EMBEDMENT STRENGTH OF NEW ZEALAND CROSS LAMINATED TIMBER

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ABSTRACT

As an innovative engineered timber product, Cross Laminated Timber (CLT) has gained popularity in New Zealand and world-wide over the last couple of decades. However, structural design with CLT is not currently covered by the New Zealand Timber Structures Standard NZS3603:1993 (NZS3603). Connection design with CLT is often a challenging task for designers, due to the cross-wise layup of timber laminations. Embedment strength is an important design parameter in timber connection design, and is not explicitly presented in the current version of NZS3603. Therefore, there is a need to establish and verify current design formulas for CLT embedment strength to give designers the required tools for safe connection design. This paper presents an experimental study evaluating the embedment strength of New Zealand made CLT. A total of 331 specimens with four different CLT layups and three different dowel diameters were subjected to half-hole embedment tests described in the ASTM D5764-97a test standard. The test results showed that the embedment strength formula given in the CLT Handbook, is generally applicable for New Zealand CLT made of radiata pine and the difference between the experimental results and the calculation results was within 5%.

1. INTRODUCTION

Currently, embedment strength of dowel-type fasteners is not explicitly featured in the New Zealand Timber Structures Standard NZS3603:1993 (NZS3603) [1]. Instead, characteristic fastener loads or bolt bearing stresses are given for different timber groups to calculate the capacity of a joint. The timber groups depend on timber species, fastener type, and loading type, regardless of the timber density. Different connection failure modes are implicitly considered in the joint strength calculation, however the fastener’s yield strength is not taken into account. The revision of NZS3603 currently underway provides an opportunity to take in new knowledge and engineering practice developed in the last 25 years and adopt more robust connection design approaches similar to contemporary timber design standards such as Eurocode 5 [2].

In Eurocode 5, ductile connection strength and behaviour are described by the European Yield Model (EYM) which is based on wood embedment strength, \( f_e \), and fastener yield moment, \( M_y \). Figure 1 depicts the EYM failure modes for a single fastener in steel-to-timber joints. It can be seen that the joint failure consists of either pure wood embedment crushing, or a combination of wood crushing and fastener yielding with formation of one or two plastic hinges. The fastener yield moment can be calculated using the plastic moment \( M_{yp} = d^3/6f_y \) [3]. The embedment strength is calculated based on the fastener diameter, \( d \), and the characteristic timber density, \( \rho_k \). As the EYM tends to provide relatively accurate predictions of the connection’s ductile capacity and failure mechanism, it is worth assessing the accuracy of the calculation methods for timber embedment strength.

The embedment strength of Cross Laminated Timber (CLT) made of New Zealand radiata pine is investigated in this study as it is of particular interest for New Zealand design engineers.

![Figure 1: European Yield Model in Eurocode 5 [2]: failure modes of single fastener in steel-to-timber joints.](image)

2. EMBEDMENT STRENGTH FORMULAS

Eurocode 5 provides embedment strength formulas for loading parallel and perpendicular to the grain, given in Equations (1) and (2), where \( \rho_f \) is the characteristic timber density (5th percentile of the timber density distribution) and \( d \) is the fastener diameter. These formulas can be used to estimate the overall panel
Embedment strength, $f_{h,k}$, as shown in Equation (3), where $t_{i,k}$ denotes the thickness of the $i$th layer loaded parallel to grain with the characteristic density $\rho_{k,i}$, $t_{j,k}$ is the thickness of the $j$th layer loaded perpendicular to grain with the characteristic density $\rho_{k,j}$, and $t$ is the panel thickness. While this method takes the CLT panel layup into account, it does not account for layer-interaction provided by the glue bond. Thus, Uibel and Blaß [4] proposed Equation 4 for the calculation of CLT embedment strength which was adopted in the CLT Handbook [5]. The equation is independent of the CLT layup which makes it attractive to designers, but it is limited to a maximum layer thickness of 40 mm and $\sum t_{||}/\sum t_\perp$ ratios between 0.95 and 2.1, where $\sum t_{||}$ is the total thickness of the layers loaded parallel to grain, and $\sum t_\perp$ is the total thickness of the layers loaded perpendicular to grain [4].

$$f_{h,0,k} = 0.082(1 - 0.01d)\rho_k$$

$$f_{h,00,k} = \frac{0.082(1 - 0.01d)\rho_k}{1.35 + 0.015d}$$

$$f_{h,k} = 0.082(1 - 0.01d)\sum t_{||,i}\rho_{k,i} + \sum t_{\perp,j}\rho_{k,j} + \sum t_{\perp}$$

$$f_{h,k} = 0.031(1 - 0.015d)\rho_k^{1.16}$$

Table 1 shows the different embedment strength values calculated with Equations (3) and (4) for 3-layer CLT with equal lamination thickness (i.e. $\sum t_{||}/\sum t_\perp = 2.0$) loaded along its strong axis considering different timber densities and different fastener sizes ($d = 12\text{mm}, 16\text{mm}$ and $20\text{mm}$). It can be seen that the difference in the strength calculations varies from 1\% to 10\%.

Table 1: Calculated embedment strengths.

<table>
<thead>
<tr>
<th>Fastener diameter $d$ [mm]</th>
<th>Timber density $\rho_k$ [kg/m$^3$]</th>
<th>$f_{h,k,EC5}$ [MPa]</th>
<th>$f_{h,k,CLTHB}$ [MPa]</th>
<th>$f_{h,k,CLTHB}/f_{h,k,EC5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>300</td>
<td>19.15</td>
<td>18.99</td>
<td>1.01</td>
</tr>
<tr>
<td>16</td>
<td>18.11</td>
<td>17.60</td>
<td>1.03</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>17.10</td>
<td>16.22</td>
<td>1.05</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>28.72</td>
<td>30.40</td>
<td>0.94</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>27.16</td>
<td>28.18</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>25.64</td>
<td>25.95</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>38.30</td>
<td>42.45</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>36.22</td>
<td>39.34</td>
<td>0.92</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>34.19</td>
<td>36.23</td>
<td>0.94</td>
<td></td>
</tr>
</tbody>
</table>

3. EXPERIMENTS

Different test standards, ASTM D5764-97a [6], ISO/DIS 10984-2 [7], and EN 383 [8] can be used to evaluate timber embedment strength for connection design. Franke and Magnière [9] compared these three test standards and recommended half-hole tests according to ASTM D5764-97a to determine embedment strength, while using the embedment specimen size given in EN383 with a specimen thickness of $t \geq \text{min} (40\text{mm}, 4d)$.

In this study, six half-hole embedment test series were carried out for different fastener sizes on different layups of CLT made out of New Zealand radiata pine. The embedment strength was evaluated with the 5\% offset method given in ASTM D5764-97a, as shown in Figure 2. The data was then analysed according to ASTM D2915-10 [10].

3.1. Test series

A total of six test series were conducted on four CLT layups and three dowel sizes. All the specimens were tested in-plane, parallel to the grain orientation of the outer layer.

Test series #1 to #3 consisted of 101 3-layer CLT samples with a 20-20-20 layup, meaning all layers were 20 mm thick with $\sum t_{||}/\sum t_\perp = 2.0$. The average moisture content of the specimens was 10.2\%. Three different dowel sizes $d = 12\text{mm}, 16\text{mm}$ and $20\text{mm}$ were tested.

Test series #4 to #6 consisted of 230 embedment tests on one layup of 3-layer CLT (20-45-20 with $\sum t_{||}/\sum t_\perp = 0.89$) and two different layups of 5-layer CLT (45-20-20-20-45 with $\sum t_{||}/\sum t_\perp = 2.75$; and 45-40-35-40-45 with...
\( \Sigma t_1 / \Sigma t_2 = 1.5 \). Only one dowel size \( d = 20\text{mm} \) was used in these series. It should be noted that test series #4 and #5 did not meet the \( \Sigma t_1 / \Sigma t_2 \) ratio limitations \((0.95 \leq \Sigma t_1 / \Sigma t_2 \leq 2.1) \) of Equation (4), and none of the layups met the maximum thickness limitation \((40 \text{ mm}) \). The average moisture content was 9.9\% for the specimens in test series #4 and #5, and 10.8\% for the specimens in test series #6.

To obtain half holes, samples of \( 14d \) height were cut, a 1 mm oversized hole was drilled in the centre of the sample, and the sample was subsequently cut in half (Figure 3). The samples were loaded with a displacement rate of 1 mm/min in order to reach the maximum load within 10 min as prescribed by ASTM D5764-97a. Photos of the test setup are shown in Figure 3. The sample dimensions are given in Table 2. All test series were compliant with the dimension requirements given in ASTM D5764-97a, while series #1 to #3 and #6 were also compliant with the dimensions given in EN383.

Table 2: Sample dimensions.

<table>
<thead>
<tr>
<th>Test series #</th>
<th>CLT layup [mm]</th>
<th>( \Sigma t_1 / \Sigma t_2 )</th>
<th>( d ) [mm]</th>
<th>( h ) [mm]</th>
<th>( w ) [mm]</th>
<th>( t ) [mm]</th>
<th>Sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20-20-20</td>
<td>2.00</td>
<td>12</td>
<td>84</td>
<td>72</td>
<td>60</td>
<td>37</td>
</tr>
<tr>
<td>2</td>
<td>20-20-20</td>
<td>2.00</td>
<td>16</td>
<td>112</td>
<td>96</td>
<td>60</td>
<td>34</td>
</tr>
<tr>
<td>3</td>
<td>20-20-20</td>
<td>2.00</td>
<td>20</td>
<td>140</td>
<td>120</td>
<td>60</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>20-45-20</td>
<td>0.89</td>
<td>20</td>
<td>100</td>
<td>100</td>
<td>85</td>
<td>105</td>
</tr>
<tr>
<td>5</td>
<td>45-20-20-20-45*</td>
<td>2.75</td>
<td>20</td>
<td>100</td>
<td>100</td>
<td>150</td>
<td>90</td>
</tr>
<tr>
<td>6</td>
<td>45-40-35-40-45</td>
<td>1.5</td>
<td>20</td>
<td>140</td>
<td>120</td>
<td>205</td>
<td>35</td>
</tr>
</tbody>
</table>

* sized according to ASTM D5764-97a with \( h = w \geq 80 \text{ mm} \)

4. RESULTS AND DISCUSSION

Figure 4 depicts typical load embedment curves from test series #6. The embedment specimens were cut out of full-sized panels and the first number designates the panel number, the second number designates the block number and a) and b) indicate the two different specimen halves. Figure 5 shows some typical embedment failures from series #5 and #6. Table 3 gives the summary of the experimental embedment strength, \( f_{h,exp} \), and the calculated strength, \( f_{h,calc} \), using Equation (4). \( f_{h,calc} \) was calculated for each individual test specimen using the specimen’s density as \( f_{h,calc} = 0.031(1-0.015d)\rho_{exp}^{1.16} \). \( f_{h,exp} \) was established with the aforementioned 5\% offset method according to ASTM D5764-93a: On the load-deformation curve, two data points corresponding to the 20\% and 60\% of the maximum load, \( F_{max} \), were used to fit a straight line as shown in Figure 2. Subsequently, this line was offset by a deformation equal to 5\% of the fastener diameter and the intersection with the load-deformation curve was established as the yield load, \( F_{h,y} \). The embedment strength was then calculated by dividing \( F_{h,y} \) by the projected embedment area \( A = d t \).

The characteristic embedment strengths, \( f_{h,k,calc} \) and \( f_{h,k,exp} \) are the 5\textsuperscript{th} percentile of the respective strength distributions.

As can be seen in Table 3, Equation (4) slightly over-predicted the characteristic embedment strength, \( f_{h,k} \) for test series #1 to #3, where \( f_{h,k} \) is taken as the lower 5\textsuperscript{th} percentile value of the strength distribution and calculated as \( f_{h,k} = f_{h,mean} (1-k*CV) \) for a normal distribution, with \( f_{h,mean} \) being the mean value and CV being the coefficient of variation. The prediction error ranged from 1.1\% to 4.5\%. For the 3-layer specimens in test series #4, Equation (4) significantly over-predicted \( f_{h,k} \) by 44.4\%. This is because the inner layer was significantly thicker than the outer layers with a \( \Sigma t_1 / \Sigma t_2 \) ratio of 0.89 which lies below the lower bound of 0.95 required by Equation (4). This indicates that \( \Sigma t_1 / \Sigma t_2 \geq 0.95 \) may strict lower bound to ensure conservative embedment strength.
estimates with Equation (4). For the 5-layer CLT in series #5 and #6 on the other hand, Equation (4) provided conservative estimates for the embedment strength, with an under-prediction of \( f_{h,k} \) by 4.7% and 6.7%, respectively. It should be noted that the \( \sum t_{||}/\sum t_{\perp} \) ratio of series #5 was 2.75 which is significantly higher than the upper bound of 2.1 required by Equation (4). It seems that Equation (4) tends to cause more significant prediction errors for CLT layups with cross-layers in majority, whereas \( \sum t_{||}/\sum t_{\perp} \) ratios of up to 2.75 still provide conservative results for 5-layer CLT.

5. CONCLUSIONS

A total of 331 CLT specimens with four different layups and three dowel diameters were subjected to half-hole embedment tests according to ASTM D5764-97a. The test results suggest that the embedment strength formula given in the CLT Handbook, 

\[
 f_{h,k} = 0.031(1-0.015d)\rho_{k}^{1.16} 
\]

is generally applicable for New Zealand CLT made out of radiata pine within its specified bounds of 0.95 ≤ \( \sum t_{||}/\sum t_{\perp} \) ≤ 2.1. For the test series within these bounds, strength predictions were slightly non-conservative for the 3-layer CLT (over-prediction of up to 4.5%), but conservative for the
5-layer CLT.
Furthermore, the test results suggest that the formula can also be used for 5-layer CLT with up to 45mm lamination thickness and $\Sigma t_i/\Sigma t_\perp$ ratios up to 2.75. On the other hand, the formula is not applicable for $\Sigma t_i/\Sigma t_\perp$ below 0.95 as it resulted in 44.4% over-prediction for a 3-layer CLT test series with $\Sigma t_i/\Sigma t_\perp = 0.89$. In conclusion, the suggested range for New Zealand CLT made out of radiata pine is thus $0.95 \leq \Sigma t_i/\Sigma t_\perp \leq 2.75$, $t_i \leq 45$mm.

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REFERENCES


