Ductility of large-scale dowelled CLT connections under monotonic and cyclic loading

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Abstract

In the last decade, several tall timber buildings have been constructed in Europe, North America and Australasia. Often engineered wood products such as Cross Laminated Timber (CLT) are used in combination with strong connections to construct timber buildings exceeding 10 storeys. For tall timber buildings located in seismic areas it can be challenging to design strong yet ductile hold-downs in CLT shear walls. One common solution is to use dowelled connections with inserted steel plates.
Design code calculation rules for timber connections are usually derived from small-scale testing assuming that strength and ductility properties can be extrapolated for larger connections in actual buildings. For CLT connections, fastener spacing requirements are derived in a similar manner under the general assumption that brittle failure modes can be prevented due to the reinforcing effect of cross-layers in CLT.
In order to assess the validity of these assumptions, experiments were conducted on different layouts of small-scale and large-scale dowelled connections in CLT, Laminated Veneer Lumber (LVL) as well as a LVL-CLT hybrid, all made out of New Zealand *Radiata pine*. The tests comprised of 40 small and 12 large samples subjected to monotonic and cyclic loading. Strength and ductility were compared between the different connection sizes and layouts. For the large-scale connections, particle tracking velocimetry (PTV) was used for the first time to measure displacements.

Keywords: dowelled connections, ductility, LVL, CLT, PTV, seismic design

1. INTRODUCTION

In the last decade, several tall timber buildings have been constructed in Europe, North America and Australasia using Cross Laminated Timber (CLT). For CLT buildings located in seismic areas it can be a challenging task to design strong yet ductile hold-downs in shear walls. A common solution is to use a slotted-in steel plate in combination with bolts and dowels. Often, connection strength and ductility are based on small-scale testing under the assumption that calculation rules and fastener spacing can be extrapolated to large-scale connections. Furthermore, ductility derived from monotonic tests is often applied in seismic design without assuring that similar ductility can be obtained under cyclic loading. From small-scale connection tests it was found that ductility of dowelled CLT connections could be improved by using wider fastener spacing (Ottenhaus et al. 2016a). In this study, a total of 12 large-scale experiments were conducted on three different layouts of dowelled CLT and CLT-LVL-hybrid connections under monotonic and cyclic loading according to the ISO loading protocol (ISO 16670:2003). One objective was to evaluate whether the ductility of the first layout "L1" could be improved by substituting timber boards in the outer layer with LVL laminations (L2) or by using a wider dowel spacing (L3). Subsequently, the ductility ratio μ was derived following the 1/6th method (EN 12512). The findings from the large-scale testing were then compared to the findings from previous small-scale testing (Ottenhaus et al. 2016b) and the strength prediction based on an extrapolation of the small-scale test results.

2. EXPERIMENTAL SETUP

2.1 Test set up and material properties

Two different connection layouts and two different panel layups were subjected to monotonic and cyclic tensile loading as shown in Figure 1. The panels were 5-ply CLT and 4.0 m long and 2.5 m wide as shown in Figure 2. For all layouts, the internal layer was 35 mm thick and the cross-layers were 40 mm thick, all made of SG10 sawn timber (NZS 3603:1993). The outer layer was made of 45 mm thick sawn timber for layout L1 (panel 01 to 04) and L3 (panel 09 to 12). For layout L2 (panel 05 to 08) the outer layer was made of 43 mm thick LVL11 laminations (AS/NZS 4357.0:2005). All timber was New Zealand *Radiata pine* and stored inside the laboratory prior to testing which had an average temperature of 16.7°C and 50% relative humidity. The average moisture content was 10.8% for CLT and 10.1% for LVL, measured by means of oven drying. The mean and characteristic densities of CLT and LVL were $\rho_{mean,CLT}$ = 447 kg/m^3 and $\rho_{k,CLT}$ = 407 kg/m^3, and $\rho_{mean,LVL}$ = 592 kg/m^3 and $\rho_{k,LVL}$ = 550 kg/m^3, respectively.

In the connection area the inner layer was left out to fit a slotted-in 25 mm thick steel plate specified Grade 350 (AS/NZS 4671:2001). The connection consisted of 12 smooth ϕ20 mm dowels and 4 additional dowels with threaded ends and washers and hand-tight nuts, installed at in the corners, all specified Grade 300 (AS/NZS 4671:2001). The internal plate was connected to a reaction frame at the centre of the panel edge. The fastener spacing for the different layouts is given in Table 1, where d stands for dowel diameter, a_x denotes the spacing between fasteners in panel x-direction, a_y denotes the spacing between fasteners in panel y-direction, and $a_{x,end}$ denotes the end distance in panel x-direction. The force was applied by the hydraulic actuators to the panel via 2x3 ϕ30mm internal tensile rods and two thick steel bearing plates. This connection was designed to remain elastic during testing, and little timber crushing (< 0.5 mm) occurred in the plate bearing area.

2.2 Instrumentation

Displacements were measured by three string potentiometers on each panel side located at the centre between two rows of dowels and by means of Particle Tracking Velocimetry (PTV) as shown in Figure 3. For this purpose, two DSLR cameras were positioned at the connection centre at 1.5 m from the panel surface on each panel side and trigged simultaneously with the force and displacement readings every 2 seconds. The images were then post-processed and analysed in *Streams 2.06*, which is an image processing and PTV system developed at the University of Canterbury in the field of fluid mechanics (Nokes 2017). Employing PTV had the advantage that not only the displacements in the x-direction but also the displacements in the y-direction as well as the panel rotations could be captured. Furthermore, all panels experienced delamination of the outer layers towards the end of the experiment which required some of the draw-wires to be removed to avoid damage. Hence, the results obtained with PTV are presented and discussed in the following.

Figure 1: *Test setup (left) and connection area (right)*

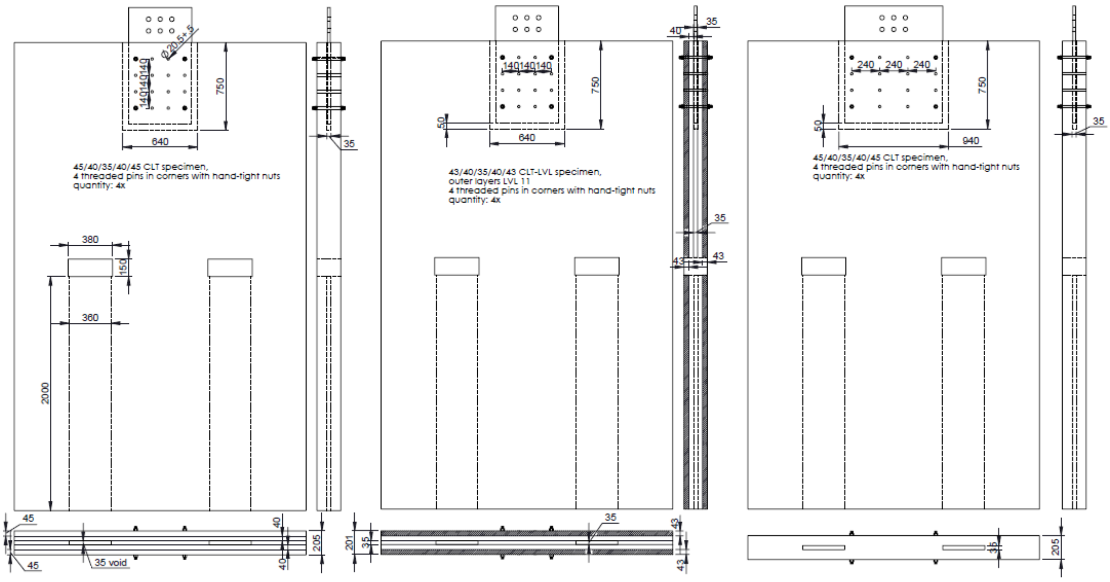

Figure 2: *Panel layout "L1" for panel 01 to 04 (left), "L2" for panel 05 to 08 (centre), and "L3" for panel 09 to 12 (right).*

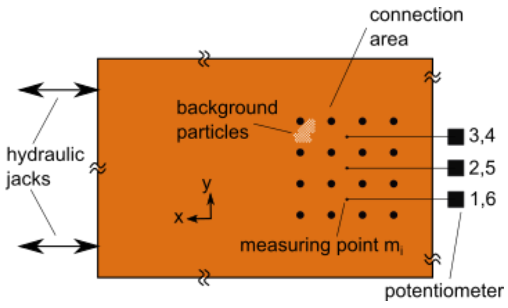

Figure 3: *Instrumentation*

Table 1: *Fastener spacing and panel layouts*

layout	L1: CLT dense	L2: CLT-LVL	L3: CLT wide
panel	01 to 04	05 to 08	09 to 12
	spacing [mm] / (dowel diameter *d*)		
a_x	140 (7*d*)	140 (7*d*)	140 (7*d*)
a_y	140 (7*d*)	140 (7*d*)	240 (12*d*)
$a_{x,end}$	140 (7*d*)	140 (7*d*)	140 (7*d*)

3. TEST RESULTS AND DISCUSSION

Figures 4 to 6 display the load displacement and backbone curves for layout L1 to L3. Panel 01, 05, and 09 were tested under monotonic loading whereas panels 02 to 04, 06 to 08, and 10 to 12 were subjected to cyclic loading according to the ISO loading protocol (ISO 16670:2003). The displacements, m_i, were obtained with PTV by tracking the string attachment point of each potentiometer as shown in Figure 3. The total displacement, m, considering both the x-displacement, m_x, and y-displacement, m_y, is calculated in Equation 1. Table 2 shows the connection properties and predicted strength based on the small-scale connection test results in terms of yield strength, F_y, maximum load, F_{max}, and ultimate load, F_u, and the corresponding displacements, Δ_i, ductility μ, as well as failure mode (B = brittle, LD = low ductility, MD = moderate ductility, HD = high ductility) classified according to Smith et al. (2006). The relationship F_u = 0.8 F_{max} was assumed in all cases except for panel 01 and 03 which failed in a very abrupt manner. Figure 7 shows a selection of final connection failure.

$$m_i = \begin{cases} \sqrt{m_{ix}^2 + m_{iy}^2} & for \quad m_{ix} \geq 0 \\ -\sqrt{m_{ix}^2 + m_{iy}^2} & \quad\quad m_{ix} < 0 \end{cases} \qquad i = 0 \ldots 6 \qquad (1)$$

Table 2: *Test results large-scale monotonic (M) and cyclic (C) connection testing*

layout	L1 CLT					L2 CLT-LVL				
panel	pred.	01 M	02 C	03 C	04 C	pred.	05 M	06 C	07 C	08 C
F_y [kN]	571	722	812	701	710	641	826	870	855	825
F_{max} [kN]	765	1023	1000	943	871	855	1311	1292	1239	1268
F_u [kN]		1023	800	943	696		1049	1033	991	1014
Δ_y [mm]		5.7	6.6	6.1	6.9		7.6	7.8	6.8	7.8
Δ_{Fmax} [mm]		25.4	22.3	20.4	17.4		35.5	38.2	30.2	38.7
Δ_u [mm]		25.4	37.0	20.4	38.0		47.5	51.0	41.0	50.1
μ		4.4	5.6	3.4	5.5		6.3	6.5	6.0	6.4
ductility		MD	MD	LD	MD		HD	HD	HD	HD

layout	L1 CLT wide spacing				
panel	pred.	09 M	10 C	11 C	12 C
F_y [kN]	571	830	849	920	849
F_{max} [kN]	765	1286	1106	1210	1177
F_u [kN]		1028	885	968	942
Δ_y [mm]		7.0	10.1	9.9	8.2
Δ_{Fmax} [mm]		33.4	27.3	28.5	28.0
Δ_u [mm]		49.4	48.9	49.8	49.0
μ		7.1	4.8	5.0	6.0
ductility		HD	MD	MD	MD

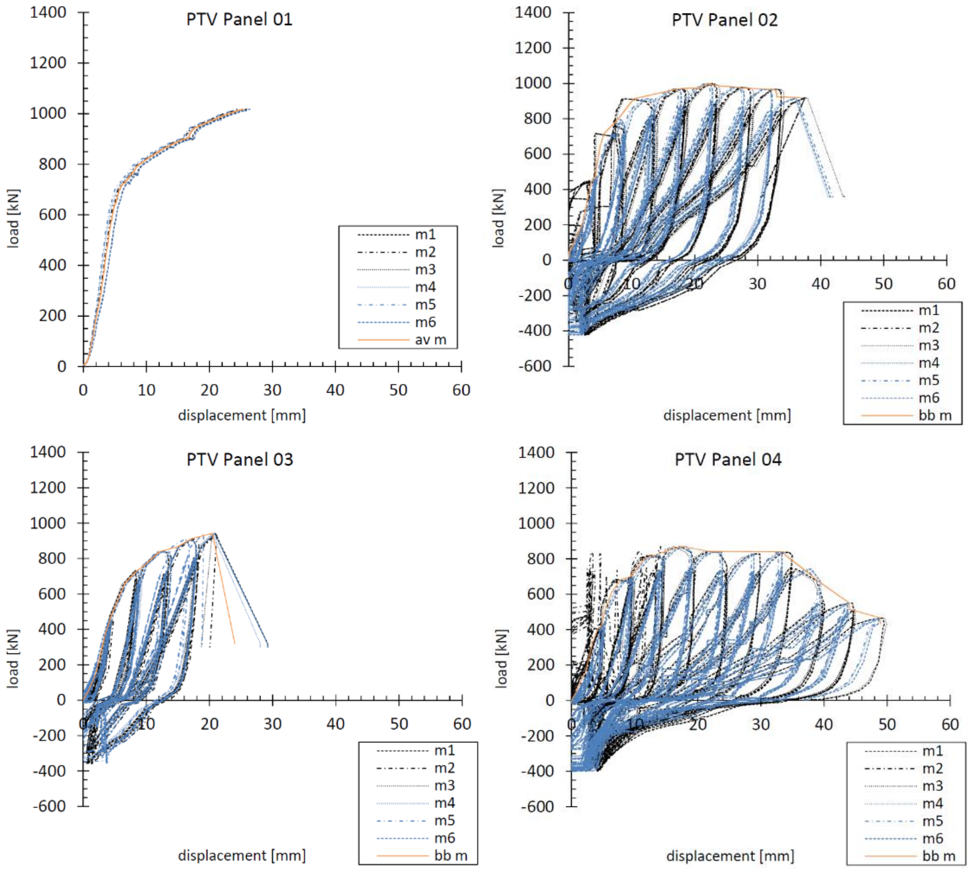

Figure 4: *PTV load-displacement curves and backbone curves, panel 01 to 04 (CLT dense dowel spacing)*

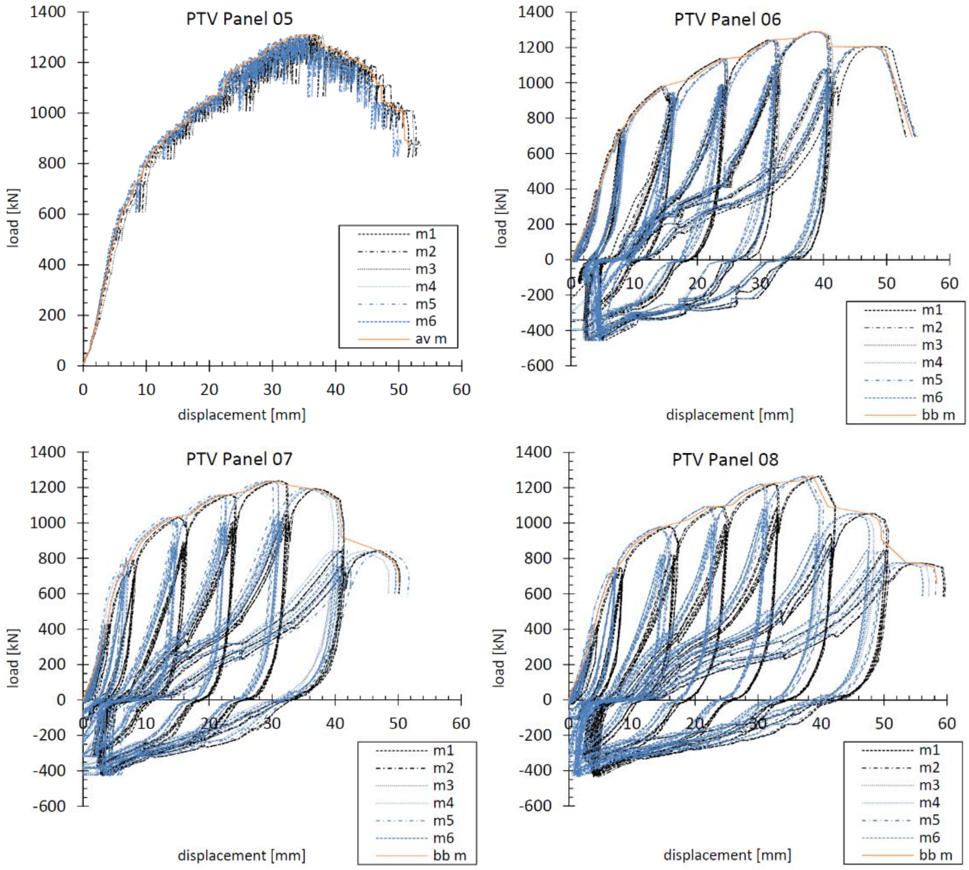

Figure 5: *PTV load-displacement curves and backbone curves, panel 05 to 08 (CLT-LVL hybrid, dense dowel spacing)*

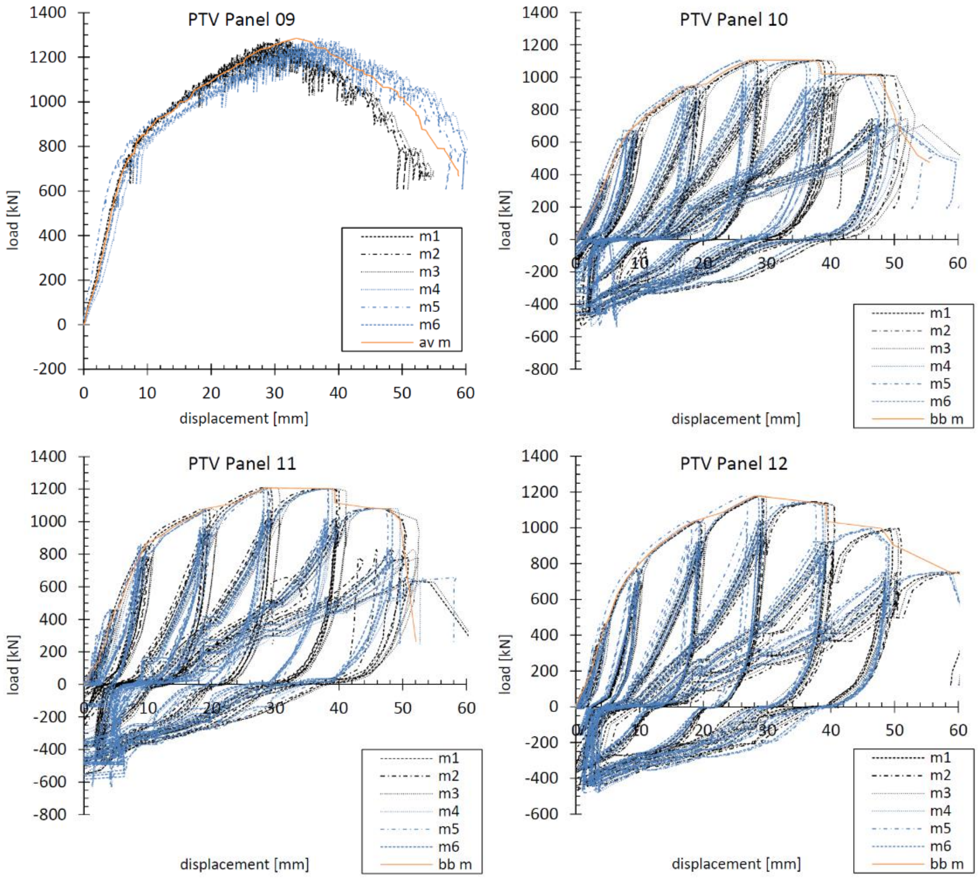

Figure 6: *PTV load displacement and backbone curves, panel 09 to 12 (CLT wide dowel spacing)*

Figure 7: *Connection failure from left to right, top to bottom: 01, 02, 04, 05, 07, 09 and 12*

Table 3 summarizes the findings from previous small-scale testing (Ottenhaus et al. 2016b). Instead of using the average ductility, the median was calculated to avoid skewing the results.

Table 3: *Test results of small-scale connections in CLT and LVL under monotonic (M) and cyclic (C) loading (Ottenhaus et al. 2016b)*

CLT	CLT M	CLT C	LVL M	LVL C
F_{max} [kN]	178	176	197	204
F_u [kN]	157	141	158	163
μ	5.5	8.6	5.5	8.7
ductility	MD	HD	MD	HD

All large-scale connections exhibited a range of different failures in the outer layers, including wood splitting, row shear and tensile failure between the fasteners as can be seen in Figure 7. Splitting and tensile failure seemed to occur randomly at different locations within the connection and independent of the different layouts.

Similar to the small-scale connection testing, delamination and wedging of the outer layers was observed although dowels with threaded ends and nuts and washers were added to the design. While all panel layouts experience delamination of the outer layers and splitting between the inner layer and cross layer to some extent, the wide dowel spacing layout exhibited especially severe delamination and warping of the panel. This behaviour was most dominant in the centre of the dowel row closest to the panel edge. This indicated that the connection behaviour might be further improved by positioning all threaded dowels in the end row closest to the panel edge in order to provide out-of-plane restraint.

From Table 2 it can be seen that all panels with one exception showed good ductility (medium to high). Strength was improved by using a wider dowel spacing and by substituting the outer layers with LVL laminations. While the first measure showed no considerable improvement of cyclic ductility, substitution with LVL laminations provided consistent ductility improvement.

Contrary to the small-scale connection testing, cyclic ductility was generally lower than monotonic ductility and also the strength was lower under cyclic testing. Ductility of the large-scale connections was generally lower than the ductility of the small-scale connections. However, the ductile strength prediction for the large-scale connections was well exceeded in all cases.

4. CONCLUSIONS

In this study, 12 large-scale dowelled CLT and CLT-LVL-hybrid connections made of New Zealand *Radiata pine* were subjected to monotonic and cyclic loading. Based on the experimental results, it was found that

1) The ductile strength prediction extrapolated from the small-scale connection test results was well exceeded in all cases.
2) All panels with one exception showed good ductility (medium to high)
3) Strength was improved by using wider dowel spacing or substituting the outer layers with LVL11 laminations. While wider dowel spacing seemed to have no considerable effect on ductility, the CLT-LVL-hybrid provided good consistent improvement of ductility.
4) The cyclic ductility of the large-scale connections was lower than the monotonic ductility; and ductility of the large-scale connections was lower than the ductility of the small-scale connections. Therefore, large-scale connection testing under cyclic loading is necessary to derive actual ductility for seismic loading.
5) In order to prevent delamination of outer layers, it is recommended to use bolts instead of dowels in the fastener end row of a connection.

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