr - 1)s_y - 3.2nk] \]

Equation 11
These equations use the connection geometry variables shown in Figure 17. Note that the rivet dimensions (6.4mm and 3.2mm) are used to subtract from the failure planes that area of wood grain disrupted by the rivets. For mode 2, the areas are

\[ A_v = w[(nc - 1)s_p + a_v] \]
\[ A_t = L_p(w - 3.2n_p) \]

Equation 12
Equation 13

For mode 3 the areas are:

\[ A_v = \frac{b}{2}\left\{ [nC - 1]s_p + a_p - 6.4n_c \right\} \]
\[ A_t = \frac{b}{2}(n_R - 1)S_q - 3.2L_pn_R \]

Equation 14
Equation 15

A simplified calculation method describing brittle failure mode when the connection is loaded perpendicular to grain is described by Stahl et al. (2004). This method no longer relies on tabular values. This model is based on the assumption that wood cracks laterally in a distance equal to the depth of rivet group (Stahl et al. 2004):

\[ P_w = \sigma_{ult \ - \ perp}A_t \]

Equation 16

Where,

\[ \sigma_{ult \ - \ perp} = \text{Ultimate strength of timber in tension perpendicular to grain direction} \]

\[ A_t = \text{Effective area over which this tension acts:} \]
\[ A_t = L_p[(n_R - 1)s_p + 2h] \]

Equation 17
If end distance $a_q$ (see Figure 17) is less than $h$, it should replace $h$ in Equation 17.

For rivet yielding failure mode, equations for dowels subjected to single shear from General Dowel Equations for Calculating Lateral Connection Values (American Forest & Paper Association 1999) are integrated into the prediction model. The foundation of this model is also Eurocode 5 (European Committee for Standardization 2004). However, assumptions are adjusted (Buchanan & Lai 1994):

- Assuming a round cross-section for Timber Rivets.
- Using bearing instead of embedment strength of wood by applying 5\% offset method.

These equations are more convenient than their original version (Stahl et al. 2004):

$$ P_{I_{III}} = F_{emd}dpl $$  \hspace{1cm} \text{Equation 18}

$$ P_{I_{IV}} = \frac{-B + \sqrt{B^2 - 4AC}}{2A} $$  \hspace{1cm} \text{Equation 19}

In Equation 18, $F_{em} = $ dowel bearing strength per unit area in the main member; and $d_l = $ dowel cross-section dimension bearing on the wood (Use $d_p$, when connection is loaded perpendicular to grain). $A$, $B$ and $C$ are defined separately for Mode III:

$$ A = \frac{1}{2F_{emd}d_l} + \frac{1}{4F_{emd}d_l} $$  \hspace{1cm} \text{Equation 20}

$$ B = \frac{L_p}{2} $$  \hspace{1cm} \text{Equation 21}

$$ C = -M_{r,p} - \frac{F_{emd}d_l^2}{4} $$  \hspace{1cm} \text{Equation 22}

And for mode IV:

$$ A = \frac{1}{2F_{em}D} + \frac{1}{2F_{em}D} $$  \hspace{1cm} \text{Equation 23}

$$ B = 0 $$  \hspace{1cm} \text{Equation 24}

$$ C = -2M_{r,p} $$  \hspace{1cm} \text{Equation 25}

$M_{r,l}$ is the moment capacity of the rivet for parallel loading, which is larger than the one for perpendicular to grain loading case ($M_{r,p}$).

The capacity of a rivet connection governed by the rivet yield/wood crush failure mode is the controlling mode capacity times the number of rivets:
\[ P_t = n_c \cdot n_R \cdot \min(P_{t_s}, P_{t_m}, P_{t_v}) \]  

**Equation 26**

*Figure 19 – Yield modes for Timber Rivet connection with steel plate on the top* (Stahl et al. 2004)

*Figure 20 – Three wood failure modes for loading parallel to grain* (Stahl et al. 2004)
2.3.4. Model by Zarnani and Quenneville

Parallel-to-grain loading – Ductile failure mode

Researchers at the University of Auckland proposed an improved EYM prediction on lateral load bearing capacity by incorporating additional withdraw and frictional effects. Tests were performed on Glulam and LVL (Zarnani & Quenneville 2012a). In this model, the possible ductile failure modes were narrowed down to the two types shown in Figure 21.

\[
Pr = \min \left\{ \frac{f_{h,odl}}{\sqrt{1 + \frac{4M_{s,l}}{f_{h,odl}L_p^2}}} - 1 + \frac{L_{efn}}{5.33} \right\} \quad \text{Mode a}
\]

\[
2\sqrt{M_{y,l}f_{h,odl}L_{efn} \over 5.33} \quad \text{Mode b}
\]

Equation 27

Where,

- \(d_l\) = the rivet cross-section dimension bearing on the wood parallel-to-grain, (equal to 3.2 mm),
- \(M_{s,l}\) = the parallel-to-grain moment capacity of the rivet, (equal to \(30000 \text{ N*mm}, (\text{Stahl et al. 2004})\)),
- \(L_p\) = the penetration depth of rivet
- \(f_{ef}\) = withdrawal resistance N/mm

\[
\begin{align*}
\cos \alpha C_f C_w F_w \\
\sin \alpha C_w F_w
\end{align*}
\]

Figure 22 – Lateral resistance induced by rivet distortion (Zarnani & Quenneville 2012a)
Zarnani and Quenneville (2012a) also provided different calculations of embedment strength both for parallel-to-grain and perpendicular-to-grain cases.

\[
f_{h,0} = \begin{cases} 
0.090(1-0.0037d)\rho & \text{for LVL} \\
0.086(1-0.0024d)\rho & \text{for glulam}
\end{cases} \quad \text{Equation 28}
\]

\[
f_{h,90} = \begin{cases} 
0.060(1-0.0037d)\rho & \text{for LVL} \\
0.043(1-0.0024d)\rho & \text{for glulam}
\end{cases} \quad \text{Equation 29}
\]

Where,

- \(d_p\) = rivet cross-section bearing on the wood perpendicular-to-grain (equal to 6.4 mm)
- \(\rho\) = the mean density of specimen. The values for lumber are also valid for Glulam.

**Parallel-to-grain loading – Brittle failure mode**

Another model was developed for connections that fail in brittle modes where the capacities are determined by tension and shear resistance in wood member (Zarnani & Quenneville 2012b). Different from the previous model, this model transfers the applied loads from the wood block to load-resisting planes depending on the stiffness ratio of each resisting plane.

\[
P_{ub} = f_{v,m}A_{ub}(1 + \frac{K_b}{K_l} + \frac{K_l}{K_b}) \quad \text{Equation 30}
\]

\[
P_{ub} = \min \left\{ P_{ub}, \frac{C_{ub}A_{ub}K_b}{C_{ab}A_{ab}K_l} P_{w1} \right\}
\]

Where,

- \(K_b\) = the average bottom shear plane stiffness
- \(K_l\) = the average lateral shear plane stiffness
- \(f_{v,m}\) = the wood’s mean strength in tension parallel to the grain
- \(f_{v,m}\) = the wood mean strength in shear along the grain
- \(C_{ab}\) and \(C_{al}\) = the ratios of the average to maximum stress on the bottom and lateral shear planes, respectively, given by Equation 31 and Equation 32

\[
C_{ab} = \frac{S_p(Nc(Nc+1)/2-1)+d_3}{Nc(L+d_3)} \quad \text{Equation 31}
\]
Perpendicular-to-grain loading – Wood splitting failure

Brittle failure in perpendicular-grain-loading is wood splitting. The major difference for the proposed model is the fundamental assumption that cracks not always grow through the entire member cross-section for slender dowel-type fasteners. However, as shown in Figure 24, there are two types of splitting modes depending on the penetration depth and member thickness ratio \( L_p/b \). The boundary of these two failure modes can be summarized as Figure 23. That is to say, given an arbitrary length of rivets, wood member thickness is a governing parameter only within certain range. Compared with model by Stahl et al., the length of cracking propagation comes with a larger factor \( \beta=2.4 \) for LVL.

\[
C_{ul} = k_e C_{ab}
\begin{cases}
ke = 1, & \text{if } de \geq 1.25Xl \\
ke = 0.8, & \text{if } de < 1.25Xl
\end{cases}
\]  
Equation 32

![Figure 23](image1.png) 

*Figure 23 – Occurrence zone of wood splitting failure modes* (Zarnani 2013)

![Figure 24](image2.png) 

*Figure 24 – Different wood splitting failure modes: (a) full thickness splitting, (b) partial thickness splitting* (Zarnani 2013)
Therefore, the splitting resistance of such connections can be calculated through

\[ P_w = n_p \cdot \min(P_{w,\text{net}}, P_{w,s}) \]  

Equation 33

Where,

\[ n_p = \text{the number of steel plates} \]

Partial splitting mode

\[ P_{w,\text{net}} = C_f f d [W_{net} + \min(\beta h_c, d_{a,l}) + \min(\beta h_c, d_{a,r})] \]  

Equation 34

Where,

\[ C_f = \begin{cases} 1.264 \zeta^{-0.37}, & \text{if } \zeta < 1.9 \\ 1, & \text{if } \zeta \geq 1.9 \end{cases} \]  

Equation 35

- \( d_{a,l} = \text{End distance on the left} \)
- \( d_{a,r} = \text{End distance on the right} \)
- \( \beta = 2.4 \)

Where,

\[ \zeta = \frac{d_{c,u}}{S_s(n_c - 1)} \]  

Equation 36

\[ Figure 25 – Perpendicular-to-grain loading connection geometry (Zarnani 2013) \]
Full width splitting:

\[
P_{t,b} = X_p \eta b C_p \sqrt{\frac{h_e}{1 - \frac{h_e}{h}}}
\]

Equation 37

Where,

\[
\eta = \frac{\min(\gamma h_e, d_{a,L}) + \min(\gamma h_e, d_{a,R}) + W_{net}}{2 \gamma h_e}
\]

Equation 38

Where,

- \(X_p\) = adjustment factor for tension perpendicular to grain (1.23 for LVL, 1.28 for Glulam and 1.31 for lumber)
- \(\gamma\) = effective crack length coefficient for splitting mode A (4 for LVL and 2.7 for Glulam)
- \(d_{a,L}\) = End distance on the left
- \(d_{a,R}\) = End distance on the right

**Perpendicular-to-grain loading – Ductile failure**

The ductile failure in perpendicular-to-grain loading is essentially a bearing failure of wood. Such bearing failure characterizes the localized wood crushing caused by compression from dowels. The model to calculate the rivet resistance on ductile failure uses the same principle as the one applied for parallel-to-grain case because they are developed based on the Eurocode 5 (European Committee for Standardization 2004). However, withdrawal resistance is considered in this model.

\[
P_R = n_p \cdot n_R \cdot n_C \cdot \min \left\{ \begin{array}{l} f_{h,90} L_d d_p (\sqrt{2 + \frac{4 M_{r,p}}{f_{h,90} d_p}} - 1) + \frac{f_{ax} L_{fix}}{5.33} \\ 2 \sqrt{M_{r,s} f_{h,90} d_p} + \frac{f_{ax} L_{fix}}{5.33} \end{array} \right\}
\]

Equation 39

Where,

- \(M\) = the perpendicular-to-grain moment capacity of rivet
- \(d_p = 6.4 \text{ mm}\)
- \(f_{h,90}\) = embedment strength for rivets bearing perpendicular to grain
- \(f_{ax}\) = withdrawal resistance N/mm
2.3.5. CSA-O86 Design procedure (Canadian Standard Association 2009)

Timber Rivets joints designed with this code should meet the requirement that factored strength is greater than or equal to the effect of factored loads. For loading parallel to grain, the factored lateral strength resistance, \( P_r \), of the joint shall be taken as:

\[
P_r = \phi P_u H
\]

Equation 40

Where,

\begin{itemize}
  \item \( \phi = 0.6 \)
  \item \( P_u \) = lateral resistance parallel to grain, kN
  \item \( H \) = material factor as listed in CSA (see table 3)
\end{itemize}

<table>
<thead>
<tr>
<th>Material</th>
<th>( H ) factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Douglas-Fir-Larch Glulam</td>
<td>1.0</td>
</tr>
<tr>
<td>Spruce-Lodge pole Pine-Jack Pine Glulam</td>
<td>0.80</td>
</tr>
<tr>
<td>Douglas-Fir-Larch Sawn Timber</td>
<td>0.50</td>
</tr>
<tr>
<td>Hem-Fir Sawn Timber</td>
<td>0.45</td>
</tr>
<tr>
<td>Spruce-Pine Sawn Timber</td>
<td>0.40</td>
</tr>
</tbody>
</table>

The unit capacity per rivet joint parallel to grain, \( P_u \), shall be calculated as the lesser of \( P_y \) or \( P_w \):

\[
P_y = (1.09L_p^{0.32}n_R n_C)J_y K_y K_T
\]

Equation 41

\[
P_w = p_w K_y K_T
\]

Equation 42

Where,

\begin{itemize}
  \item \( L_p \) = length of penetration, mm
  \item \( n_R \) = number of rows of rivets parallel to direction of load
  \item \( n_C \) = number of rivets per row
  \item \( J_y \) = side plate factor
  \item \( p_w \) = lateral resistance parallel to grain
\end{itemize}

For loading perpendicular to grain, the factored lateral strength resistance, \( Q_r \), of the joint shall be taken as follows:

\[
Q_r = \phi Q_w H
\]

Equation 43
Where,

- \( \phi = 0.6 \)
- \( Q_u = \) lateral resistance perpendicular to grain, kN
- \( H = \) material factor

The unit per rivet joint perpendicular to grain, \( Q_u \), shall be calculated as the lesser of \( Q_y \) or \( Q_w \), as follows:

\[
Q_y = (0.62L_p^{0.32}n_{nc}n_RC_Ln_Kn_Jn_K)K_T
\]

Equation 44

\[
Q_w = (q_wL_p^{0.8}C_tK_DK_SK_T)
\]

Equation 45

Where,

- \( L_p = \) length of penetration, mm
- \( n_R = \) number of rows of rivets parallel to direction of load
- \( n_C = \) number of rivets per row
- \( J_y = \) side plate factor
- \( q_w = \) lateral resistance perpendicular to grain
- \( C_t \) is determined from Table 10.7.2.5 B in CSA O86-09 Summary of prediction models

Based on the above descriptions, a summary of different input parameters being used by each model is shown in Table 4.

### Table 4 – Summary of input parameter in each predictive model

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Foschi &amp; Longworth</th>
<th>Stahl</th>
<th>Zarnani</th>
<th>CSA O86</th>
</tr>
</thead>
<tbody>
<tr>
<td>loaded edge distance, ( d_{el} )</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Unloaded edge distance, ( d_{eu} )</td>
<td>YES</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Connection width, ( S_p(n_R-1) )</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Connection length, ( S_p(n_C-1) )</td>
<td>YES</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Penetration depth, ( L_p )</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>End distance, ( d_a )</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Member thickness, ( b )</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
<td>NO</td>
</tr>
</tbody>
</table>
3. Experimental Investigation

In 2013, the University of British Columbia Vancouver (UBC) was approached by Timber System Ltd. regarding the application of Timber Rivet connections in LVL. The proposed research was supported through a NSERC research grant to Dr. Tannert. A total of 29 series with 103 specimens made of Engineered Wood Products (LVL and CLT) were produced and subsequently tested under quasi-static monotonic and cyclic tests.

3.1. Materials

The timber members for the connections consisting of LVL were cut from LP Solidstart® LVL 2950Fb-2.0E beams. Panels were secondary laminated by Brisco Manufacturing Ltd into thick panels and then cut into beams. Those timber members consisting of CLT were cut from Structurlam SPF No.2 panels. Rivets in this project were manufactured by Specialized Timber Fasteners and sponsored by Timber System Ltd. Rivets of two different lengths (65mm and 90mm) were used to assemble two-sided Timber Rivet connections.

Steel plates were custom cut into different lengths but the same width to meet different testing purposes. Plates were made from CAN3-G40.21-M87 Grade 300W steel and painted yellow for better visual contrast with wood, see Figure 26. All corners of the steel plates were rounded as 6 mm fillet to avoid potential risk of injury during assembly. The steel plates were attached to the wood products by hammering rivets through the predrilled holes on the steel plates. Further installations were completed by using a RIDGID® pneumatic palm hammer. All rivets were installed by aligning the long axis of their cross sections with the wood grain direction (outer layer grain directions for CLT). To fulfill rivets’ functions, these were driven in as deep as possible. The slight deformation on the tapered rivet head creates extra fixity preventing rivets from rotating.

![Painted and predrilled steel plate](Figure 26)
3.2. Specimen Description

For the experiments, samples with different sizes and rivet layouts were divided into different groups according to following variables: $n_R \times n_C$ = number of rows by columns of rivets, $S_p$ = rivet row spacing, $S_q$ = rivet column spacing, $b$ = LVL member thickness, $w$ = LVL member width, $d_u$, $d_e$, $de$ = rivet end, bottom, and edge distance. 2*8, 3*3, 4*4 and 4*6 Timber Rivets layouts were adopted in the experiment due to their popularity in the practical uses. A schematic of the connection layout is shown in Figure 27.

![Connection layout](image)

*Figure 27 – Connection layout (Zarnani 2013)*

3.2.1. LVL Samples

The design considered spacing between rivets and end distances aiming to distribute failure modes evenly in brittle and ductile failure modes. To achieve brittle failure mode, for each series, a control group was intentionally designed with 15 mm rivet spacing perpendicular to the grain direction. The bearing end distance in parallel-to-grain loading and the end distance in perpendicular-to-grain loading were also used as parameters controlling the failure modes. Configurations of samples are shown in Table 5 where $d_{eu}$ is the unloaded edge distance and $d_{el}$ is the loaded edge distance.
Table 5 – LVL Connection sample configurations

<table>
<thead>
<tr>
<th>Loading Direction</th>
<th>Group Name</th>
<th>Number of replicates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perpendicular</td>
<td>P28-725</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>P28-1225</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>P28-715</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>P28-1215</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>P33-725</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>P33-1225</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>P33-715</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>P33-1215</td>
<td>5</td>
</tr>
<tr>
<td>Parallel</td>
<td>L44-15150</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>L44-1575</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>L44-2575</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>L44-25150</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>L33-2575</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>L33-25150</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>L33-1575</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>L33-15150</td>
<td>3</td>
</tr>
</tbody>
</table>

3.2.2. CLT Samples

CLT samples had two types of thickness: 100 mm and 315 mm and were all subjected to parallel-to-grain loading. Following two different thickness, two rivet lengths were adopted in the experiment namely 65 mm on 3-ply CLT and 65/90 mm on 9-ply CLT. Major configuration parameters are listed in Table 6. Due to limitation in the thickness of 3-ply CLT, the 65 mm rivets were not able to be installed following the method instructed in the CSA O86 designing code. The author tentatively installed them in a staggered way shown in Figure 28.
Figure 28 – Schematic staggered installation of rivets on 3-ply CLT

Table 6 – CLT connection sample configurations

<table>
<thead>
<tr>
<th>Group Name</th>
<th>$n_k\times n_C$</th>
<th>$d_a$</th>
<th>$b\times h\times l$</th>
<th>$S_p$ [mm]</th>
<th>$S_q$ [mm]</th>
<th>Rivet $L$ [mm]</th>
<th>Number of replicates</th>
</tr>
</thead>
<tbody>
<tr>
<td>L46-25</td>
<td>4*6</td>
<td>75</td>
<td>100<em>140</em>850</td>
<td>50</td>
<td>25</td>
<td>65</td>
<td>3</td>
</tr>
<tr>
<td>L46-15</td>
<td>4*6</td>
<td>75</td>
<td>100<em>140</em>850</td>
<td>50</td>
<td>15</td>
<td>65</td>
<td>3</td>
</tr>
<tr>
<td>L46-25(9)</td>
<td>4*6</td>
<td>75</td>
<td>315<em>140</em>600</td>
<td>25</td>
<td>25</td>
<td>65</td>
<td>3</td>
</tr>
<tr>
<td>L46-15(9)</td>
<td>4*6</td>
<td>75</td>
<td>315<em>140</em>600</td>
<td>25</td>
<td>15</td>
<td>65</td>
<td>3</td>
</tr>
<tr>
<td>L46-25(9-90)</td>
<td>4*6</td>
<td>75</td>
<td>315<em>140</em>600</td>
<td>25</td>
<td>25</td>
<td>90</td>
<td>3</td>
</tr>
<tr>
<td>L46-15(9-90)</td>
<td>4*6</td>
<td>75</td>
<td>315<em>140</em>600</td>
<td>25</td>
<td>15</td>
<td>90</td>
<td>3</td>
</tr>
</tbody>
</table>
3.3. Methods

3.3.1. Material Strength Tests

In order to get material strength parameters as inputs for prediction models, strength tests were performed on Douglas Fir LVL following the ASTM D143 “Standard Test Methods for Small Clear Specimens of Timber”. Properties tested included shear strength parallel to grain, tension strength parallel to grain and tension strength perpendicular to grain. In terms of parallel-to-grain tension strength tests, dog-bone samples with reduced center width were made to replace the design in ASTM D143 (Tannert et al. 2012). A schematic and photo of a dog-bone sample are shown in Figure 29 with thickness equal to 10 mm. Samples for testing on shear strength and tension perpendicular to grain were prepared according to ASTM D143 requirements. Figure 30 shows the sample prepared for shear tests parallel to grain. Figure 31 shows the sample prepared for tension tests perpendicular to grain.

Figure 29 – Dog-bone samples for tests on tension strength parallel to grain
Tests on material strength were performed according to ASTM D143 “Standard Test Methods for Small Clear Specimens of Timber” (ASTM International 2007). The loading speed was set at 1 mm/min. 30 replicates were tested for each mechanical property. For dog-bone samples, the width and thickness of the center cross section were measured before each test individually. A typical setup of tests on dog-bone samples is shown in Figure 32.
Figure 32 – Tension test on dog-bone LVL samples
3.3.2. Design of steel plates

The design of the steel plates consisted of two parts: the layouts of the holes for the rivets and the holes for the bolt connections between the plates and the test fixtures. CSA O86 (Canadian Standard Association 2009) defines the rules on the holes for Timber Rivets. The considerations for the steel plate design were to avoid gross-area yield, net-area rupture, plate gross-area shear failure, and net-area shear failure under the potential maximum load (200 kN shared between two plates). Properties of ASTM A36 steel were used according to the requirements from CSA O86 (Canadian Standard Association 2009). The steel plates were designed in accordance with CAN/CSA-S16-01 (Canadian Standards Association 2001). Figure 33 shows the schematic potential failure modes. The parameters affecting the results were plate thickness, hole diameter, edge distance, and bearing end distance as they determined the cross section area subjected to tension or shear during loading. The weakest resistance governed the whole design. All the detailed technical drawings of steel plates are summarized in Appendix D.

![Steel plate failure modes](image)

*Figure 33 – Steel plate failure modes: left) Tensile net area rupture (through the bolt line); middle) Tension and shear block failure; right) Plate shear failure (by bolts pulling out the end of the plate)*
3.3.3. Parallel to Grain Loading Tests

The tests were performed in the Wood Mechanics Laboratory at UBC in a test frame with a 250 kN capacity actuator. As shown in Figure 34, the steel fixtures were pin-connected to allow for rotation and avoid any additional moment loading caused by unequal stiffness of the two sides during loading.

One end of connections was connected to the load cell, while the other end of the connection was connected to the horizontal steel frame by a steel fixture identical to the one connecting to the load cell. Four transducers with 25.4 mm stroke were installed to measure the relative displacement between the steel plates and the timber member following the method shown in Figure 36.

![Figure 34 – Setup for parallel-to-grain loaded samples](image-url)
3.3.4. Perpendicular to Grain Loading Tests

As shown in Figure 35, connections under loading perpendicular to grain were clamped by steel frames on two ends on the two steel blocks linked to the same test frame by bolts. Transducers with 25.4 mm stroke were installed under steel plates to record the relative displacement between each steel plate and the wood member.

![Figure 35 – Setup for perpendicular-to-grain loaded samples](image)

3.3.5. Monotonic tests

Quasi-static monotonic tension tests were conducted following ASTM D1761-12 “Standard Test Methods for Mechanical Fasteners in Wood” (ASTM International 2012a). The loading was displacement-controlled at 1.4 mm/min so that samples were expected to reach failure after approximately 10 to 15 minutes. The applied load from the actuator and the relative displacements between steel plates and wood (on each side of the specimen) were recorded by transducers installed on the wood member. As shown in Figure 36, the body of a transducer was fixed on the wood member while the arm of the transducer was touching the edge of a steel plate or a magnetic block (or button) attached on the steel plate. Tests were stopped when the load measured by the load cell dropped 20% below peak load or the displacement reached values outside the ranges of transducers (25.4 mm). Data were recorded at a frequency of 4 Hz.

Although the entire loading process was recorded, the connection capacities were taken as the maximum load reading up to 4.8 mm relative displacement measured in the tests. The average dimension of the two axis of a rivet’s oval shape cross section (3.2mm by 6.4 mm) is 4.8 mm. This procedure was also adopted in the published literature (Buchanan & Lai 1994), (Karacabeyli et al. 1998), (Stahl et al. 2004), (Zarnani
2013). Therefore, by using 4.8 mm as an indicator for ultimate load of a rivet array, results in this experiment are comparable with those from previous research.

![Figure 36 – Schematic installation of transducers](image)

### 3.3.6. Cyclic Tests

Cyclic tests were performed on selected LVL and CLT series according to ISO 16670 (Technical Committee ISO/TC 165 2003) with a cycle frequency equal to 0.2 Hz. Loading was displacement-controlled with two different displacement patterns. In the pattern 1, each step consisted of one single cycle while in the other pattern each step was made up of 3 same cycles. Amplitude in each step was based on the ultimate displacement recorded in the same series tested in the monotonic tests. The first-step amplitude calculated for each sample was approximately 3 mm. In order to smooth the progress of cyclic tests, two start-up steps (1 and 2 mm) were added into loading protocol additionally. Since steel plates in this experiment were designed for tension only, the compression half cycle was cut in the whole experiment to avoid potential buckling. A schematic cyclic displacement schedule and an amplitude table are respectively shown in Figure 37 and Table 7. The installation of transducers followed the method used in the monotonic tests. Data were recorded at a frequency of 100 Hz.
The procedure from ASTM E2126 (ASTM International 2011) was used to obtain the connection properties from the hysteresis curves. In ASTM E2126, an envelope curve is defined as a locus of extremities from the load-slip hysteresis loops. The first cycle envelope curves are made up of the first cycle peak load in each loading step. In a typical hysteresis curve, a positive displacement produces a positive envelope curve while a negative displacement produces a negative envelope curve. In this experiment, the displacement was merely generated with the tension tests so that only the positive envelope curves could be obtained from the load-slip curves.

A series of connection properties can be drawn from first cycle envelope curves, which include yielding load \(F_y\), yield displacement \(\Delta_y\), peak load \(F_{\text{max}}\), peak load displacement \(\Delta F_{\text{max}}\), ultimate displacement \(\Delta_u\), initial stiffness \(K\), ductility and over strength ratio. Yielding load was calculated based on Equation 46 (ASTM International 2011)

\[
F_y = (\Delta_u - \sqrt{\Delta_u^2 - \frac{2A}{K}})K
\]  

Equation 46

If \(\Delta_u^2 - \frac{2A}{K} < 0\), it is permitted to assume \(F_y = 0.85 \ F_{\text{max}}\)

Where,

- \(F_y\) = yield load, kN
- \(A\) = the area under envelope curve from zero to ultimate displacement \((\Delta_u)\) of the connection, J
- \(F_{\text{max}}\) = the peak load resisted by the connection in the given envelope curve, kN
- \(\Delta_{0.4}\) = displacement at 0.4 \(F_{\text{max}}\), mm
- \(K\) = connection initial stiffness, kN/mm
**Figure 37 – Schematic schedule for cyclic loading protocol**

**Table 7 – Displacement amplitude**

<table>
<thead>
<tr>
<th>Step</th>
<th>Number of cycle</th>
<th>Amplitude (% of Ultimate displacement)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1 mm</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2 mm</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1.3%</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>2.5%</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>5.0%</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>7.5%</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>10%</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>20%</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>40%</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>60%</td>
</tr>
<tr>
<td>11</td>
<td>3</td>
<td>80%</td>
</tr>
<tr>
<td>12</td>
<td>3</td>
<td>100%</td>
</tr>
<tr>
<td>13</td>
<td>3</td>
<td>120%</td>
</tr>
<tr>
<td>14</td>
<td>3</td>
<td>140%</td>
</tr>
</tbody>
</table>
3.3.7. Statistical analyses

Statistical analyses in this research consisted of calculating 95% confidence intervals for connection capacities and performing analysis of variance to evaluate the effect of the input parameters. To calculate the 95% confidence interval, student’s distribution was used, because the variance of connection capacity in the population was unknown and had to be estimated from the sample data. The difference between the student’s distribution and the normal distribution is the shape of distribution curve when sample size is small. With a small sample size, the student’s distribution is leptokurtic (a distribution with long tail), which means it has relatively more scores in the tail than the normal distribution. As a result, more extension is needed from the mean to contain a given proportion of the area (Lane 2011).

Following the calculations of 95% confidence interval for each series, the predictions were checked if they fell into their respective 95% confidence intervals. Acceptance or rejection from such tests was treated as an indicator of the goodness of the prediction. The $F$-test in one-way analysis of variance was used to assess whether the connection capacity in a certain series is different from the control series thereby suggesting whether this parameter was significant in affecting the final connection capacity. The parameters tested in the $F$-test were determined by the discrepancies among the parameters adopted in different Timber Rivet design models.
4. Results and Discussion

4.1. LVL material parameters

Material parameters obtained in the tests included tension strength parallel to grain, tension strength perpendicular to grain, and shear strength parallel to grain. These properties are summarized in Table 8. These strength properties were subsequently used as strength input values for the prediction models discussed in Section 2.3.

Table 8 – Mean strength of Douglas fir LVL – S (2.0E)

<table>
<thead>
<tr>
<th>Strength Type</th>
<th>Strength (MPa)</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension parallel to grain</td>
<td>56.7</td>
<td>33.6%</td>
</tr>
<tr>
<td>Shear parallel to grain</td>
<td>6.7</td>
<td>8.6%</td>
</tr>
<tr>
<td>Tension perpendicular to grain</td>
<td>1.0</td>
<td>16.9%</td>
</tr>
</tbody>
</table>

4.2. Quasi-static monotonic tests on LVL – parallel to the grain

Delta ($\Delta$) was used to evaluate the deviation of test results from the predictions generated by the New Zealand model:

$$\Delta = \left( \frac{P_{\text{test}} - P_{\text{prediction}}}{P_{\text{prediction}}} \right)$$  

Equation 47

Where,

- $P_{\text{test}}$ = Connection Capacity in the tests
- $P_{\text{prediction}}$ = Connection Capacity predicted by New Zealand models

4.2.1. Connection performance

Two typical load slip curves are presented in Figure 38 and Figure 39. The load slip curves for all test series are included Appendix A. Tested results with respective predictions are summarized in Table 9. Neither the expected capacities nor the tested capacities refer to the maximum capacity a Timber Rivet connection can reach during loading. Rather, they all point to the maximum load at which point the connection displacement reached 4.8 mm. Despite the adoption of 4.8 mm as the determining point for connection capacity, the maximum load of each sample and displacement at the maximum load is summarized in Appendix C. In order to obtain predictions close to the test results, all the reduction factors
for engineering design were eliminated from the prediction models and a short duration of load assumption was applied to the calculations.

**Figure 38 – Load-slip curve for typical ductile failure (LVL)**

**Figure 39 – Load-slip curve for typical brittle failure (LVL)**
Most of the models in the literature separate Timber Rivet connection failure into two modes: ductile and brittle. However, a mixed failure mode consisting of both rivet deflection and timber splitting has been proposed (Zarnani & Quenneville 2014). Based on the experimental observations, only those samples whose load-slip curves demonstrated a sudden dip should be considered to be a potential mixed failure mode. As shown in Table 9, there were multiple failure modes within replicates for each single series. This was due to intrinsic variations within the wood and the connections themselves and the close boundary condition for this type of rivet layout. The patterns tested in the experiment were based on the most common layouts used in the construction industry, which explains why the failure modes were severely skewed to the ductile side.

Typical failure modes are shown in Figure 40 and Figure 41. In Figure 40, the Timber Rivets show a consistent yielded shape under the testing load. In the case of the timber member, crushing failure is so evident that the holes into which the rivets had been driven can hardly be seen. This kind of failure is defined as ductile failure mode. However, two cracks propagated from the bottom rivet column to the end of the timber member. These two columns were in the outermost rivet rows, suggesting these two rows were subjected to a larger load than the inner rows. Although such cracks are defined as brittle failure, no evidence suggesting brittle failure was found on the load-slip plot. In Figure 41, a block of wood was separated and pulled out by the rivet array although the Timber Rivets had not yielded. This type of failure is defined as brittle failure mode.

<table>
<thead>
<tr>
<th>Group Name</th>
<th>Expected failure</th>
<th>Expected capacity [kN]</th>
<th>Average test capacity [kN]</th>
<th>Δ</th>
<th>Failure mode in tests</th>
<th>COV [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L44-1575</td>
<td>Ductile</td>
<td>150.0</td>
<td>122.0</td>
<td>-19%</td>
<td>Brittle</td>
<td>14.2</td>
</tr>
<tr>
<td>L44-15150</td>
<td>Ductile</td>
<td>150.0</td>
<td>133.7</td>
<td>-11%</td>
<td>Ductile/Mixed</td>
<td>13.6</td>
</tr>
<tr>
<td>L44-2575</td>
<td>Ductile</td>
<td>150.0</td>
<td>141.3</td>
<td>-6%</td>
<td>Ductile</td>
<td>6.5</td>
</tr>
<tr>
<td>L44-25150</td>
<td>Ductile</td>
<td>150.0</td>
<td>148.0</td>
<td>-1%</td>
<td>Ductile</td>
<td>5.5</td>
</tr>
<tr>
<td>L33-2575</td>
<td>Ductile</td>
<td>85.0</td>
<td>87.7</td>
<td>+3%</td>
<td>Ductile</td>
<td>3.5</td>
</tr>
<tr>
<td>L33-25150</td>
<td>Ductile</td>
<td>85.0</td>
<td>98.3</td>
<td>+16%</td>
<td>Ductile</td>
<td>1.6</td>
</tr>
<tr>
<td>L33-1575</td>
<td>Ductile</td>
<td>85.0</td>
<td>85.7</td>
<td>+1%</td>
<td>Ductile/Mixed</td>
<td>7.1</td>
</tr>
<tr>
<td>L33-15150</td>
<td>Ductile</td>
<td>85.0</td>
<td>95.7</td>
<td>+13%</td>
<td>Ductile</td>
<td>5.3</td>
</tr>
</tbody>
</table>

*Table 9 – Tests results on parallel-to-grain loading groups (LVL)*
Figure 40 – Typical ductile failure on parallel-to-grain loading samples

Figure 41 – Typical brittle failure on parallel-to-grain loading samples
4.2.2. The performance of the “stronger” end connection

Parallel-to-grain loaded samples were prepared by installing a double-sided rivet connection at both ends of a timber member. Popovski and Karacabeyli (2002) reported that two-end connections showed significantly different displacements between the two ends during the monotonic tests. This is because once non-linear deformation begins to develop in one end, the reduced stiffness of that particular connection will result in an increasing deformation.

Although the relatively weaker end connections were subjected to the greatest displacement applied by the actuator head, the performance of the “stronger” end connections warranted examination. Table 10 shows the comparison of the connection capacities from two different ends. $P_{\text{strong}}$ is the connection capacity of the “stronger” end. To estimate the connection capacities of the “stronger” end, the displacement recorded at the “stronger” end was used, along with the load readings. A maximum load of up to 4.8 mm relative displacement was adopted as the connection capacity. $P_{\text{weak}}$ is the connection capacity of the “weaker” end and also the connection capacity discussed in Section 4.2.1. Judging from $P_{\text{strong}}/P_{\text{weak}}$, the intact ends of the connections were, for the most part, less than 10% stronger than those that failed during the monotonic tests. Figure 42 shows a close-up photograph of the “stronger end. Since the relative displacement on at the “stronger” end was much smaller than on at the other end, after loading and its own recovery, the residual displacement was merely 1-2 mm.

The curves in Figure 43 and Figure 44 are two typical load-slip curves of the “stronger” end plotted with relative displacement data from the “stronger” end. Since the curves were plotted with the same load readings discussed in Section 4.2.1, the only difference was the smaller displacement at the same load level. In Figure 45, the load slip curves from the stronger end were named with an additional “S”. The stiffness of the “stronger” end connections (the slopes of the initial curves) were higher than the “weaker” end stiffness. With less stiffness, displacement was mostly accumulated at the weaker end.
Figure 42 – Close up of the “stronger” end

Table 10 – Comparison of stronger end and weaker end (LVL)

<table>
<thead>
<tr>
<th>Series</th>
<th>Stronger end [kN]</th>
<th>Weaker end [kN]</th>
<th>( P_{\text{strong}}/P_{\text{weak}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>L44-1575</td>
<td>127.9</td>
<td>121.00</td>
<td>1.1</td>
</tr>
<tr>
<td>L44-2575</td>
<td>147.3</td>
<td>141.3</td>
<td>1.0</td>
</tr>
<tr>
<td>L44-15150</td>
<td>138.3</td>
<td>131.7</td>
<td>1.1</td>
</tr>
<tr>
<td>L44-25150</td>
<td>158.8</td>
<td>141.0</td>
<td>1.1</td>
</tr>
<tr>
<td>L33-1575</td>
<td>87.5</td>
<td>85.7</td>
<td>1.0</td>
</tr>
<tr>
<td>L33-2575</td>
<td>88.4</td>
<td>87.7</td>
<td>1.0</td>
</tr>
<tr>
<td>L33-15150</td>
<td>95.8</td>
<td>95.7</td>
<td>1.0</td>
</tr>
<tr>
<td>L33-25150</td>
<td>98.7</td>
<td>98.4</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Where the edge of the steel plate used to be.
Figure 43 – Typical load-slip curve of the “stronger” end connection of ductile failure series (LVL)

Figure 44 – Typical load-slip curve of the “stronger” end connection of brittle failure series (LVL)
Figure 45 – Load-slip curves from two ends of the same series (LVL)
4.3. Quasi-static monotonic test on LVL – perpendicular-to-grain loading

Connection capacities were determined based on the same criterion for parallel-to-grain loading: the loads at 4.8 mm displacement were taken as the connection capacities. Test results are summarized in Table 11.

<table>
<thead>
<tr>
<th>Group Name</th>
<th>Expected Failure</th>
<th>Expected Capacity [kN]</th>
<th>Average test capacity [kN]</th>
<th>Δ</th>
<th>Failure mode in tests</th>
<th>COV [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>P28-725</td>
<td>Brittle</td>
<td>106.0</td>
<td>93.2</td>
<td>-12%</td>
<td>Brittle</td>
<td>13.9</td>
</tr>
<tr>
<td>P28-1225</td>
<td>Mixed</td>
<td>111.0</td>
<td>138.7</td>
<td>25%</td>
<td>Mixed</td>
<td>2.2</td>
</tr>
<tr>
<td>P28-715</td>
<td>Brittle</td>
<td>85.0</td>
<td>88.5</td>
<td>4%</td>
<td>Brittle</td>
<td>13.0</td>
</tr>
<tr>
<td>P28-1215</td>
<td>Mixed</td>
<td>107.0</td>
<td>87.5</td>
<td>-18%</td>
<td>Mixed/Brittle/Ductile</td>
<td>9.3</td>
</tr>
<tr>
<td>P33-725</td>
<td>Mixed</td>
<td>60.0</td>
<td>58.8</td>
<td>-2%</td>
<td>Ductile/Mixed</td>
<td>6.5</td>
</tr>
<tr>
<td>P33-1225</td>
<td>Mixed</td>
<td>60.0</td>
<td>60.3</td>
<td>0%</td>
<td>Ductile/Mixed</td>
<td>14.6</td>
</tr>
<tr>
<td>P33-715</td>
<td>Brittle</td>
<td>52.0</td>
<td>50.6</td>
<td>-3%</td>
<td>Mixed</td>
<td>9.3</td>
</tr>
<tr>
<td>P33-1215</td>
<td>Brittle</td>
<td>52.0</td>
<td>53.8</td>
<td>3%</td>
<td>Ductile</td>
<td>4.8</td>
</tr>
</tbody>
</table>

Perpendicular-to-grain loading samples showed a greater number of mixed failure modes than was observed in the parallel-to-grain loading. As defined in the literature, the brittle failure modes in perpendicular-to-grain loading cases consist of the splitting of a timber member of the splitting of timber members along the grain direction, while the ductile failure is majorly the bearing failure of timber member. Therefore, the mixed failure should be a mixture of such two failure modes as shown in Figure 46. The example shown in Figure 46 came from series P28, where the rivet layout was 2*8 and the rivet spacing across the grain 25 mm. All other load-displacement curves are included in Appendix A.3.
Figure 46 – Mixed failure mode in perpendicular-to-grain loading tests (LVL)

Figure 47 – Typical load slip curve for mixed failure mode
Figure 48 – Brittle failure in traverse to grain loading (LVL)

Figure 49 – Typical load-slip curve for brittle failure in perpendicular-to-grain loading (LVL)
4.4. Discussion of static LVL tests

The accuracy of the prediction with respect to connection capacity was evaluated by determining whether or not the prediction values fall into the 95% interval calculated on the basis of the tested values. Failure to fall into the interval means that (at $\alpha=0.05$ levels) the null-hypotheses (result = prediction) was rejected. Connection capacities were assumed to be distributed normally because the central limit theorem states that the mean of several random variables independently drawn from the same distribution is approximately distributed normally (Grinstead & Snell 1998).

Judging from the LVL sample test results, New Zealand model (Zarnani 2013) produced close estimations using Douglas fir LVL strength parameters obtained from ASTM standard tests. There were 12 of the 16 series’ predictions falling within the 95% confidence interval. Even in the case of the rejected predictions, the predicted values were not far off from either the lower or upper limits of the 95% confidence interval. Specifically, only P28-1215 (marked as red in Table 12) had a prediction higher than the upper limit, which was considered unsafe. Although outside the 95% confidence interval, the other three series may be considered conservative in terms of engineering design.

<table>
<thead>
<tr>
<th>Loading Direction</th>
<th>Group Name</th>
<th>Expected Failure</th>
<th>LL of 95% Conf. Int.</th>
<th>UL of 95% Conf. Int.</th>
<th>Expected [kN]</th>
<th>Accept</th>
<th>Failure Mode in Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perp.</td>
<td>P28-725</td>
<td>Brittle</td>
<td>96.5</td>
<td>127.1</td>
<td>106.0</td>
<td>YES</td>
<td>Brittle</td>
</tr>
<tr>
<td></td>
<td>P28-1225</td>
<td>Mixed</td>
<td>122.4</td>
<td>155</td>
<td>111.0</td>
<td>NO</td>
<td>Mixed</td>
</tr>
<tr>
<td></td>
<td>P28-715</td>
<td>Brittle</td>
<td>68.9</td>
<td>108.1</td>
<td>85.0</td>
<td>YES</td>
<td>Brittle</td>
</tr>
<tr>
<td></td>
<td>P28-1215</td>
<td>Mixed</td>
<td>77</td>
<td>98</td>
<td>107.0</td>
<td>NO</td>
<td>Mixed/Brittle/Ductile</td>
</tr>
<tr>
<td></td>
<td>P33-725</td>
<td>Mixed</td>
<td>53.5</td>
<td>64.1</td>
<td>60.0</td>
<td>YES</td>
<td>Ductile/Mixed</td>
</tr>
<tr>
<td></td>
<td>P33-1225</td>
<td>Mixed</td>
<td>52.3</td>
<td>68.3</td>
<td>60.0</td>
<td>YES</td>
<td>Ductile/Mixed</td>
</tr>
<tr>
<td></td>
<td>P33-715</td>
<td>Brittle</td>
<td>45.3</td>
<td>55.9</td>
<td>52.0</td>
<td>YES</td>
<td>Mixed</td>
</tr>
<tr>
<td></td>
<td>P33-1215</td>
<td>Brittle</td>
<td>45.8</td>
<td>61.8</td>
<td>52.0</td>
<td>YES</td>
<td>Ductile</td>
</tr>
<tr>
<td>Parallel</td>
<td>L44-1575</td>
<td>Ductile</td>
<td>87.5</td>
<td>156.5</td>
<td>150.0</td>
<td>YES</td>
<td>Brittle</td>
</tr>
<tr>
<td></td>
<td>L44-15150</td>
<td>Ductile</td>
<td>98.7</td>
<td>168.6</td>
<td>150.0</td>
<td>YES</td>
<td>Ductile/Mixed</td>
</tr>
<tr>
<td></td>
<td>L44-2575</td>
<td>Ductile</td>
<td>106.8</td>
<td>175.9</td>
<td>150.0</td>
<td>YES</td>
<td>Ductile</td>
</tr>
<tr>
<td></td>
<td>L44-25150</td>
<td>Ductile</td>
<td>113</td>
<td>183</td>
<td>150.0</td>
<td>YES</td>
<td>Ductile</td>
</tr>
<tr>
<td></td>
<td>L33-2575</td>
<td>Ductile</td>
<td>75.7</td>
<td>99.7</td>
<td>85.0</td>
<td>YES</td>
<td>Ductile</td>
</tr>
<tr>
<td></td>
<td>L33-25150</td>
<td>Ductile</td>
<td>89.1</td>
<td>107.6</td>
<td>85.0</td>
<td>NO</td>
<td>Ductile</td>
</tr>
<tr>
<td></td>
<td>L33-1575</td>
<td>Ductile</td>
<td>73.7</td>
<td>97.7</td>
<td>85.0</td>
<td>YES</td>
<td>Ductile/Mixed</td>
</tr>
<tr>
<td></td>
<td>L33-15150</td>
<td>Ductile</td>
<td>86.4</td>
<td>104.9</td>
<td>85.0</td>
<td>NO</td>
<td>Ductile</td>
</tr>
</tbody>
</table>
The failure mode predictions proved to be fairly accurate as was observed during the later tests. Although some failed to predict the connection failure modes precisely, they were on the conservative side, which is acceptable by design standards. Only one series (L44-1575) demonstrated brittle failure mode, whereas the predictions from the New Zealand model suggested the failure mode to be ductile. As there were only 3 replicates in this series, the model may have provided misleading predictions, something that can be verified by testing a larger number of replicates.

F-tests were also performed on the controlling factor in each series to test if the factor was significant for the tested capacities by comparing tested capacities with results from control group. Such tests were warranted owing to the discrepancies among the input parameters in each model. Results from the F tests are summarized in Table 13.

Results from the F-test failed to show the expected correlation between the proposed input parameters and connection capacity. This can be attributed to the limited number of replicates in each series. However, it can be also explained by the dominance of the ductile failure modes among all the samples, which was the result of selecting the most common rivet layout in the practice (3*3, 4*4, 4*6 and 2*8). Parameters, such as end distance, rivet spacing across grain direction and bearing end distance, are used to control the capacity of the wood in the cases where the connections were supposed to be failed in brittle method. In the ductile failure range, such parameters do not contribute to the connection capacity since the latter is governed by the yielding behavior of metal fasteners. These results, on the other hand, justify using the European Yield Mode to predict connection capacity in ductile failure modes. By referencing the Δ in Table 9 and Table 11, it is evident that the predictive model worked best on ductile and mixed failure modes within +/- 10% margins of the tested values.
### Table 13 – F test results on controlling parameters

<table>
<thead>
<tr>
<th>Factor</th>
<th>Group Name</th>
<th>Average test capacity[kN]</th>
<th>Significance</th>
<th>Failure mode in tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>End distance</td>
<td>P28-725</td>
<td>93.2</td>
<td>YES</td>
<td>Brittle</td>
</tr>
<tr>
<td></td>
<td>P28-1225</td>
<td>138.7</td>
<td></td>
<td>Mixed</td>
</tr>
<tr>
<td></td>
<td>P28-715</td>
<td>88.5</td>
<td>NO</td>
<td>Brittle</td>
</tr>
<tr>
<td>Rivet spacing across grain</td>
<td>P28-1215</td>
<td>87.5</td>
<td>YES</td>
<td>Mixed/Brittle/Ductile</td>
</tr>
<tr>
<td></td>
<td>P28-725</td>
<td>93.2</td>
<td></td>
<td>Brittle</td>
</tr>
<tr>
<td></td>
<td>P28-715</td>
<td>88.5</td>
<td>YES</td>
<td>Mixed</td>
</tr>
<tr>
<td></td>
<td>P28-1225</td>
<td>138.7</td>
<td></td>
<td>Mixed</td>
</tr>
<tr>
<td>End distance</td>
<td>P33-725</td>
<td>58.8</td>
<td>NO</td>
<td>Ductile/Mixed</td>
</tr>
<tr>
<td></td>
<td>P33-1225</td>
<td>60.3</td>
<td></td>
<td>Ductile/Mixed</td>
</tr>
<tr>
<td></td>
<td>P33-715</td>
<td>50.6</td>
<td>NO</td>
<td>Mixed</td>
</tr>
<tr>
<td>Rivet spacing across grain</td>
<td>P33-1215</td>
<td>53.8</td>
<td>YES</td>
<td>Ductile/Mixed</td>
</tr>
<tr>
<td></td>
<td>P33-725</td>
<td>58.8</td>
<td></td>
<td>Mixed</td>
</tr>
<tr>
<td></td>
<td>P33-715</td>
<td>50.6</td>
<td></td>
<td>Mixed</td>
</tr>
<tr>
<td></td>
<td>P33-1225</td>
<td>60.3</td>
<td>NO</td>
<td>Ductile/Mixed</td>
</tr>
<tr>
<td></td>
<td>P33-1215</td>
<td>53.8</td>
<td></td>
<td>Ductile</td>
</tr>
<tr>
<td>Bearing end distance</td>
<td>L44-1575</td>
<td>122.0</td>
<td>NO</td>
<td>Brittle</td>
</tr>
<tr>
<td></td>
<td>L44-15150</td>
<td>133.7</td>
<td></td>
<td>Ductile/Mixed</td>
</tr>
<tr>
<td></td>
<td>L44-2575</td>
<td>141.3</td>
<td>NO</td>
<td>Ductile</td>
</tr>
<tr>
<td></td>
<td>L44-25150</td>
<td>148.0</td>
<td></td>
<td>Ductile</td>
</tr>
<tr>
<td>Bearing end distance</td>
<td>L33-2575</td>
<td>87.7</td>
<td>YES</td>
<td>Ductile</td>
</tr>
<tr>
<td></td>
<td>L33-25150</td>
<td>98.3</td>
<td></td>
<td>Ductile</td>
</tr>
<tr>
<td></td>
<td>L33-1575</td>
<td>85.7</td>
<td>NO</td>
<td>Ductile/Mixed</td>
</tr>
<tr>
<td>Rivet spacing across grain</td>
<td>L33-15150</td>
<td>95.7</td>
<td></td>
<td>Ductile</td>
</tr>
<tr>
<td></td>
<td>L44-1575</td>
<td>122.0</td>
<td>NO</td>
<td>Brittle</td>
</tr>
<tr>
<td></td>
<td>L44-2575</td>
<td>141.3</td>
<td></td>
<td>Ductile</td>
</tr>
<tr>
<td></td>
<td>L33-2575</td>
<td>87.7</td>
<td>NO</td>
<td>Ductile</td>
</tr>
<tr>
<td></td>
<td>L33-1575</td>
<td>85.7</td>
<td></td>
<td>Ductile/Mixed</td>
</tr>
<tr>
<td>Rivet spacing across grain</td>
<td>L44-15150</td>
<td>133.7</td>
<td>NO</td>
<td>Ductile/Mixed</td>
</tr>
<tr>
<td></td>
<td>L44-25150</td>
<td>148.0</td>
<td></td>
<td>Ductile</td>
</tr>
<tr>
<td></td>
<td>L33-15150</td>
<td>95.7</td>
<td>NO</td>
<td>Ductile</td>
</tr>
<tr>
<td></td>
<td>L33-25150</td>
<td>98.3</td>
<td></td>
<td>Ductile</td>
</tr>
</tbody>
</table>

CSA O86 uses a reliability-based design approach with the characteristic strength referring to the strength taken at the 5th percentile of the strength distribution based on practical tests (Foschi et al. 1993). The calibration factor, \( \Phi \), reflects the reliability level of a particular structural member at limit state. The adjusting factor, \( \Phi \), in Timber Rivet design is set to 0.6 in CSA O86. In order to compare CSA O86
predictions and test results observed under laboratory conditions, the 5th percentile strength was replaced by the mean material strength of LVL and the reliability factor was not included.

Similarly, after removal of all reduction factors in all the other prediction models (and using the mean strength values of LVL), the strength of all tested configurations was predicted using the different design approaches. Table 14 summarizes the results generated by current predictive models and test results from this experiment. The results are also illustrated in Figure 50, where the vertical axis is the predicted capacity and the horizontal axis the tested capacity. The solid line is a line with slope equal to 1. Thus, points lying above the line suggest the predictions are more aggressive, points below the line the converse. Judging for the plot, CSA O86 had a consistent conservative tendency in its predictions. Foschi and Longworth’s model had the most of their predictions on the conservative side, but a few series were obviously overestimated. Zarnani’s model, distributing equally and closely to the “perfect” prediction line, was considered the most accurate one. Stahl’s predictions were generally on the conservative side. And while the failure modes of his model, are generally brittle modes, few such failures were discovered in the experiment.

**Table 14 – Comparison of predictions on capacities and failure modes**

<table>
<thead>
<tr>
<th>Group Name</th>
<th>Foschi and Longworth [kN]</th>
<th>Stahl/US code [kN]</th>
<th>Zarnani [kN]</th>
<th>CSA O86 (Converted) [kN]</th>
<th>Average test capacities [kN]</th>
<th>Observed failure modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>P28-725</td>
<td>156.0</td>
<td>51/brittle</td>
<td>106/brittle</td>
<td>72/Ductile</td>
<td>93.2</td>
<td>Brittle</td>
</tr>
<tr>
<td>P28-1225</td>
<td>156.0</td>
<td>51/brittle</td>
<td>111/Mixed</td>
<td>72/Ductile</td>
<td>138.7</td>
<td>Mixed</td>
</tr>
<tr>
<td>P28-715</td>
<td>162.0</td>
<td>36/brittle</td>
<td>85/Brittle</td>
<td>72/Ductile</td>
<td>88.5</td>
<td>Brittle</td>
</tr>
<tr>
<td>P28-1215</td>
<td>162.0</td>
<td>36/brittle</td>
<td>107/Mixed</td>
<td>72/Ductile</td>
<td>87.5</td>
<td>Mixed/Brittle/Ductile</td>
</tr>
<tr>
<td>P33-725</td>
<td>52.0</td>
<td>30/brittle</td>
<td>60/Mixed</td>
<td>40/Ductile</td>
<td>58.8</td>
<td>Ductile/Mixed</td>
</tr>
<tr>
<td>P33-1225</td>
<td>52.0</td>
<td>30/brittle</td>
<td>60/Mixed</td>
<td>40/Ductile</td>
<td>60.3</td>
<td>Ductile/Mixed</td>
</tr>
<tr>
<td>P33-715</td>
<td>44.0</td>
<td>26/brittle</td>
<td>52/Brittle</td>
<td>40/Brittle</td>
<td>50.6</td>
<td>Mixed</td>
</tr>
<tr>
<td>P33-1215</td>
<td>44.0</td>
<td>26/brittle</td>
<td>52/Brittle</td>
<td>40/Brittle</td>
<td>53.8</td>
<td>Ductile</td>
</tr>
<tr>
<td>L44-1575</td>
<td>35.0</td>
<td>96/brittle</td>
<td>150/Ductile</td>
<td>53/Brittle</td>
<td>122.0</td>
<td>Brittle</td>
</tr>
<tr>
<td>L44-15150</td>
<td>35.0</td>
<td>127/brittle</td>
<td>150/Ductile</td>
<td>53/Brittle</td>
<td>133.7</td>
<td>Ductile/Mixed</td>
</tr>
<tr>
<td>L44-2575</td>
<td>77.0</td>
<td>145/brittle</td>
<td>150/Ductile</td>
<td>126/Ductile</td>
<td>141.3</td>
<td>Ductile</td>
</tr>
<tr>
<td>L44-25150</td>
<td>77.0</td>
<td>183/brittle</td>
<td>150/Ductile</td>
<td>126/Ductile</td>
<td>148.0</td>
<td>Ductile</td>
</tr>
<tr>
<td>L33-2575</td>
<td>47.0</td>
<td>99/brittle</td>
<td>85/Ductile</td>
<td>71/Ductile</td>
<td>87.7</td>
<td>Ductile</td>
</tr>
<tr>
<td>L33-25150</td>
<td>47.0</td>
<td>131/ductile</td>
<td>85/Ductile</td>
<td>71/Ductile</td>
<td>98.3</td>
<td>Ductile</td>
</tr>
<tr>
<td>L33-1575</td>
<td>25.0</td>
<td>67/brittle</td>
<td>85/Ductile</td>
<td>71/Ductile</td>
<td>85.7</td>
<td>Ductile/Mixed</td>
</tr>
<tr>
<td>L33-15150</td>
<td>25.0</td>
<td>96/brittle</td>
<td>85/Ductile</td>
<td>7/Ductile</td>
<td>95.7</td>
<td>Ductile</td>
</tr>
</tbody>
</table>
To further illustrate the models’ prediction accuracy, each model was individually plotted, see Figure 51 to Figure 54. In order to make a more straightforward comparison of prediction accuracy, mean absolute percentage error (MAPE) of each model was calculated by Equation 48. The lower MAPE indicates the better prediction accuracy.

\[
MAPE = \frac{100\%}{n} \sum_{i=1}^{n} \left| \frac{A_i - F_i}{A_i} \right| \\
\text{Equation 48}
\]

Where,
- \( A_i \) = Tested value
- \( F_i \) = Prediction value

Based on the MAPE associated with each prediction model, it is clear that Zarnani’s model (New Zealand model) produced the best estimation among the four models. The MAPE also showed that CSA O86 generated better prediction than Foschi and Longworth’s model. The performance of CSA O86 was also comparable with Stahl’s model on the capacity prediction. However, the clear conservative tendency of CSA O86 shown in the tested series still requires further verifications with a wider selection of rivet layouts and a larger sample size.

Figure 50 – Comparison of model predictions
Figure 51 – Prediction tendency of CSA O86

Figure 52 – Prediction tendency of Stahl’s model
**Figure 53 – Prediction tendency of Zarnani’s model**

**Figure 54 – Prediction tendency of Foschi and Longworth’s model**
As is shown in Figure 55 and Figure 56, failure at glue lines of LVL was also observed in perpendicular-to-grain loading series. Current models do not contain any descriptions or anticipations on such a failure mode. It was observed in the experiment that this kind of failure tended to take up on series with short timber members (700 mm). Although LVL members in the project were secondarily laminated by Brisco®, the failure did not happen on the secondary glue lines. Judging from Figure 56, the failed surface was majorly dark brown, which is the color of PF resin. Such failure indicted that the strength of the bonding surface was lower than the tension stress perpendicular to the lamination layers. However, more evidence (e.g. through internal bonding tests on the LVL) is needed to verify whether such failure was caused by low quality bonding.
4.5. Static tests on CLT samples

4.5.1. The weaker end connection performance

The CLT samples were loaded in a direction parallel to the face layer grain direction. Connection capacities were determined by the maximum load up to 4.8 mm of displacement. The test results, which are summarized in Table 15 show that 3-ply CLT and 9-ply CLT demonstrated different failure behaviors during the tests. Brittle failure of the 3-ply CLT was characterized by limited surface cracking and splitting. However, brittle failure of the 9-ply CLT was more intense and was often accompanied by failure of the glue line between the inner layers. Typical ductile and brittle failure modes are shown in Figure 57 and Figure 58.

Figure 57 – Ductile failure (left) and brittle failure (right) on 3-ply CLT
Figure 58 – Ductile failure (left) and brittle failure (right) on 9-ply CLT

Table 15 – Test results on CLT Samples

<table>
<thead>
<tr>
<th>Group Name</th>
<th>Expected failure mode</th>
<th>Expected capacity [kN]</th>
<th>Average test capacity [kN]</th>
<th>Δ [%]</th>
<th>Failure mode in tests</th>
<th>COV [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L46-25</td>
<td>Ductile</td>
<td>150</td>
<td>166.0</td>
<td>11</td>
<td>Ductile/Mixed</td>
<td>0.6</td>
</tr>
<tr>
<td>L46-15</td>
<td>Brittle</td>
<td>107</td>
<td>160.6</td>
<td>51</td>
<td>Mixed/Ductile</td>
<td>4.0</td>
</tr>
<tr>
<td>L46-25(9)</td>
<td>Ductile</td>
<td>150</td>
<td>151.0</td>
<td>1</td>
<td>Ductile</td>
<td>8.2</td>
</tr>
<tr>
<td>L46-15(9)</td>
<td>Brittle</td>
<td>107</td>
<td>141.0</td>
<td>32</td>
<td>Brittle/Ductile</td>
<td>6.8</td>
</tr>
<tr>
<td>L46-25(9-90)</td>
<td>Ductile</td>
<td>168</td>
<td>172.7</td>
<td>3</td>
<td>Ductile/Brittle</td>
<td>5.4</td>
</tr>
<tr>
<td>L46-15(9-90)</td>
<td>Brittle</td>
<td>107</td>
<td>148.7</td>
<td>39</td>
<td>Brittle</td>
<td>10.1</td>
</tr>
</tbody>
</table>

Predictions for CLT/rivet connections were generated on the basis of the CSA O86 (Canadian Standard Association 2009) model on Glulam and without reliability factor. This design approach was adopted merely to provide a conservative anticipation of the results for the experimental investigations. Table 15 shows the differences between the predictions and the test data. Table 16 suggests if the predictions fall into the 95% confidence interval of connection capacities for each series. In terms of CLT/rivet samples, there exists no model that predicts such a combination. Based on the test results obtained in the experiment, the model derived from CSA O86, which was developed for glulam, failed to predict the performance of CLT/rivet connections failing in the brittle manner. Predictions on brittle failure capacity were all rejected based on a 95% confidence interval. The predictions for the staggered installed series tended to fall on the conservative side. Judging from Table 15, CSA O86 tended to underestimate the wood capacity when it was applied on CLT. However, the predictions associated with ductile or mixed failures were close to test results and did not show the level of conservative tendency that was observed in LVL applications. Since, the capacity in ductile failure was not severely affected by timber properties, the change in tendency could be caused by different calibration of adjusting factors. To assess the feasibility of using Timber Rivets on CLT, further research is required.
Regarding the mean and predicted capacities, the 3-ply CLT with staggered Timber Rivets actually performed far better than expected. Moreover, all the failure modes observed were ductile and mixed. Reducing rivet spacing across the grain usually increases the probability of brittle failure, but with this particular connection layout, no obvious reduction in connection capacity or change in the failure mode was observed. In contrast to the ductile failures observed in the LVL/rivet connections, the rivets in the CLT/rivet samples, it was observed, had withdrawn. Because withdrawal resistance is affected by the density of the wood member, moreover, the lower withdrawal resistance might have been caused by the lower density of CLT compared with that of LVL. A typical failed CLT/rivet connection is shown in Figure 57.

Intuitively speaking, the rivet length should affect the connection capacity given that in all the prediction theories a rivet is treated as a beam subjected to a bending moment created by single shear. In ductile failure mode, the length of the rivet affects the moment arm of such a bending model, and under a brittle failure scenario the length of the rivet determines the surface area subjected to shear and tension. However, only one series testing this effect confirmed the significance of this parameter.

![Figure 59 – Shear failure at the glue line of 9-ply CLT samples](image)

The speculation is that the brittle failures observed in the 9-ply CLT series were not the same as those described by the predictive models: failure occurred at the glue line on one side of the connection. As shown in Figure 59, the connections failed not on the weaker end but on the weaker side.
### Table 16 – 95% Confidence interval of connection capacity on CLT

<table>
<thead>
<tr>
<th>Group Name</th>
<th>Expected failure</th>
<th>LL of 95% confidence interval</th>
<th>UL of 95% confidence interval</th>
<th>Expected capacity [kN]</th>
<th>Accept</th>
<th>Failure mode in tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>L46-25</td>
<td>Ductile</td>
<td>154.6</td>
<td>177.4</td>
<td>150.0</td>
<td>NO</td>
<td>Ductile/Mixed</td>
</tr>
<tr>
<td>L46-15</td>
<td>Brittle</td>
<td>149.2</td>
<td>172.1</td>
<td>107.0</td>
<td>NO</td>
<td>Mixed/Ductile</td>
</tr>
<tr>
<td>L46-25(9)</td>
<td>Ductile</td>
<td>136.7</td>
<td>165.3</td>
<td>150.0</td>
<td>YES</td>
<td>Ductile</td>
</tr>
<tr>
<td>L46-15(9)</td>
<td>Brittle</td>
<td>112.5</td>
<td>169.5</td>
<td>107.0</td>
<td>NO</td>
<td>Brittle/Ductile</td>
</tr>
<tr>
<td>L46-25(9-90)</td>
<td>Ductile</td>
<td>141.7</td>
<td>203.6</td>
<td>168.0</td>
<td>YES</td>
<td>Ductile/Brittle</td>
</tr>
<tr>
<td>L46-15(9-90)</td>
<td>Brittle</td>
<td>117.7</td>
<td>181.0</td>
<td>107.0</td>
<td>NO</td>
<td>Brittle</td>
</tr>
</tbody>
</table>

### Table 17 – F-tests on controlling parameters

<table>
<thead>
<tr>
<th>Factor</th>
<th>Group Name</th>
<th>Average test capacity [kN]</th>
<th>Significance</th>
<th>Failure mode in tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rivet spacing across grain</td>
<td>L46-25</td>
<td>166.0</td>
<td>NO</td>
<td>Ductile/Mixed</td>
</tr>
<tr>
<td>Rivet spacing across grain</td>
<td>L46-15</td>
<td>160.6</td>
<td></td>
<td>Mixed/Ductile</td>
</tr>
<tr>
<td>Rivet spacing across grain</td>
<td>L46-25(9)</td>
<td>151.0</td>
<td>NO</td>
<td>Ductile</td>
</tr>
<tr>
<td>Rivet spacing across grain</td>
<td>L46-15(9)</td>
<td>141.0</td>
<td></td>
<td>Brittle/Ductile</td>
</tr>
<tr>
<td>Rivet spacing across grain</td>
<td>L46-25(9-90)</td>
<td>172.7</td>
<td>NO</td>
<td>Ductile/Brittle</td>
</tr>
<tr>
<td>Rivet spacing across grain</td>
<td>L46-15(9-90)</td>
<td>148.7</td>
<td></td>
<td>Brittle</td>
</tr>
<tr>
<td>Rivet length</td>
<td>L46-25(9)</td>
<td>151.0</td>
<td>YES</td>
<td>Ductile</td>
</tr>
<tr>
<td>Rivet length</td>
<td>L46-25(9-90)</td>
<td>172.7</td>
<td></td>
<td>Ductile/Brittle</td>
</tr>
<tr>
<td>Rivet length</td>
<td>L46-15(9)</td>
<td>141.0</td>
<td>NO</td>
<td>Brittle/Ductile</td>
</tr>
<tr>
<td>Rivet length</td>
<td>L46-15(9-90)</td>
<td>172.7</td>
<td></td>
<td>Brittle</td>
</tr>
</tbody>
</table>
4.5.2. The performance of the “stronger” end connection

The analysis procedure outlined in 4.2.2 was performed with the CLT series. A comparison of the capacities of the “stronger” and “weaker” end connections, along with the estimates is summarized in Table 18. Figure 60 and Figure 61 were plotted based on the displacement recorded at the “stronger” end. Compared with the respective load-slip curves for the “weaker” end, the difference was a smaller displacement at the same loading level. A comparison of the residual displacements on two different ends is shown in Figure 62. Figure 63 shows the load-slip curves of 6 connections in the same series but from different ends. The series named with an additional “S” represents the curve from the “strong” end. As is shown in Figure 63, the slopes of the curves from the “strong” end were larger than the curves from “weaker” side, which indicated larger stiffness on the “strong” end. Judging from the $P_{\text{strong}}/P_{\text{weak}}$ values, the difference in the connection capacities of two ends were less than 6%.

The major difference between the connections from different ends existed in the initial stiffness. Figure 63 shows the load-slip curves of 6 connections in the same series but from different ends. The series named with an additional “S” represents the curve from the “strong” end. As is shown in Figure 63, the slopes of the curves from the “strong” end were larger than the curves from “weaker” side, which indicated larger stiffness on the “strong” end.

*Table 18 – Comparison of stronger end, weaker end and estimation capacities (CLT)*

<table>
<thead>
<tr>
<th>Series</th>
<th>Stronger end [kN]</th>
<th>Estimate [kN]</th>
<th>Weaker end [kN]</th>
<th>$P_{\text{strong}}/P_{\text{weak}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>L46-25</td>
<td>170.7</td>
<td>149.5</td>
<td>166.0</td>
<td>1.0</td>
</tr>
<tr>
<td>L46-15</td>
<td>167.8</td>
<td>106.7</td>
<td>160.6</td>
<td>1.0</td>
</tr>
<tr>
<td>L46-25(9)</td>
<td>158.1</td>
<td>149.5</td>
<td>151.0</td>
<td>1.1</td>
</tr>
<tr>
<td>L46-15(9)</td>
<td>144.6</td>
<td>106.7</td>
<td>141.0</td>
<td>1.0</td>
</tr>
<tr>
<td>L46-25(9-90)</td>
<td>183.9</td>
<td>168.3</td>
<td>172.7</td>
<td>1.1</td>
</tr>
<tr>
<td>L46-15(9-90)</td>
<td>148.8</td>
<td>106.7</td>
<td>148.7</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Figure 60 – Typical load-slip curve of the “stronger” end connection of ductile failure series (CLT)

Figure 61 – Typical load-slip curve of the “stronger” end connection of brittle failure series (CLT)
Figure 62 – Comparison of the “stronger” (left) and “weaker” end (right) after loading (CLT)

Figure 63 – Load-slip curves from two different ends (CLT)
4.6. Cyclic tests on LVL parallel to the grain

4.6.1. Connection Failure Modes

The cyclic loading protocol was only applied to the series with 25 mm rivet spacing across the grain, which was designed to fail in the ductile manner. Within the limited number of replicates, no brittle failure or mixed failure was observed in the parallel-to-grain series. Thus, the observed failure mode was ductile only. In contrast to the observations made during the quasi-monotonic tests, the connections that failed in the cyclic tests demonstrated greater withdrawal effects on the row farthest from the load-bearing end.

*Figure 64 – Ductile failure with withdrawal effect observed in the cyclic tests (LVL)*
4.6.2. Connection Performance

Figure 65 and Figure 66 demonstrate the positive cyclic curves for two types of rivet connections (3*3 and 4*4) in parallel-to-grain loading. All other envelope curves are shown in Appendix B.1. Based on the definition of first-cycle envelope curve, the first cycle envelope curve was plotted by linking the extremities on each first cycle loop with straight lines. The connection properties shown in Table 19 were calculated by averaging the property values of each replicate in the cyclic testing series.

Although the limited number of replicates does not allow for statistically valid conclusions to be drawn, certain tendencies are discernible in Table 19 and Table 20. Judging from Table 20, both the ductility and stiffness of these two rivet layouts are close. However, the same connection exhibited different properties in the cyclic and monotonic tests. Connections subjected to monotonic tests testing tended to have a higher yielding strength and maximum strength than those subjected to cyclic tests. Moreover, the displacement at either yielding strength or max strength was greater than that in the cyclic tests. This tendency confirms what Popovski et al. (2002) observed: curves obtained from monotonic tests show higher values for ductility and maximum load. That is to say, connections are more likely to reach their max capability under a cyclic load.

The area enclosed by each loop represents the energy dissipated by the connection. In a single step, the first cycle always dissipated the most energy because the wood fiber surrounding the connection had not been damaged to the deformation level of that step. The energy dissipated by subsequent cycles was due to the metal fasteners themselves (Popovski et al. 2002). Figure 67 and Figure 68 were plotted to show the energy dissipation rate and the amount energy dissipated by each connection during the whole cyclic testing process. A wave-shaped energy curve was observed. Moreover, after a certain testing period (around 40 seconds), it could be clearly ascertained that the amount of dissipated energy increased rapidly after every three waves. This observation corresponded to the design of the cyclic loading protocol, where each step consisted of the three same cycles. Figure 67 and Figure 68 also show that energy dissipation rates were higher during the transitions to the loading steps. This observation confirms what had previously been speculative: that the first cycle dissipates the most energy in that step.
### Table 19 – Connection properties based on the first cycle envelope curves (LVL)

<table>
<thead>
<tr>
<th>Layout</th>
<th>4*4</th>
<th>3*3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group</td>
<td>L44C</td>
<td>L33C</td>
</tr>
<tr>
<td>Yield Load, $F_y$ (kN)</td>
<td>130.5</td>
<td>77.7</td>
</tr>
<tr>
<td>Yield Displacement, $\Delta y$</td>
<td>3.9</td>
<td>3.6</td>
</tr>
<tr>
<td>Maximum Load, $F_{\text{max}}$ (kN)</td>
<td>137.9</td>
<td>84.2</td>
</tr>
<tr>
<td>Displacement at $F_{\text{max}}$ (mm)</td>
<td>7.9</td>
<td>7.7</td>
</tr>
<tr>
<td>Ultimate Displacement, $\Delta u$ (mm)</td>
<td>13.5</td>
<td>12.4</td>
</tr>
<tr>
<td>Initial Stiffness, $K$ (kN/mm)</td>
<td>65.7</td>
<td>67.1</td>
</tr>
<tr>
<td>Ductility ($\Delta u/\Delta y$)</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Over Strength ($F_{\text{max}}/F_{\text{prediction}}$)</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

### Table 20 – Connection properties in cyclic and monotonic tests (LVL)

<table>
<thead>
<tr>
<th>Layout</th>
<th>3*3</th>
<th>4*4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group</td>
<td>L33C</td>
<td>L33</td>
</tr>
<tr>
<td>Yield Load, $F_y$ (kN)</td>
<td>77.7</td>
<td>87.5</td>
</tr>
<tr>
<td>Yield Displacement, $\Delta y$</td>
<td>3.6</td>
<td>5.0</td>
</tr>
<tr>
<td>Maximum Load, $F_{\text{max}}$ (kN)</td>
<td>84.2</td>
<td>92.2</td>
</tr>
<tr>
<td>Displacement at $F_{\text{max}}$ (mm)</td>
<td>7.7</td>
<td>8.3</td>
</tr>
<tr>
<td>Ultimate deformation, $\Delta u$ (mm)</td>
<td>12.4</td>
<td>17.8</td>
</tr>
<tr>
<td>Initial stiffness, $K$ (kN/mm)</td>
<td>67.1</td>
<td>54.6</td>
</tr>
<tr>
<td>Ductility ($\Delta u/\Delta y$)</td>
<td>3.5</td>
<td>3.6</td>
</tr>
<tr>
<td>Over strength ($F_{\text{max}}/F_{\text{prediction}}$)</td>
<td>1.0</td>
<td>1.1</td>
</tr>
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</table>
Figure 65 – Hysteresis curve and first cycle envelope curve (LVL)

Figure 66 – Hysteresis curve and first cycle envelope curve (LVL)
Figure 67 – Energy dissipated by the connection (LVL)

Figure 68 – Energy dissipated by the connection (LVL)
4.6.3. Performance of the “Stronger” End Connection

Similar to the process described in Section 4.6.2, the first cycle envelope curve from the “stronger” end was plotted. Figure 69 shows the envelope curves from one two-ended sample in LVL series. The curve from the “stronger” end (L33C-1S) had larger initial slope than the curve from the “weaker” end (L33C-1), which indicated the larger initial stiffness. The small difference in the initial stiffness allocated the majority of the applied displacement to the weaker end, which led to the huge difference in displacement on two ends when they were subjected to the same level of load. This observation in the cyclic loading tests also corresponded to the observation in the quasi-monotonic loading tests discussed in Section 4.2.2.

![Figure 69 – First cycle envelope curves from two different ends on one member (LVL)](image-url)
4.7. Cyclic tests on LVL perpendicular-to-grain loading

4.7.1. Connection Failure Modes

The perpendicular loading samples were subjected to the same analyses as the parallel to grain loading samples. The connections tested in the cyclic manner, which were also from this series, which were designed for ductile failure mode. Thus, the failure modes observed in the tests are close to what was observed in the monotonic tests, see Figure 71 and Figure 72. Figure 70 shows the load slip curve for the connection that failed in a mixed manner, and Figure 73 shows a representative curve for the connections that failed in a mixed manner. The failure modes were judged based on the first cycle envelope curve, which was comparable to the load slip curves from the monotonic tests.

The mixed failure mode observed in the tests consists of the splitting of a timber member along the grain direction and the crushing of localized wood, the result of compression caused by the rivet shanks. It has to be noted that the brittle failure described in the New Zealand prediction model was not observed during the limited number of tests conducted here. In the New Zealand prediction, connections loaded perpendicular to grain are supposed to fail with the propagation of splitting along the grain direction until an unstable point is reached (Zarnani 2013). However, the brittle failure observed was due exclusively to failure at the glue line of the timber member. This kind of phenomenon had been observed during the monotonic tests described in the previous section.

![Hysteresis curve and first cycle envelope curve of mixed failure (LVL)](image)

*Figure 70 – Hysteresis curve and first cycle envelope curve of mixed failure (LVL)*
Figure 71 – Mixed Failure of the Connection Loaded Perpendicular to grain in the Cyclic Tests (LVL)
– Splitting during loading in P33 series

Figure 72 – Mixed Failure of the Connection Loaded Perpendicular to grain in the Cyclic Tests (LVL)
– Mixed failure and withdrawal effect in P28 series
4.7.2. Connection Properties and Hysteresis Curves

Judging by the hysteresis curves and connection properties listed in Table 22, the 2*8 and 3*3 series differ in terms of stiffness. Although the former had the higher capacity it tended to reach max capacity with a smaller displacement. In other words, the 2*8 series demonstrated greater stiffness. In these two series, the energy dissipation curves overlapped, thus showing greater consistency than is the case for the curves in the parallel-to-grain loaded series. This consistency may be the result of using a smaller number of connections in the perpendicular-to-grain loading series as opposed to the parallel-to-grain series. The perpendicular-to-grain loaded series had only one set of connections, whereas the parallel-to-grain series had one set of connections at each end. Instead of using another set of Timber Rivet connections, the perpendicular-to-grain loaded timber members were attached to the test frames by two clamps. In this way, the variations within the connections could be reduced.

Regarding the different connection capacities associated with different loading situations scenarios, the principle observed in parallel-to-grain loading still held: connections subjected to monotonic loading tend to have a greater capacity and reach larger displacements. The maximum load of the P33 series did not follow this pattern, possibly explained by the limited number of replicates. Judging from Figure 75 and Figure 76, the greater initial stiffness of the P28C series connections accounts for their greater energy dissipation rate as opposed to that of the P33C series; however, the P28C series failed at a lower displacement level.
Figure 73 – Hysteresis Curve and First Cycle Envelope Curve (LVL)

Figure 74 – Hysteresis Curve and First Cycle Envelope Curve (LVL)
Figure 75 – Energy Dissipated by the connection (LVL)

Figure 76 – Energy Dissipated by the connection (LVL)
Table 21 – Connection properties based on the first cycle envelope curve (LVL)

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<thead>
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<tbody>
<tr>
<td>Group</td>
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<td>P33C</td>
</tr>
<tr>
<td>Yield Load, $F_y$ (kN)</td>
<td>121.8</td>
<td>61.0</td>
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<tr>
<td>Yield Displacement, $\Delta y$</td>
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<td>3.9</td>
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<tr>
<td>Maximum Load, $F_{max}$ (kN)</td>
<td>136.1</td>
<td>70.7</td>
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<tr>
<td>Displacement at $F_{max}$ (mm)</td>
<td>6.5</td>
<td>6.9</td>
</tr>
<tr>
<td>Ultimate Displacement, $\Delta u$ (mm)</td>
<td>8.6</td>
<td>10.3</td>
</tr>
<tr>
<td>Initial Stiffness, $K$ (kN/mm)</td>
<td>81.8</td>
<td>51.7</td>
</tr>
<tr>
<td>Ductility ($\Delta u/\Delta y$)</td>
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<td>2.6</td>
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<tr>
<td>Over strength ($F_{max}/F_{prediction}$)</td>
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Table 22 – Connection Properties in Cyclic and Monotonic Tests (LVL)

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<tr>
<td>Maximum Load, $F_{max}$ (kN)</td>
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<td>67.4</td>
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<tr>
<td>Displacement at $F_{max}$ (mm)</td>
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<td>8.1</td>
</tr>
<tr>
<td>Ultimate Displacement, $\Delta u$ (mm)</td>
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<td>12.4</td>
</tr>
<tr>
<td>Initial stiffness, $K$ (kN/mm)</td>
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<td>Ductility ($\Delta u/\Delta y$)</td>
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<td>2.5</td>
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<tr>
<td>Over strength ($F_{max}/F_{prediction}$)</td>
<td>1.2</td>
<td>1.1</td>
</tr>
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</table>
4.8. Cyclic tests on CLT parallel to face layer grain

4.8.1. Connection Failure Modes

The analyses of cyclic tests on CLT samples followed the one applied to the LVL samples. Different from LVL series, performing cyclic tests on CLT increased observations of brittle failure compared with the observations in the monotonic loading tests. Figure 77 shows the hysteresis curve and the respective first cycle envelope curve. The failure mode was brittle but the failure was formed at the glue line of CLT member instead of around the rivet array. This failure mode has been described in the previous section of monotonic loading tests. Judging by the test results, cyclic loading increased the probability of brittle failure at the glue lines. Figure 78 and Figure 79 demonstrate two types of brittle failure observed in the cyclic tests on CLT samples.

![Typical hysteresis curve and first cycle envelope curve from cyclic test (9-ply CLT)](image)

*Figure 77 – Typical hysteresis curve and first cycle envelope curve from cyclic test (9-ply CLT)*
Figure 78 – Brittle failure caused by tension and shear failure under cyclic loading (CLT)

Figure 79 – Brittle failure caused by shear failure at the glue line under cyclic load (CLT)
4.8.2. Connection Properties and Hysteresis Curves

Based on calculation of extremities of cyclic curves, connection properties are summarized in Table 23. In Table 24, connection properties reflected in the cyclic tests are compared with respective connection properties calculated through load-slip curves from monotonic loading tests. Judging by Table 23, staggered installation had better performance either compared with the same layout (4*6) on 9-ply CLT or even with 90 mm rivets. The staggered installation series demonstrated larger yield load, larger yield displacement and higher maximum load. One major reason was 9-ply CLT series (with 65 mm and 90 mm rivets) failed in brittle way at quite small displacement, which was nearly pure wood capacity (shear parallel to grain or tension parallel to grain). However, the failure mode demonstrated by 3-ply CLT series was mixed failure.

**Table 23 – Connection properties based on the first cycle envelope curves (CLT)**

<table>
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<tbody>
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<tr>
<td>Yield Load, $F_y$ (kN)</td>
<td>65 mm</td>
</tr>
<tr>
<td>Yield Displacement, $\Delta y$</td>
<td>159.0</td>
</tr>
<tr>
<td>Maximum Load, $F_{max}$ (kN)</td>
<td>2.9</td>
</tr>
<tr>
<td>Displacement at $F_{max}$ (mm)</td>
<td>180.7</td>
</tr>
<tr>
<td>Ultimate Displacement, $\Delta u$ (mm)</td>
<td>4.7</td>
</tr>
<tr>
<td>Initial stiffness, $K$ (kN/mm)</td>
<td>4.7</td>
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<tr>
<td>Ductility ($\Delta u/\Delta y$)</td>
<td>1.6</td>
</tr>
<tr>
<td>Over strength ($F_{max}/F_{prediction}$)</td>
<td>1.2</td>
</tr>
</tbody>
</table>

**Table 24 – Comparison of Connection Properties in Cyclic and Monotonic Tests (CLT)**

<table>
<thead>
<tr>
<th>Layout</th>
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<tr>
<td>Rivet Length (mm)</td>
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</tr>
<tr>
<td>Yield Load, $F_y$ (kN)</td>
<td>65</td>
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<tr>
<td>Yield Displacement, $\Delta y$</td>
<td>159.0</td>
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<tr>
<td>Maximum Load, $F_{max}$ (kN)</td>
<td>2.9</td>
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<tr>
<td>Displacement at $F_{max}$ (mm)</td>
<td>180.7</td>
</tr>
<tr>
<td>Ultimate Displacement, $\Delta u$ (mm)</td>
<td>4.7</td>
</tr>
<tr>
<td>Initial stiffness, $K$ (kN/mm)</td>
<td>4.7</td>
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<tr>
<td>Ductility ($\Delta u/\Delta y$)</td>
<td>92.3</td>
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<tr>
<td>Over strength ($F_{max}/F_{prediction}$)</td>
<td>1.6</td>
</tr>
</tbody>
</table>
In a comparison between connection properties under cyclic loading and monotonic loading tests, the pattern stated in the previous LVL sections still applied on CLT series: under monotonic loading the connection tended to have higher yield load, higher yield displacement, higher maximum load and higher ultimate displacement. However, the ductility of connections was subjected to a major degradation from switching to cyclic loading protocol, which was not observed in LVL series. It might be caused by the loading speed in the cyclic tests, where loading speed could reach 12 mm/s while in the monotonic loading tests, the loading speed was controlled at 1.4 mm/s.

Figure 80 to Figure 82 demonstrate the relationship of time and the amount of energy dissipated within connections. As is shown in Figure 82, one of the replicates with 90 mm rivets failing after 140 seconds dissipated energy as high as 8700 J. However, it was the only one replicate of the four subjected to the same loading protocol. The amount of energy dissipated by other three was close to 1000 J or even lower. Figure 80 shows that two of three replicates steadily dissipated energy around 3500 J. The difference between these two series was the failure mode (mixed and brittle). This observation, on the other hand, corresponded to the knowledge that the ductile behavior of a connection is desired in the situation where energy dissipation is needed, for example, earthquake.

![Figure 80 – Energy Dissipated by 4*6 rivet Layout on 3-ply CLT (65 mm rivets)](image-url)
Figure 81 – Energy Dissipated by 4*6 Rivet Layout on 9-ply CLT (65 mm rivets)

Figure 82 – Energy Dissipated by 4*6 Rivet Layout on 9-ply CLT (90 mm rivets)
4.8.3. Connection Properties of the “strong” End

Following the method described in Section 4.8.1, the first cycle envelope curves from two different ends on a same member were plotted in Figure 83. The connections on two ends were subjected to quite different displacement at the same load level. That was caused by the minor difference in the initial stiffness of the two connections. With the progress of cyclic loading, smaller initial stiffness led to a larger reduction in the stiffness, which consequently aggravated the “weaker” connection. This observation not only corresponded to what was observed in quasi-monotonic tests on CLT series, but also the LVL series loaded parallel to grain.

![Graph showing first cycle envelope curves from two different ends on one member (CLT)](image)

*Figure 83 – First cycle envelope curves from two different ends on one member (CLT)*
4.9. Influence of plate thickness and clamping method

Even though the thickness of the steel plates was constant at 6.4 mm in this experiment, two speculations can be made regarding the effect of steel plate thickness on the connection capacity: Firstly, the thickness of steel plates directly affected the penetration length of rivets. In all the previously cited models, the penetration length is associated with the area of planes subjected to either shear or tension. A reduction in the rivet penetration length would lead to a decreased area subjected to tension and shear force and consequently reduce the capacity of wood associated with the brittle failure mode. Regarding the calculating mechanism of the prediction models, the reduction of the capacity of wood will result in increased prediction outcomes on brittle failure modes. Secondly, plate thickness is related to the design of steel plates as discussed in Section 3.3.2. In the laboratory scenario, the end of the Timber Rivet connection was bolted to the test apparatus. The thickness of steel plates was important in calculating the area of steel subjected to tensile and shearing forces. With a thicker steel plate, the spacing between two bolt holes, the edge distance, and the end distance could be different.

The clamping method used in the perpendicular-to-grain loading tests was aimed to simulate the practical scenario. However, the clamping method reinforced the beam, preventing the propagation of wood splitting from the center of the timber member to its two ends. In the New Zealand model, full width splitting and partial width splitting are clearly differentiated from each other, while the two different splitting modes were not observed in this experiment. Figure 84 and Figure 85 demonstrate the two different schematic failure modes and the same failure modes observed in the experiment conducted by Zarnani and Quenneville (2013). Figure 86 shows the crack propagation observed during the loading process performed at UBC. Timber cracking was observed at different depths of the timber beam, mostly starting within the height of the Timber Rivet array. The discrepancy in the observation of the failure modes could be caused by the clamping method used in the experiment, which made it more difficult for the timber member to crack under the compressive forces from the steel tubes. It could also lead to an overestimation in the test results on the Timber Rivet connections loaded perpendicular to grain.
Figure 84 – Different schematic failure modes of wood splitting: full width splitting (left) and partial width splitting (right) (Zarnani & Quenneville 2014)

Figure 85 – Different failure modes of wood splitting: full width splitting (left) and partial width splitting (right) (Zarnani & Quenneville 2014)

Figure 86 – Crack propagation observed in the experiment on a 1200 mm beam (LVL)
5. Conclusions

In this project, the performance of Timber Rivet connection in LVL and CLT was investigated. The material strength parameters of Douglas fir LVL was determined on small specimens and then used as inputs for models that predict the performance of Timber Rivet connections. Subsequently quasi-static monotonic and cyclic tests were performed on connections parallel and perpendicular to the grain in LVL and CLT. Based on the experimental research carried out in the framework of this thesis, following main conclusions can be drawn:

The connection capacity of each sample was determined by the maximum applied load up to a relative connection displacement of 4.8 mm. Several connection layouts were tested; the layout of 2*8 rivets reached a higher capacity than the 3*3 layout in the perpendicular-to-grain loading. Layouts with a 25 mm rivet spacing across grain, both 3*3 and 2*8 series showed higher capacities than layout with 15 mm rivet spacing. In the parallel-to-grain loading series, the 4*4 layout reached higher capacities than 3*3 series. An increase of rivet spacing across grain from 15 mm to 25 mm also yielded higher capacities. F-tests suggested that, within the variations tested herein, neither bearing end distance nor rivet spacing across grain affected the capacity of the connection tested. This finding could be attributed to the dominance of the ductile failures observed in the experiments because the bearing end distance and the rivet spacing across grain only play an important role in predicting the brittle failure modes which are driven by wood capacity.

In the parallel-to-grain loaded series, the connections were installed on both ends of the timber members which provided the possibility of recording the behaviour of two connections in one test. Observations of the “stronger ends” suggested no significant differences between the capacities of the connections from the two different ends. The differences in initial stiffness between the two ends, however, made the weaker end exhibit most of the displacement. Subsequently, the weaker end continuously distributed a larger proportion of total displacement until its failure.

After the adoption of the material strength data determined for the LVL, predictions of available models for Timber Rivet connections were compared to the experimental results. The comparison between the models proposed by Zarnani, Stahl, CSA O86, and Foschi & Longworth showed that Zarnani’s model is best suited to predict performance of rivet connections in LVL with the lowest MAPE. To be specific, CSA O86, Stahl’s and Foschi & Longworth’ models are overly conservative even with removal all reduction factors. With the calculation of 95% confidence intervals for all the LVL series tested through quasi-monotonic method, the New Zealand model was verified to produce close or conservative predictions for capacities and accurate predictions on the failure modes.
Although rivet connections were installed only on a limited set of CLT specimens, the discrepancies between the predictions and tested capacities suggest that the model for Glulam in CSA O86 is not applicable for Timber Rivets connections in CLT in predicting capacity. The different orientations of CLT layers pose additional difficulties to determining appropriate prediction models. A model should be developed for using Timber Rivets in CLT applications. To reach this goal, significant further research is deemed necessary. Given the rapid growth in the construction of CLT buildings and their intrinsic energy dissipation requirements for seismic design, future studies on the performance of Timber Rivets in CLT are recommended.

Cyclic tests were conducted on selected series with 25 mm rivet spacing across grain on both CLT and LVL. The connections in LVL generally failed under the same modes as observed in the quasi-static monotonic tests. However, the cyclic loading on Timber Rivet connections in CLT significantly increased the tendency to create brittle failure. For both materials, it was found that connections tested under cyclic loading reached their capacity and failed with smaller displacements than those tested under monotonic loading. The energy dissipation rate was always higher in the first cycle than any of the subsequent cycles.

Since the connections were all tested under laboratory environment with short term loading procedure, the results may not reflect the true behavior of Timber Rivet connections under standard load duration. The effect of moisture content in practical applications was not considered in this experiment. The steel plates designed in this experiment was not expected to deform at all, but with considerable displacement (25 mm), part of steel plates deformed in the experiment, which might have an effect on the data. The cyclic tests only included tension and release, which was not able to fully simulate the behavior of Timber Rivet connections in real situation. Future studies might examine the seismic properties of Timber Rivet connections by performing reversed cyclic tests.

This research has summarized the current approaches used in Timber Rivet connection design, focusing in particular on the design of Timber Rivet Connections for LVL and CLT. Verification of each prediction model was based on the experimental investigation of products made from North American timber species. The test results from this research, along with the New Zealand model, could serve as a reference for engineering applications for Timber Rivet connections used with LVL in Canada.
References


Forest Products Laboratory, 1987. Wood handbook: Wood as an engineering material, Madison, WI.

Foschi, R.O., 1973. Stress analysis and design of glulam rivet connections for parallel-to-grain loading of wood, Vancouver, BC.


Appendices

Appendix A - Load-slip curves

A.1 Load-slip curves of the LVL series loaded parallel to grain

![Graph of Load-slip curves](image-url)
L44-1575 series

L44-15150 series
A.2 Load-slip curves of the “stronger end” connections in the LVL series

L33-1575S series

L33-15150S series
L33-2575S series

L33-25150S series
A.3 Load-slip curves of the LVL series loaded perpendicular to grain

P28-715 series
P28-725 series

P28-1215 series

P28-1225 series
P33-715 series

P33-725 series
### P33-1215 series

![Graph of P33-1215 series](image)

### P33-1225 series

![Graph of P33-1225 series](image)
A.4 Load-slip curves of the CLT series

![Graph showing load-slip curves for L46-25 series](image)

L46-25 series
L46-25(9-90) series

A.5 Load-slip curves of the “stronger end” connections in the CLT series

L46-15S series
L46-25S series

L46-15(9)S series
Appendix B – Hysteresis curves and energy dissipation curves

B.1 Hysteresis curves and envelope curves

![Hysteresis Curves and Envelope Curves](image-url)
First cycle envelope curve

L46C(3)-1

L46C(3)-2
L46C(9-90)-4

First cycle envelope curve

P28C-1
P33C-1

First cycle envelope curve

P33C-5

First cycle envelope curve
P33C-2
First cycle envelope curve

P33C-5
B.2 Energy dissipation curves

![Energy dissipation curves for L33C and L44C series](image_url)

**L33C series**

**L44C series**
L46C(3) series

L46C(9) series
L46C(9-90) series
Appendix C – Maximum load and respective displacement

Parallel-to-grain loading series (LVL)

<table>
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<th>Sample ID</th>
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<td>L33-1575-2</td>
<td>93.4</td>
<td>9.1</td>
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<tr>
<td>L33-1575-3</td>
<td>94.2</td>
<td>6.7</td>
</tr>
<tr>
<td>L33-15150-1</td>
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<td>7.2</td>
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<tr>
<td>L33-15150-2</td>
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### Parallel-to-grain loading series (CLT)

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### Perpendicular-to-grain loading series (LVL)

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Appendix D – Technical drawings of the steel plates

36 - P10 - 102 x 6 x 327 (3.7)
ALL HOLES 6.75 (17/64") DIA U.N.O.

36 - P11 - 102 x 6 x 202 (2.3)
ALL HOLES 6.75 (17/64") DIA U.N.O.
22 - P12 - 102 x 6 x 257 (2.9)
ALL HOLES 6.75 (17/64") DIA U.N.O.

22 - P13 - 102 x 6 x 182 (2.0)
ALL HOLES 6.75 (17/64") DIA U.N.O.

14 - P42 - 102 x 6 x 338 (3.8)
ALL HOLES 6.75 (17/64") DIA U.N.O.

14 - P50 - 102 x 6 x 337 (3.8)
ALL HOLES 6.75 (17/64") DIA U.N.O.
56 - P20 - 102 x 6 x 312 (3.5)
ALL HOLES 6.75 (17/64") DIA U.N.O.

14 - P21 - 102 x 6 x 438 (4.9)
ALL HOLES 6.75 (17/64") DIA U.N.O.
14 - P22 - 102 x 6 x 462 (5.2)
ALL HOLES 6.75 (17/64") DIA U.N.O.

28 - P23 - 102 x 6 x 237 (2.7)
ALL HOLES 6.75 (17/64") DIA U.N.O.
28 - P30 - 102 x 6 x 312 (3.5)
ALL HOLES 6.75 (17/64") DIA U.N.O.

7 - P31 - 102 x 6 x 438 (4.9)
ALL HOLES 6.75 (17/64") DIA U.N.O.
7 - P32 - 102 x 6 x 462 (5.2)
ALL HOLES 6.75 (17/64") DIA U.N.O.

14 - P33 - 102 x 6 x 262 (2.9)
ALL HOLES 6.75 (17/64") DIA U.N.O.
14 - P40 - 102 x 6 x 313 (3.5)
ALL HOLES 6.75 (17/64") DIA U.N.O.

14-P42-102x6x338(3.8)
ALL HOLES 6.75(17/64") DIA U.N.O
14-P51-102x6x237(2.7)
ALL HOLES 6.75(17/64") DIA U.N.O

14-P52-102x6x312(3.5)
ALL HOLES 6.75(17/64") DIA U.N.O