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Ductility of dowelled New Zealand Douglas-Fir CLT connections under monotonic and cyclic loading

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ABSTRACT

Cross-laminated Timber (CLT) is gaining popularity in Australasia as a building material for multi-storey structures. Designing strong but ductile hold-downs for CLT shear walls in these seismic areas has challenges and requires careful structural connection design. In this study, dowelled connections in New Zealand Douglas-Fir (D.Fir) CLT with inserted steel plates were experimentally investigated as a solution for hold-downs in multi-storey timber buildings. The dowel group spacing was varied for CLT3 (3-ply, 135 mm thick), CLT5 (5-ply, 175 mm thick) and CLT7 (7-ply, 275 mm thick) D.Fir CLT to investigate the spacing impact on ductility of the hold-down connections under both monotonic and quasi-static cyclic loading. These results were also compared with past similar testing of dowelled connections in 5-ply (150 mm) Radiata Pine CLT. A total of 12 monotonic and 36 quasi-static cyclic tests were carried out and it was observed that increased dowel spacing increases ductility with similar strength when compared to past more dense dowel spacing tests. Furthermore, to deter the onset of tension perpendicular to grain brittle failure, fully threaded screws and nuts were added to the dowelled connection and the impact of this is discussed.

1 INTRODUCTION

Timber buildings with Cross-laminated Timber (CLT) walls used as their lateral force resisting system are commonly used in seismic areas, and hold-down connections are required to resist the axial forces (Figure 1). A recently completed three-storey CLT structure in Christchurch (Figure 2) uses dowelled hold-down connections similar to those tested in this programme. Further, there is a significant available resource of New Zealand (NZ) Douglas-Fir (D.Fir), which has not been widely used in NZ CLT manufacturing but has some natural durability properties superior to Radiata Pine that is topical for building in New Zealand's unique climate. As such, experimental connection testing is required for design engineers to specify NZ D.Fir CLT in timber building design.

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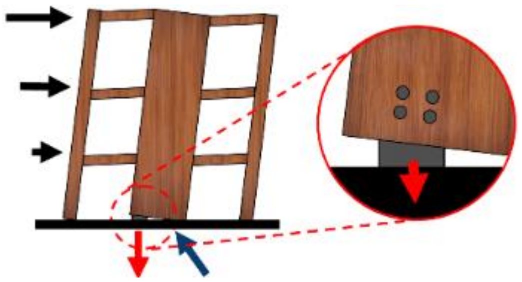

Figure 1: Earthquake loading inducing tensile force in dowelled hold-down connection

Figure 2: 3-storey CLT structure, Christchurch (c/o EngCo and PTL Structural Consultants)

2 EXPERIMENTAL PROGRAMME

The experimental programme goal was to investigate the impact of increased spacing on connection ductility. Previous experimental testing by Ottenhaus et al. (2016) used more dense dowel spacing to investigate brittle failure modes and hypothesized that increasing spacing a_2 and a_3 (Figure 3) would increase ductility.

2.1 Test Programme

The test programme is shown below in Table 1. The increased dowel spacing is indicated with the specimen name CLT-Mod., and the CLT-Reinf. specimens were reinforced with either inclined fully threaded screws or had the lower two dowels changed to dowels complete with threaded ends, nuts and washers.

Table 1: CLT specimen and test programme

Panel	Layup – Total Thickness (mm)	Dowel Diameter (mm)	Specimen Name	Monotonic	Cyclic
CLT3	45/45/45-135	12	CLT3-Std.	3	5
			CLT3-Mod.	-	5
CLT5	45/25/45/25/45-175	20	CLT5-Std.	3	5
			CLT-Mod.	-	5
CLT7	45/35/35/45/35/35/45-275	20	CLT7-Std.	3	5
			CLT7-Mod.	-	5
All	All	12 or 20	CLT-Reinf.	3	6

In this experimental study, dowel spacing parameters a_2 and a_3 (shown in Table 2 and Figure 3) were investigated. With reference to design codes, it is interesting to note the differences and the mentioning of CLT (Mohammad et al., 2018). The current NZS3603 (NZS, 1993), the upcoming DZ NZS AS 1720.1 (for comment) and Eurocode5 (CEN, 2004), other than German and Austrian National Annex's (NAs), do not specifically mention CLT. Dowel spacing in CLT in these NAs and the CLT Handbook (2011) are predominantly adopted from previous work by Blaß and Uibel (2007). The new CSA 086 2016 Supplement (CSA, 2014) and NDS 2015 (AWC, 2015) provide spacing and adjustment factors for joints in CLT. Each of these standards provides slightly different spacing requirements which is shown in Table 3.

Table 2: Dowel spacing in past research and programme

Spacing	Ottenhaus (2018)			Programme	
	RS	GT	Ductile	CLT-Std.	CLT-Mod.
a1	4d	4d	5d	5d	5d
a2	3d	2d	3d	4d	6d
a3	7d	7d	5d	7d	9d

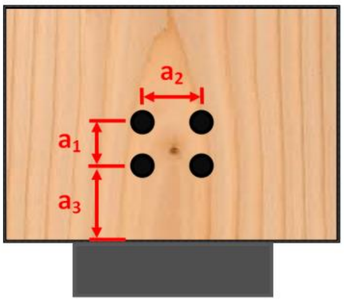

Figure 3: Connection spacing

Table 3: Design code dowel spacing

Spacing	NZS3603 **	DZ NZS AS 1720.1 (For Comment) **	Eurocode 5 **	CLT Handbook	CSA-086 (Canada)	NDS (USA)
a1	5d	4d	5d	4d	5d	4d
a2	Eq. 4.10*	3d	3d	4d	3d	3d
a3	8d	5d	7d	5d	5d	7d

*For experimental programme, a2 = 2.5d following NZS 3603

** Dowel spacing not specific to CLT, but to general timber connection design

2.2 Test set up and material properties

Figure 4: Experimental test set-up

The CLT specimens were fabricated by XLAM Ltd. The D.Fir lamella were graded SG8 with average Modulus of Elasticity of 8 GPa according to NZS3603 (NZS, 1993). The CLT specimens had an average moisture content of 10.5%, and the mean and characteristic density were ρ_{mean} = 467 kg/m^3 ρ_{char} = 432 kg/m^3 respectively. The dowels were grade 300 round bar as per AS/NZS 4671 R300E (AS/NZS, 2001). Holes in the CLT were drilled to the same diameter as the dowel, and the internal slot in each CLT specimen had 2 mm tolerance around the steel plate. The holes in the internal steel plates were drilled with 2 mm oversize as per NZS3404 (NZS, 1992), which accounted for approximately 1 mm initial slip in the connection discussed later.

A reaction frame (Figure 4) was designed for the tests with a 1000 kN actuator. The bottom connection with 4 dowels was tested to failure, whereas the top overstrength connection was required to connect the specimen to the actuator. The key measurement recorded during each test was the relative movement between the CLT and the inner steel plate of the bottom connection. The specimens were tested following a modified half cyclic loading protocol based on ISO16670 (2003).

3 EXPERIMENTAL PREDICTIONS

The strength prediction for each specimen was based on the minimum of the three ductile failure modes of the European Yield Model (EYM) shown in Figure 5 and Equation 1. The embedment strength ($f_{h,1,k}$) and dowel effective plastic moment capacity ($M_{y,Rk}$) were calculated using the CLT Handbook (2011) and Eurocode5 (CEN, 2004) respectively. The strength prediction (F_{pred}) for each CLT layup are shown in the results Tables 4, 5, 6, and 7. Rope effect was not considered in the strength prediction.

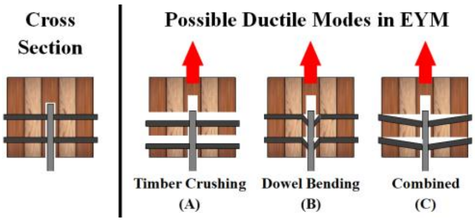

Figure 5: European yield model ductile failure modes

$$F_{pred} = min(F_{v,Rk,A}, F_{v,Rk,B}, F_{v,Rk,C}) \quad (1)$$

where: $F_{v,Rk,A} = f_{h,1,k}t_1d$; $F_{v,Rk,B} = f_{h,1,k}t_1d\left[\sqrt{2+\frac{4M_{y,Rk}}{f_{h,1,k}dt_1^2}}-1\right]$; $F_{v,Rk,C} = 2.3\sqrt{M_{y,Rk}f_{h,1,k}d}$

where: t_1 = side member thickness, d = dowel diameter

4 EXPERIMENTAL RESULTS

The yield point, F_y, was calculated according to EN12512 (2005) with correction for initial slip. Tables 4, 5, 6, and 7 below list yield, peak and ultimate strength, F_y, F_{max}, F_u, displacements Δ_y, Δ_{max}, Δ_u, initial stiffness, K and ductility μ_1 and μ_2. The definitions of ductility were recommended by Jorissen & Fragiacomo (2011):

$$\mu_1 = \frac{\Delta_u}{\Delta_y} \ ; \ \mu_2 = \frac{\Delta_{max}}{\Delta_y} \quad (2)$$

where: $\mu_2<4$ low ductility (LD), $4\leq\mu_2\leq6$ moderate ductility (MD) $\mu_2> 6$ Ductile (D) (Smith, Asiz, Snow, & Chui, 2006).

For the specimens with standard spacing, the similar three-stage failure mechanism described by Ottenhaus et al. (2018) was observed: onset of dowelled yielding, continued yielding, and the onset of crack growth in the cross layers leading to eventual brittle rupture. In the CLT3 specimens, a definite row shear failure plane developed in each test, followed by crack propagation in the cross layer causing the panel to split. In the CLT5, and especially the CLT7 specimens, the row shear failure plane in the outer lamella was not as prominent. At large displacements, the cross layer of CLT5 and CLT7 specimens split with tension perpendicular to grain, leading to a sudden brittle failure and sharp drop in load. Figures 6, 7 and 8 below show the typical failure modes.

Figure 6: CLT3 (row shear)

Figure 7: CLT5 (panel splitting)

Figure 8: CLT7 (panel splitting)

Table 4: CLT3 results summary

Result	Monotonic Tests			Cyclic Tests									
Test	M1	M2	M3	C1	C2	C3	C4	C5	C7	C8	C9	C10	C11
Spacing	Std.	Std.	Std.	Std.	Std.	Std.	Std.	Std.	Mod.	Mod.	Mod.	Mod.	Mod.
$F_{pred.}$ (kN)	81.8	81.8	81.8	81.8	81.8	81.8	81.8	81.8	81.8	81.8	81.8	81.8	81.8
F_y (kN)	53.5	55.3	57.0	71.0	59.5	60.3	64.5	66.0	62.8	57.0	56.2	63.5	55.0
F_{max} (kN)	109.6	118.3	96.3	99.8	119.2	84.5	104.9	108.1	120.6	117.0	118.6	104.0	110.8
F_u (kN)	87.3	94.6	77.1	79.8	94.5	68.1	83.9	86.5	96.5	93.6	94.9	83.2	88.6
Δ_y (mm)	1.9	1.5	2.0	4.8	2.1	4.9	3.3	3.3	2.4	2.0	2.2	3.0	2.3
Δ_{max} (mm)	20.5	11.6	12.5	20.7	22.0	15.9	16.3	19.6	20.1	19.1	15.9	21.3	21.7
Δ_u (mm)	28.0	11.9	18.0	27.5	32.8	30.0	30.3	33.3	27.7	26.0	29.7	27.9	29.7
$K_{pred.}$ (kN/mm)	84.2	84.2	84.2	84.2	84.2	84.2	84.2	84.2	84.2	84.2	84.2	84.2	84.2
K (kN/mm)	28.0	36.9	28.6	14.7	28.3	12.4	19.6	19.9	29.8	28.0	26.1	20.8	23.6
Mode	D	D	D	MD	D	D	D	D	D	D	D	D	D
μ_1	10.7	7.7	6.3	4.3	10.5	3.3	4.9	5.9	8.3	9.4	7.4	7.0	9.3
μ_2	14.6	7.9	9.0	5.7	15.6	6.2	9.2	10.0	11.4	12.8	13.8	9.2	12.7

Table 5: CLT5 results summary

Result	Monotonic Tests			Cyclic Tests									
Test	M1	M2	M3	C1	C2	C3	C4	C5	C7	C8	C9	C10	C11
Spacing	Std.	Std.	Std.	Std.	Std.	Std.	Std.	Std.	Mod.	Mod.	Mod.	Mod.	Mod.
$F_{pred.}$ (kN)	161.0	161.0	161.0	161.0	161.0	161.0	161.0	161.0	161.0	161.0	161.0	161.0	161.0
F_y (kN)	135.0	139.0	135.5	155.0	151.0	160.0	135.0	135.0	164.5	161.0	144.0	193.5	170.0
F_{max} (kN)	292.8	286.4	276.7	268.7	291.9	295.3	267.9	268.5	270.3	267.1	275.5	265.5	270.3
F_u (kN)	234.2	229.1	221.4	213.4	233.5	236.2	214.3	214.8	216.2	213.7	284.4	253.8	216.2
Δ_y (mm)	1.5	1.4	1.4	2.1	1.6	2.0	1.3	1.6	1.7	2.2	1.8	3.1	2.6
Δ_{max} (mm)	27.4	24.6	24.6	17.8	19.2	17.8	18.7	16.8	18.3	31.4	33.0	17.2	31.7
Δ_u (mm)	34.9	35.1	37.8	34.3	26.0	29.8	28.3	30.9	35.9	42.8	42.5	39.4	40.5
$K_{pred.}$ (kN/mm)	140.4	140.4	140.4	140.4	140.4	140.4	140.4	140.4	140.4	140.4	140.4	140.4	140.4
K (kN/mm)	90.9	100.8	95.7	74.0	94.6	78.8	105.6	83.1	99.4	72.4	78.5	61.9	66.6
Mode	D	D	D	D	D	D	D	D	D	D	D	D	D
μ_1	18.5	17.8	17.3	8.5	12.1	8.8	14.6	10.3	11.1	14.1	18.0	5.5	12.4
μ_2	23.5	25.4	26.7	16.4	16.3	14.7	22.1	19.0	21.7	19.2	23.2	12.6	15.9

Table 6: CLT7 results summary

Result	Monotonic Tests			Cyclic Tests									
Test	M1	M2	M3	C1	C2	C3	C4	C5	C7	C8	C9	C10	C11
Spacing	Std.	Std.	Std.	Std.	Std.	Std.	Std.	Std.	Mod.	Mod.	Mod.	Mod.	Mod.
$F_{pred.}$ (kN)	204.6	204.6	204.6	204.6	204.6	204.6	204.6	204.6	204.6	204.6	204.6	204.6	204.6
F_y (kN)	160.0	193.0	217.0	209.4	225.0	224.3	216.0	236.0	220.5	217.0	200.0	206.8	201.0
F_{max} (kN)	308.5	328.1	354.2	351.3	360.0	362.1	355.0	325.8	348.7	363.6	372.2	350.2	361.3
F_u (kN)	246.8	262.5	283.4	295.5	288.0	306.0	284.0	260.6	336.0	363.6	314.5	341.3	344.6
Δ_y (mm)	1.6	2.4	3.0	2.3	3.5	4.0	3.4	4.1	2.7	3.8	2.3	2.3	2.0
Δ_{max} (mm)	52.1	49.2	44.5	36.5	32.0	30.8	36.4	18.8	45.4	42.8	35.3	50.3	34.9
Δ_u (mm)	67.3	66.7	69.5	63.1	48.8	55.1	49.7	58.4	≥ 48.7	≥ 42.8	49.3	≥ 64	≥ 60.9
$K_{pred.}$ (kN/mm)	140.4	140.4	140.4	140.4	140.4	140.4	140.4	140.4	140.4	140.4	140.4	140.4	140.4
K (kN/mm)	103.0	81.4	73.1	92.1	64.9	56.2	63.0	57.3	81.8	56.8	88.2	89.2	99.2
Mode	D	D	D	D	D	D	D	D	D	D	D	D	D
μ_1	33.5	20.8	15.0	16.1	9.2	7.7	10.6	4.6	16.8	11.2	15.6	21.7	17.2
μ_2	43.3	28.2	23.4	27.8	14.1	13.8	14.5	14.2	≥ 18.1	≥ 11.2	21.8	≥ 27.6	≥ 30

Table 7: Testing averages and reinforced specimens

Result	CLT3						CLT5						CLT7					
Test	M4	M	C6	C	C12	C	M4	M	C6	C	C12	C	M4	M	C6	C	C12	C
Spacing	Std.	Std.	Std.	Std.	Mod.	Mod.	Std.	Std.	Std.	Std.	Mod.	Mod.	Std.	Std.	Std.	Std.	Mod.	Mod.
	Reinf.	Avg.	Reinf.	Avg.	Reinf.	Avg.	Avg.	Avg.	Reinf.	Avg.	Reinf.	Avg.	Reinf.	Avg.	Reinf.	Avg.	Reinf.	Avg.
$F_{pred.}$ (kN)	81.8	81.8	81.8	81.8	81.8	81.8	161.0	161.0	161.0	161.0	161.0	161.0	204.6	204.6	204.6	204.6	204.6	204.6
F_y (kN)	61.6	55.3	85.7	64.3	63.0	58.9	137.5	136.5	150.0	147.2	150.0	166.6	176.0	190.0	177.5	222.1	198.0	209.1
F_{max} (kN)	105.7	108.1	113.9	103.3	122.5	114.2	289.8	285.3	319.2	278.5	282.4	269.7	352.9	330.3	337.9	350.8	382.3	359.2
F_u (kN)	89.5	86.3	91.1	82.6	98.0	91.4	231.8	228.2	255.4	222.4	225.9	236.9	328.7	264.2	270.3	286.8	381.8	340.0
Δ_y (mm)	2.3	1.8	5.7	3.7	2.7	2.4	1.2	1.4	1.7	1.7	1.7	2.3	1.8	2.3	2.9	3.5	2.7	2.6
Δ_{max} (mm)	22.1	14.8	20.4	18.9	21.7	19.6	22.8	25.5	25.0	18.1	16.4	26.3	45.5	48.6	45.4	30.9	49.0	41.7
Δ_u (mm)	38.7	19.3	35.3	30.8	36.3	28.2	40.5	35.9	50.3	29.9	45.8	40.2	70.0	67.8	63.4	55.0	≥ 61.8	49.3
$K_{pred.}$ (kN/mm)	84.2	84.2	84.2	84.2	84.2	84.2	140.4	140.4	140.4	140.4	140.4	140.4	140.4	140.4	140.4	140.4	140.4	140.4
K (kN/mm)	27.3	31.2	15.1	18.9	23.1	25.6	117.0	95.8	90.4	87.2	86.8	75.8	100.2	85.8	60.5	66.7	73.5	83.0
Mode	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
μ_1	9.8	8.2	3.6	5.8	8.0	8.3	19.4	17.9	15.1	10.9	9.5	12.2	D	23.1	15.5	9.6	18.2	16.5
μ_2	17.2	10.5	6.2	9.3	13.3	12.0	34.4	25.2	30.3	17.7	26.5	18.5	39.9	31.6	21.6	16.9	≥ 23	21.8

Figures 9 through 14 below show the experimental monotonic and hysteresis curves for all test specimens.

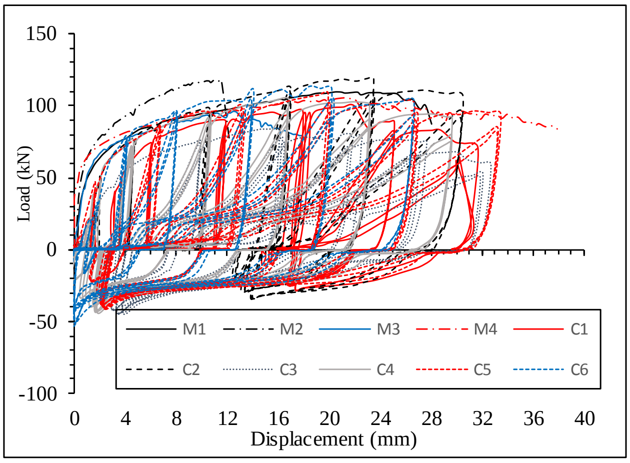

Figure 9: Load-slip curves of CLT3-Std. specimens

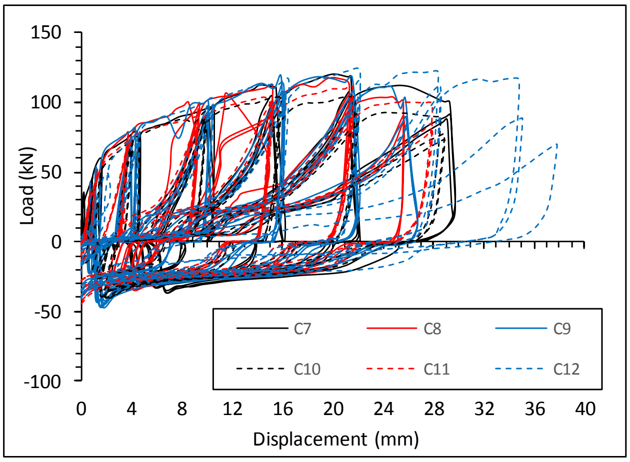

Figure 10: Load-slip curves of CLT3-Mod. specimens

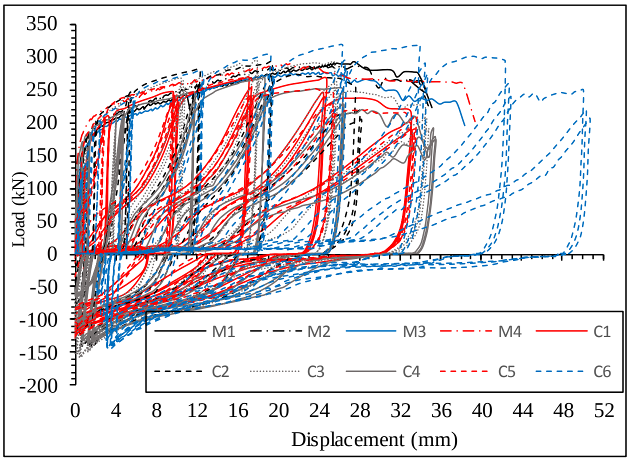

Figure 11: Load-slip curves of CLT5-Std. specimens

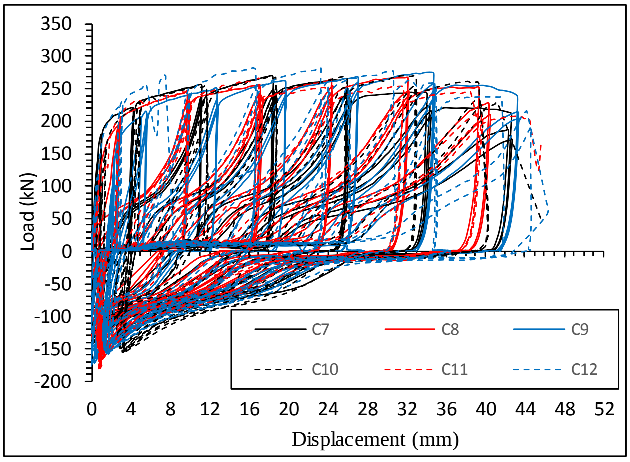

Figure 12: Load-slip curves of CLT5-Mod. specimens

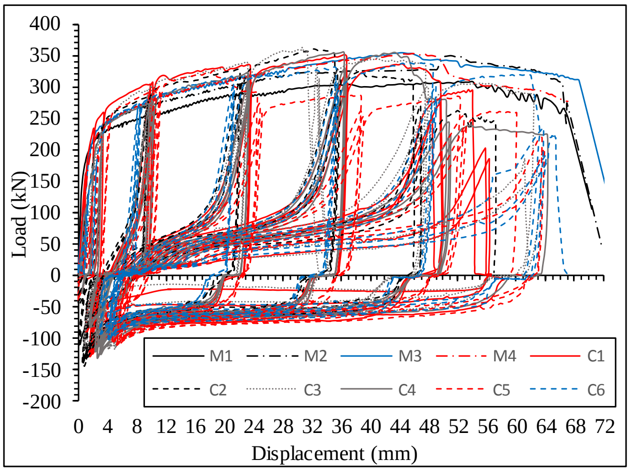

Figure 13: Load-slip curves of CLT7–Std. specimens

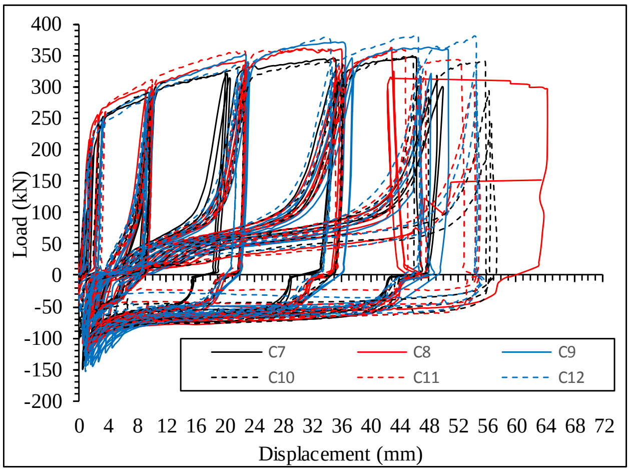

Figure 14: Load-slip curves of CLT7-Mod. specimens

Row shear failure was not observed in the CLT3-Mod. and CLT5-Mod. specimens while panel splitting occurred at the displacements generally larger than 30 mm. This increased ductility with similar peak forces, as shown in Tables 4, 5, 6, and 7. In general the CLT5 specimens did not experience large crack propagation and sudden brittle failure in the internal layers which was observed in the CLT3 specimens. Load-slip curves for CLT3 and CLT5 specimens are shown in Figures 9, 10 and 11, 12 respectively.

For the CLT7 specimens, row shear failure did not occur in the CLT7-Std. or CLT7-Mod. specimens, and all CLT7 specimens maintained loads above 80% F_{max} at 30 mm displacements. It was only beyond 30 mm displacement that the CLT7-Mod. specimens maintained higher loads than CLT7-Std. specimens. In the CLT7-Mod. specimens, the test was stopped before the load dropped to 80% F_{max} because the limits of the potentiometers were reached. Figure 13 and Figure 14 above show the load-slip curves of the CLT7 specimens.

In general, it was found that the increased dowel spacing increased the ductility but did not influence F_y or F_{max} significantly. For the CLT3 and CLT7 specimens, stiffness also increased with increased spacing; however, the stiffness decreased for the CLT5 specimens with increased spacing.

5 DISCUSSION

For all CLT3, CLT5 and CLT7 specimens, the cyclic ductility was significantly lower than the monotonic ductility, which emphasizes the importance of conducting cyclic testing for these connections. The ductility definition is very sensitive to the yield displacement and in this study 1 mm correction for the initial slip was used to adequately account for the effect of the oversized holes in the internal steel plates. The experimental stiffness was lower than the prediction equation, from Eurocode5 (CEN, 2004), as shown in Equation 3:

$$K_{pred} = \rho_m^{1.5} * \frac{d}{23} * n_{shear} * \gamma \qquad (3)$$

where: ρ_m = mean density, d = dowel diameter, n_{shear} = number of shear planes, γ = 2 for steel, 1 for timber

This difference between the test results and the prediction equation was more significant in CLT3 and CLT7 specimens in which thickness ratios between the parallel-layer and the cross layer were 90:45 and 160:115. However, for the CLT5 specimens, the ratio was 135:40. Thus, the majority of the timber was loaded parallel to grain, leading to potentially higher connection stiffness.

When comparing the test results to previous work that investigated brittle failure modes, it is clear that by using adequate spacing larger displacements can be achieved as the onset of brittle failure is delayed. The addition of fully threaded screws installed inclined or nuts with washers was investigated with a small number of samples and the results showed potential benefit in delaying brittle failure. A comparison of the CLT5 specimens with testing by Ottenhaus et al. (2018) is shown in Table 8. Refer to Table 2 for dowel spacing.

Table 8: Ductility comparison with past research

	Ottenhaus (2018)				Experimental programme					
Name	DT-M	DT-C	GT	RS	Std.-M	Std-M	Std.-C	Std.-C	Mod-C	Mod.-C
Description	Avg.	Avg.	Avg.	Avg.	Reinf.	Avg.	Reinf.	Avg.	Reinf.	Avg.
Quantity	5	5	5	5	1	3	1	5	1	5
Δ_u [mm]	5.7	5.7	7.9	12.9	40	36	50	30	46	40
μ_2	7.3	8.4	9.2	14.6	34	25	30	18	27	19

where: M = monotonic test, C = cyclic test, Avg. = average, Reinf. = fully threaded screws or nuts added

Increased dowel spacing appears to change the sequence of brittle failure modes at large displacements. In standard spacing specimens, the sequence was generally: (1) ductile yielding, (2) development of row shear planes along a_1 and a_3, and (3) panel splitting due to tension perpendicular to grain forces. In the CLT3-Mod. and CLT5-Mod. specimens, row shear failure along a_1 and a_3 was eliminated, allowing for larger connection displacement capacity until panel splitting eventually occurred. Furthermore, adding inclined fully threaded screws and nuts with washers further increased the displacement capacity. For the CLT7 specimens, row shear failure did not occur in both CLT7-Std. and CLT7-Mod. specimens. It is hypothesised that this occurred for two reasons: first the cross layers provided substantial reinforcement to the parallel layers, and second a less equal load distribution occurred between the outer and inner CLT layers as the mild steel ductile dowel developed a second plastic hinge on each side of the steel plate. This will be investigated further. Based on these results it is inferred that increased spacing is more important and beneficial in smaller CLT3 versus larger CLT7 panels.

6 CONCLUSIONS

A total of 48 experimental tests were performed on dowelled CLT connections with three different CLT sizes, two different dowel spacing layouts, and qualitatively with the addition of reinforcing elements. The key findings of this research are:

- Ductility and connection displacement capacity generally increases with increased dowel spacing
- Thicker CLT panels can delay final brittle failure due to more cross layer reinforcement
- Further investigation is required to critically evaluate the yield point
- Connection stiffness is lower than the Eurocode5 prediction equation

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