BEHAVIOUR OF NAILED TIMBER-PLYWOOD CONNECTIONS UNDER MONOTONIC AND CYCLIC LOADING

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KEYWORDS

Nailed connections, timber, plywood, strength, ductility, monotonic loads, cyclic loads

ABSTRACT

Nailed timber-plywood connections are critical components in plywood shear walls to provide shear wall strength, stiffness, ductility and energy dissipation. In this study, a total of eight connection types consisting of nails with three sizes (ø2.8×60, ø3.15×75, and ø3.55×90) and plywood sheets with three thicknesses (12mm, 17mm, and 25mm) were experimentally tested under monotonic and cyclic loading. The connection properties in terms of strength, stiffness and ductility were derived based on the load-slip curves of the connections to study the influence of nail size, plywood thickness, load-grain angle and loading type on the connection performance. Experimental results showed all the connection types had very ductile behaviour under monotonic and cyclic loading. The overstrength factor of 1.6 provided in NZS 3603 was also applicable for these nailed connections with relatively thick plywood panels. It was also found that the connection strength was mainly affected by the nail size and the increase of plywood thickness from 12mm to 17mm or 25mm did not change the connection strength significantly.

1 INTRODUCTION

In New Zealand, bracing walls sheathed with gypsum plasterboards are extensively used in low-rise light timber framed (LTF) buildings to resist wind and seismic loads (NZS 3604, 2011). For multi-storey LTF buildings, plywood shear walls with higher bracing capacity are often used. In plywood shear walls, nailed timber-plywood connections are critical components to provide system ductility and energy dissipation under seismic loading (Folz and Filiatrault, 2001; Li, et al. 2012). Figure 1 shows a typical loading mechanism of a nailed timber-plywood connection carrying shear loads between plywood sheathing and timber studs in a shear wall under racking loads.

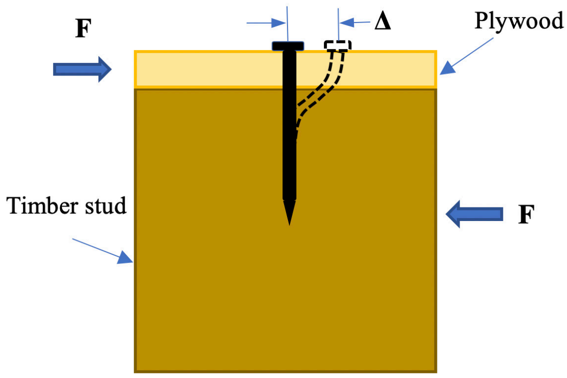

Figure 1: *Typical nailed timber-sheathing connection under shear loads*

A number of studies have been conducted to understand the behaviour of nailed timber-plywood connections. Stewart (1987) conducted a comprehensive study on nailed connections including timber-plywood nailed connections. It was found that the connection behaviour was governed by various parameters including nail sizes, coating materials, penetration depth, timber density, load-grain direction, etc. It was also found that the connections with thick plywood (12mm) had significantly higher ductility and less strength degradation than the connections with thin plywood (7.5mm). Dolan (1989) conducted monotonic and cyclic tests on nailed connections with 9 mm thick plywood. It was found that the load-grain direction seemed to have little influence on the connection behaviour. Dean (1996) conducted monotonic and cyclic tests on nailed timber-plywood connections manufactured from New Zealand Radiata pine. Plywood thicknesses of 7.5mm, 9mm and 12mm and nail diameters from 2.24mm to 4mm were selected for the testing. Considerable difference was found in the connections with three different plywood thicknesses in terms of peak loads and post-peak responses, mainly attributed to the ability of plywood to withdraw the nails from the timber. To achieve ductile connection behaviour, it is desirable for the nails to incrementally withdraw from the timber member under cyclic loading and the nail head pull through failure is avoided. This however requires sufficient plywood thickness as well as appropriate nail penetration depth.

This study is to experimentally evaluate monotonic and cyclic performance of nailed timber-plywood connections with relatively thick plywood sheathing in thickness of 12mm, 17mm, and 25mm. The connection properties in terms of strength, stiffness and ductility will be derived to study the influence of nail size, plywood thickness, load-grain angle and loading type on the connection performance. The experimental results will also be compared with NZS3603 (1993) specified strength values, as shown in Table 1. A plywood factor of 1.4 has been applied considering the plywood sheathing with flat head nail fasteners used in the table. It should be noted that the characteristic strength Qk in NZS3603 is independent of plywood thickness and the requirements for minimum nail spacing and nail penetration depth should be satisfied. In NZS3603, an overstrength factor of 1.6 is provided to define the upper bound of the characteristic strength for capacity design.

2 MATERIALS AND EXPERIMENTAL SETUP

Monotonic and cyclic tests were carried out to evaluate the connection behaviour considering three nail sizes (ø2.8×60; ø3.15×75; and ø3.55×90) and three plywood thicknesses (12mm, 17mm and 25mm). The combination of ø2.8×60 and 25 mm plywood was not selected due to the large thickness and relatively small nail penetration depth. Thus, a total of eight connection types with different combinations of nail size and plywood thickness were tested. Meanwhile, two load-grain directions, parallel to grain and perpendicular to grain, were considered. In parallel to grain loading, the shear load was applied parallel to both timber grain direction and plywood face grain direction. In the perpendicular to grain loading, the shear load was applied perpendicular to both timber grain direction and plywood face grain direction. The actual loading-grain angles of nailed connections in a plywood shear wall under lateral loading depend on the wall configurations and the locations of individual nails. The loading angles can vary between the parallel to grain direction and the perpendicular to grain direction.

For each combination of nail size, plywood thickness and load-grain direction, five replicates were tested under monotonic loading and six replicates were tested under cyclic loadings. The monotonic tests were conducted first and the results were used to determine the cyclic loading protocol following the ISO16670 (2003) test standard. In total, 176 connections were tested and Table 2 shows the test matrix.

Table 1: Nailed timber-plywood strengths with J5 timber (Radiata pine)(kN)

	Nail Diameter (mm)									
	ø2.0	ø2.24	ø2.5	ø2.8	ø2.87	ø3.15	ø3.33	ø3.55	ø3.75	ø4
Characteristic strength Q_k (NZS3603)	0.37	0.46	0.57	0.71	0.74	0.88	0.97	1.11	1.22	1.39
Overstrength ($1.6{\times}Q_k$)	0.60	0.74	0.91	1.13	1.18	1.41	1.56	1.77	1.94	2.22

Table 2: Test matrix of nailed timber-plywood connections

Nail size	**Loading parallel to grain**						**Loading perpendicular to grain**					
	Monotonic loading			Cyclic loading			Monotonic loading			Cyclic loading		
	12mm ply	17mm ply	25mm ply	12mm ply	17mm ply	25mm ply	12mm ply	17mm ply	25mm ply	12mm ply	17mm ply	25mm ply
ø2.8×60	5	5	-	6	6	-	5	5	-	6	6	-
ø3.15×75	5	5	5	6	6	6	5	5	5	6	6	6
ø3.55×90	5	5	5	6	6	6	5	5	5	6	6	6

Grade SG8 Radiata pine timber and Grade F8 plywood were used in this study. Both materials are commonly used in plywood shear wall construction in New Zealand. Using an electronic moisture meter, moisture content of the plywood was measured from 9.1% to 13.7%. Moisture content of the timber studs was measured from 10.0% to 14.0%.

Figure 2 shows the test setup with front and rear views. The timber member was fully restrained onto the test table with threaded rods and steel plates. The plywood was clamped tightly by two steel plates via a M12 bolt. With sufficient contact areas between the steel plates and the plywood, enough friction was achieved to avoid slippage under the loading. The load was then applied vertically by the loading head connected to the steel plate clamping the plywood.

Each connection consisted of two identical hand driven nails. Therefore, each nail carried half of the total load. Table 3 lists the nail spacing, end and edge distances following the minimum spacing requirements in NZS3603. For Radiata pine timber, the minimum nail spacing is10d along the grain and 5d across the grain, the minimum edge distance is 5d and the minimum end distance is 12d, in which d is the nail diameter. Following the minimum spacing requirements, brittle failure modes such as edge tear-out and wood spitting normally can be eliminated. Figure 3 shows the schematics of the test setup.

The monotonic loading was displacement controlled with a rate of 2mm/min until the peak load and then the loading rate was increased to 5mm/min until the ultimate displacement Δ_{ult} was reached. Δ_{ult} is defined as either the failure displacement (i.e. brittle failure), or the displacement corresponding to $0.8F_{max}$ on the post-peak load-slip curve. The data sampling rate was 2 Hz.

Following the ISO 16670 standard (2003), the cyclic loading protocol was determined by Δ_{ult} obtained from the monotonic load-slip curves. As shown in Figure 4, the protocol consists of a number of cycle groups with gradually increasing displacement amplitudes in percentages of Δ_{ult} (1.25%, 2.5%, 5%, 7.5%, 10%, 20%, 40%, 60%, 80%, 100%, 120%,…). And the cycle groups with amplitudes exceeding $10\%\Delta_{ult}$ contain three identical cycles. The cyclic loading rate started at 5 mm/min and was gradually increased up to 50 mm/min to control the total testing time within 10 min. The data sampling rate was 2 Hz. The tests were terminated until the load dropped to half of the peak load or brittle failure occurred.

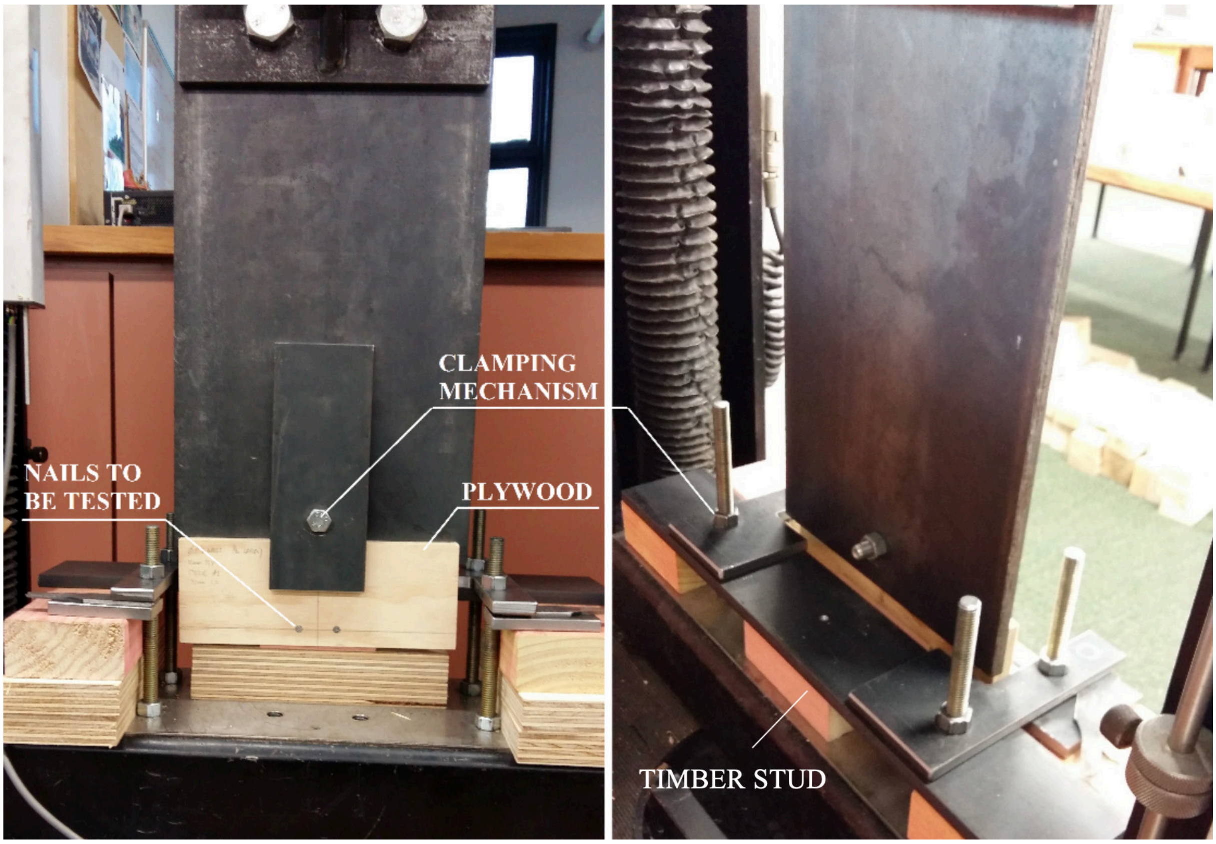

Figure 2: *Connection test setup - front view and rear view*

Table 3: *Nail spacing in connections*

Nail Size	S_1	S_2	S_3
ø2.8x60mm	28mm (10d)	34mm (12d)	14mm (5d)
ø3.15x75mm	32mm (10d)	38mm (12d)	16mm (5d)
ø3.55x90mm	36mm (10d)	43mm (12d)	18mm (5d)

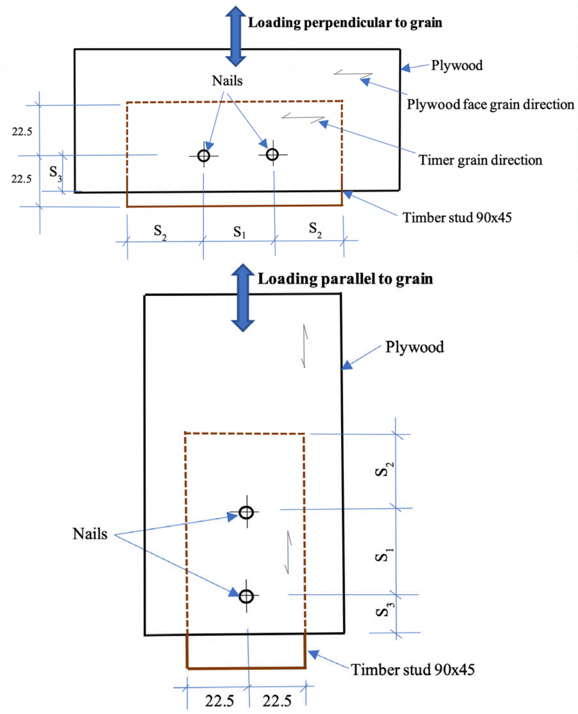

Figure 3: *Definition of nail spacing, end and edge distances (units in mm)*

According to the European standard EN 12512 (2001), critical connection properties were derived from the monotonic load-slip curves and the backbone curves of hysteretic load-slip loops. These properties include initial stiffness k_i, yield force F_y, yield displacement Δ_y, peak load F_{max} and peak displacement Δ_{max}, ultimate load F_{ult}, and ultimate displacement Δ_{ult}, ductility ratio μ and strength degradation factor $F_{(1-3)}$.

The initial stiffness k_i is defined as

$$k_i = \frac{0.3F_{max}}{\Delta_{0.4Fmax} - \Delta_{0.1Fmax}} \quad (1)$$

where $\Delta_{0.4Fmax}$ is the displacement at the load of $0.4F_{max}$, and $\Delta_{0.1Fmax}$ is the displacement at the load of $0.1F_{max}$.

Ductility μ is defined as the ratio between Δ_{ult} and Δ_y

$$\mu = \frac{\Delta_{ult}}{\Delta_y} \quad (2)$$

The strength degradation factor (F_{1-3}) is to consider the peak load reduction on the backbone curves of all the second and the third cycles in the cycle groups compared with the peak load on the backbone of the first cycles in the cycle groups.

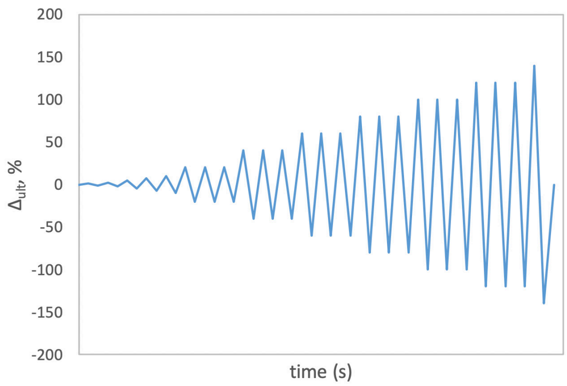

Figure 4: *ISO 16670 cyclic loading protocol*

3 EXPERIMENTAL RESULTS

Figure 5 shows the typical failure modes of the connections under monotonic loading. As the load increased, the nail began to crush against the surrounding timber medium and plywood. Then, the nail bending deformation increased significantly and further embedded into the wood medium. The overall connection behaviour was very ductile, partially due to the fact that the fastener gradually withdrew from the timber. As the nail withdrawal occurred, the location of the maximum bending moment along the nail shank also changed, resulting in very ductile behaviour. No splitting of the plywood or timber studs were observed which indicated sufficient nail spacing, end and edge distances. Nail head pull-through was also observed in a small number of connections, particularly with ø2.8x60 nails which have relatively small heads.

Under cyclic loading, the connections showed similar ductile behaviour to those tested under monotonic loading. Typical failure modes also included nail bending yielding, nail withdrawal as well as wood embedment crushing. Additional low cycle fatigue failure was observed in some connections where nail heads were sheared off under reversed cyclic loading, as shown in Figure 6. It should be noted that the ISO16670 (2003) loading protocol is a demanding protocol consisting of a large number of loading cycles. This caused the fastener fatigue failure.

Figures 7~9 show the average monotonic load-slip curves of three nail sizes with various plywood thicknesses

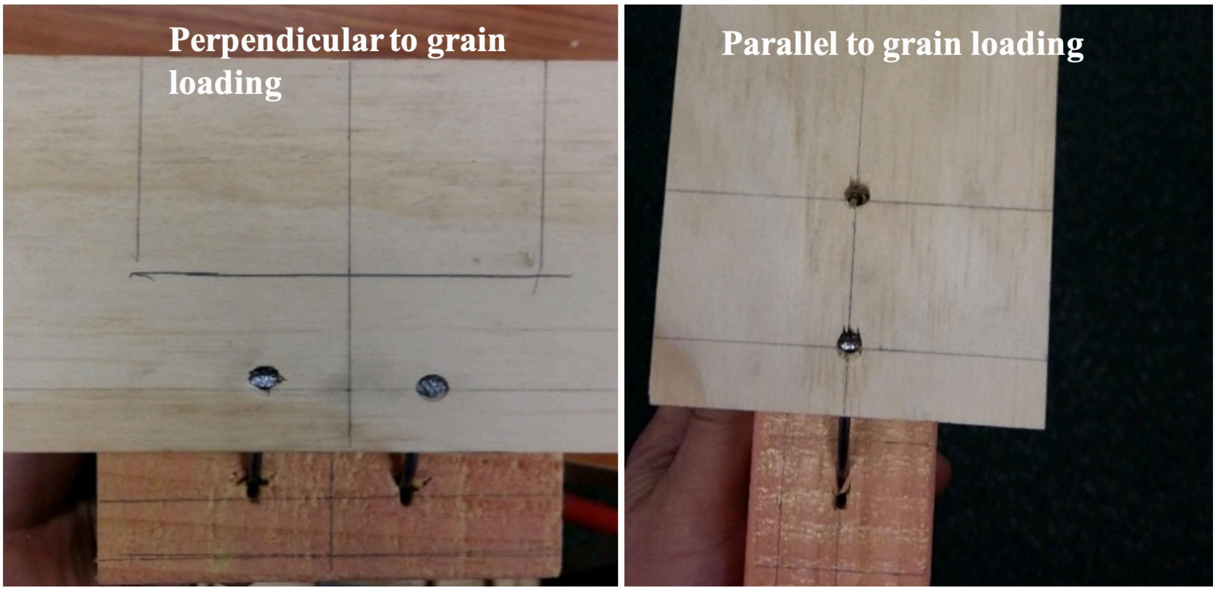

Figure 5: *Failure modes under monotonic loading (ø2.8x60mm nails with 12 mm ply)*

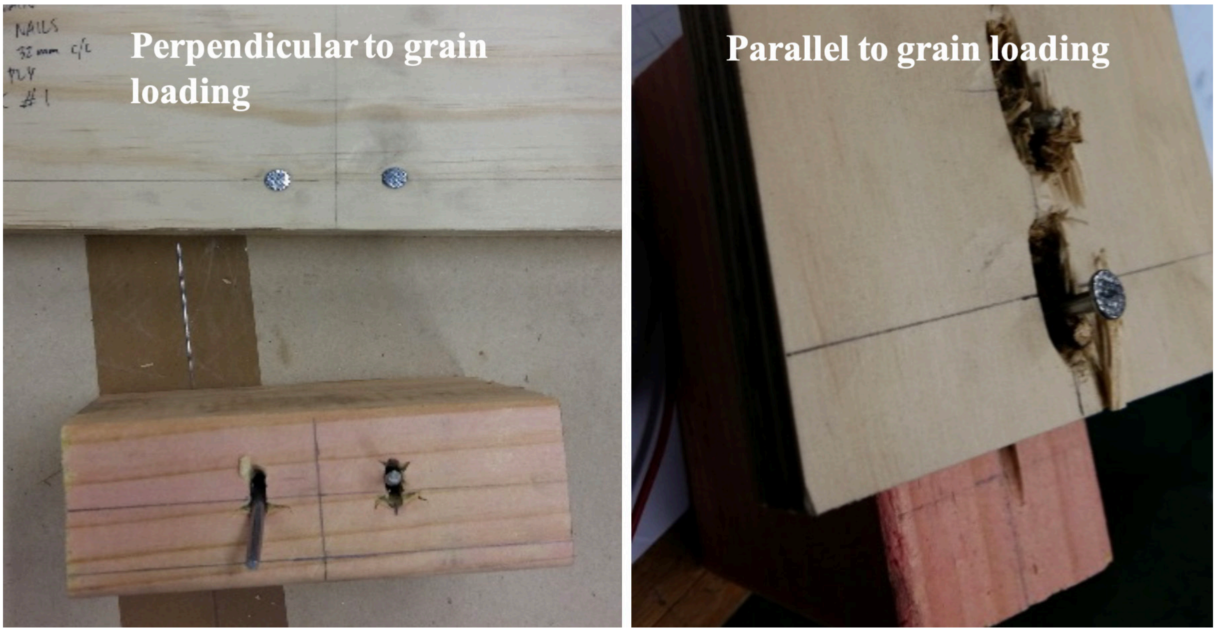

Figure 6: *Nail fatigue failure under cyclic loading (ø2.8x60mm nails with 12 mm ply)*

loaded in parallel to grain and perpendicular to grain directions. Each curve represents the average of five connection replicates. Figure 10 shows the load-slip hysteretic loops of three nail sizes with various plywood thicknesses that were loaded parallel to grain. For each connection type, the results of six replicates from specimen I to specimen VI were plotted. Figures 11~13 show the average positive and negative backbone curves of all the connection types loaded along parallel to grain and perpendicular to grain directions. Each curve represents the average of the six connection replicates. The NZS3603 specified connection characteristic strength Q_k and the overstrength 1.6*Q_k were also plotted.

Table 4 through Table 6 provide the summary of average connection properties for ø2.8×60 nails, ø3.15×75 nails and ø3.55×90 nails, respectively. The results are categorised in two loading-grain directions, monotonic or cyclic loading schemes and different plywood thicknesses. Table 7 gives the summary of average connection properties of eight connection types in combinations of nail size and plywood thickness. Based on the test results, main findings are presented as follows:

All the connection types showed highly ductile behaviour. The ductility ratios ranged from 8.9 to 30.8 with an average of 17.2, indicating the nailed timber-plywood connections are a reliable source of ductility

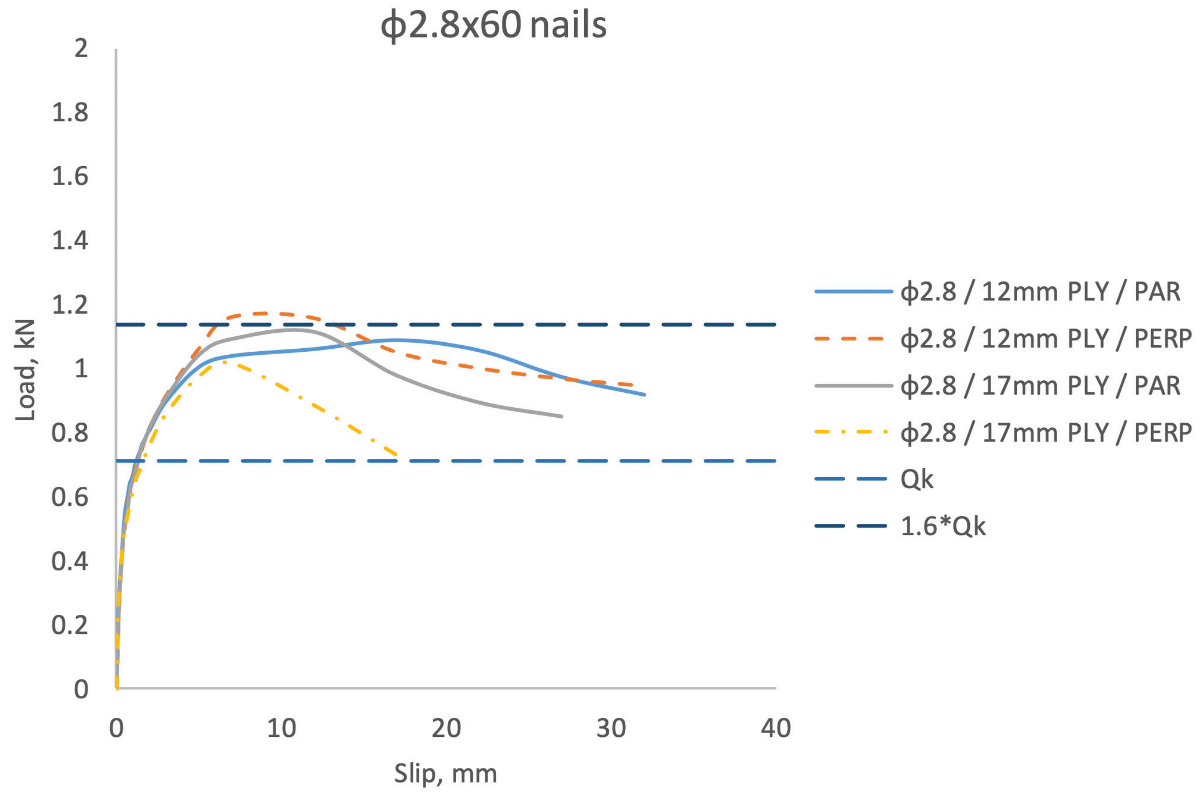

Figure 7: *Average monotonic curves of ø2.8x60 nails along two directions (with characteristic strength and overstrength)*

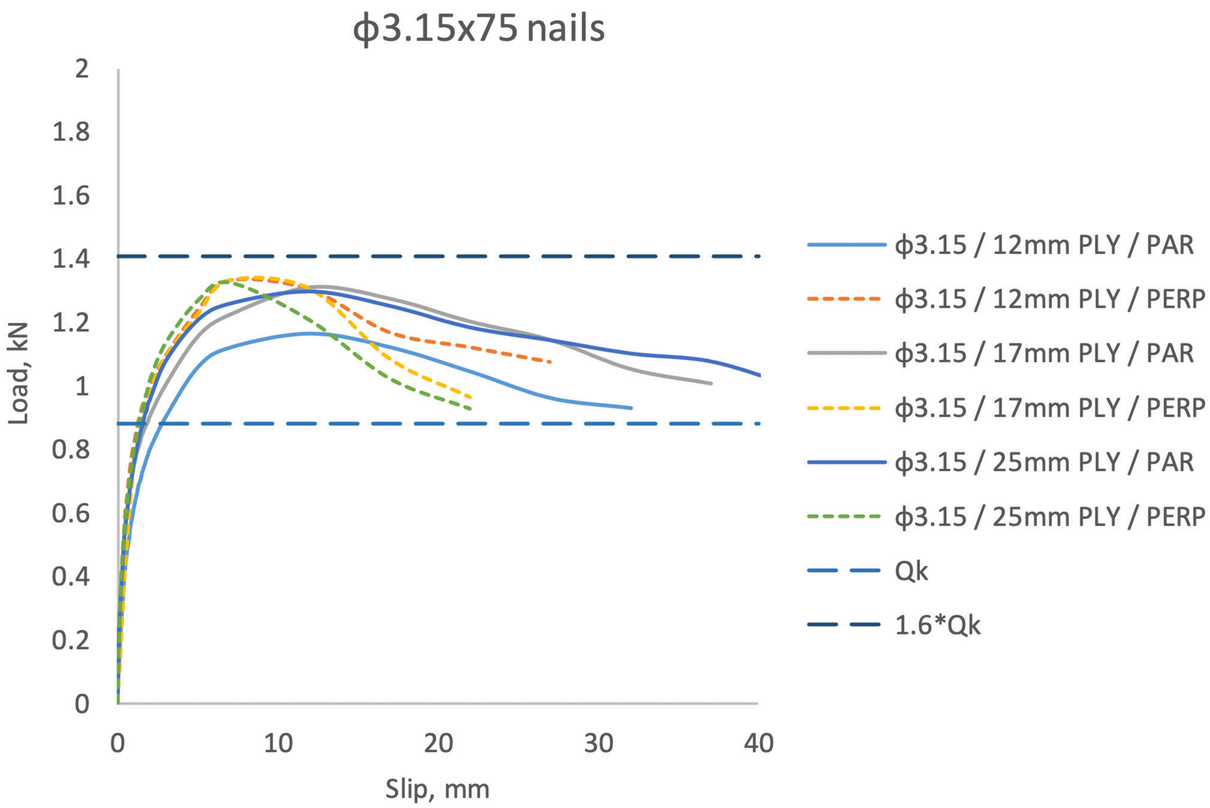

Figure 8: *Average monotonic curves of ø3.15x75 nails along two directions (with characteristic strength and overstrength)*

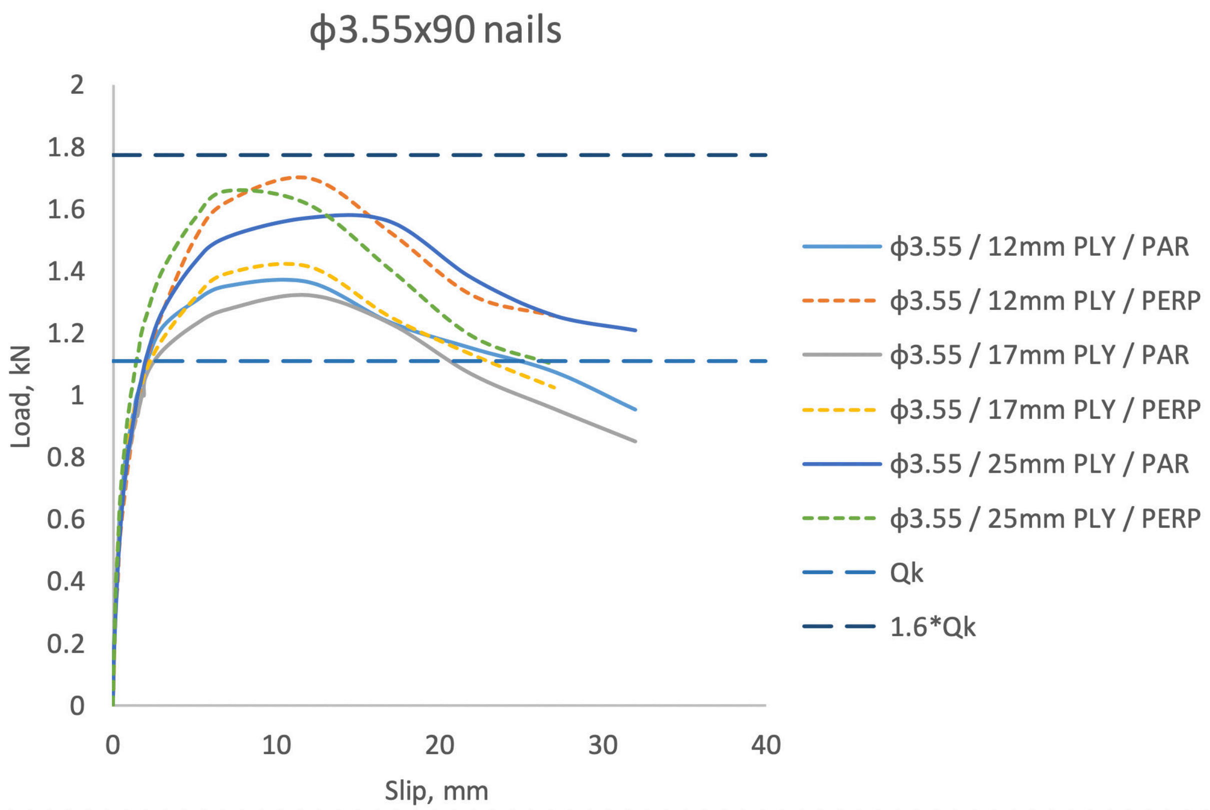

Figure 9: *Average monotonic curves of ø3.55x90 nails along two orthogonal directions (with characteristic strength and overstrength)*

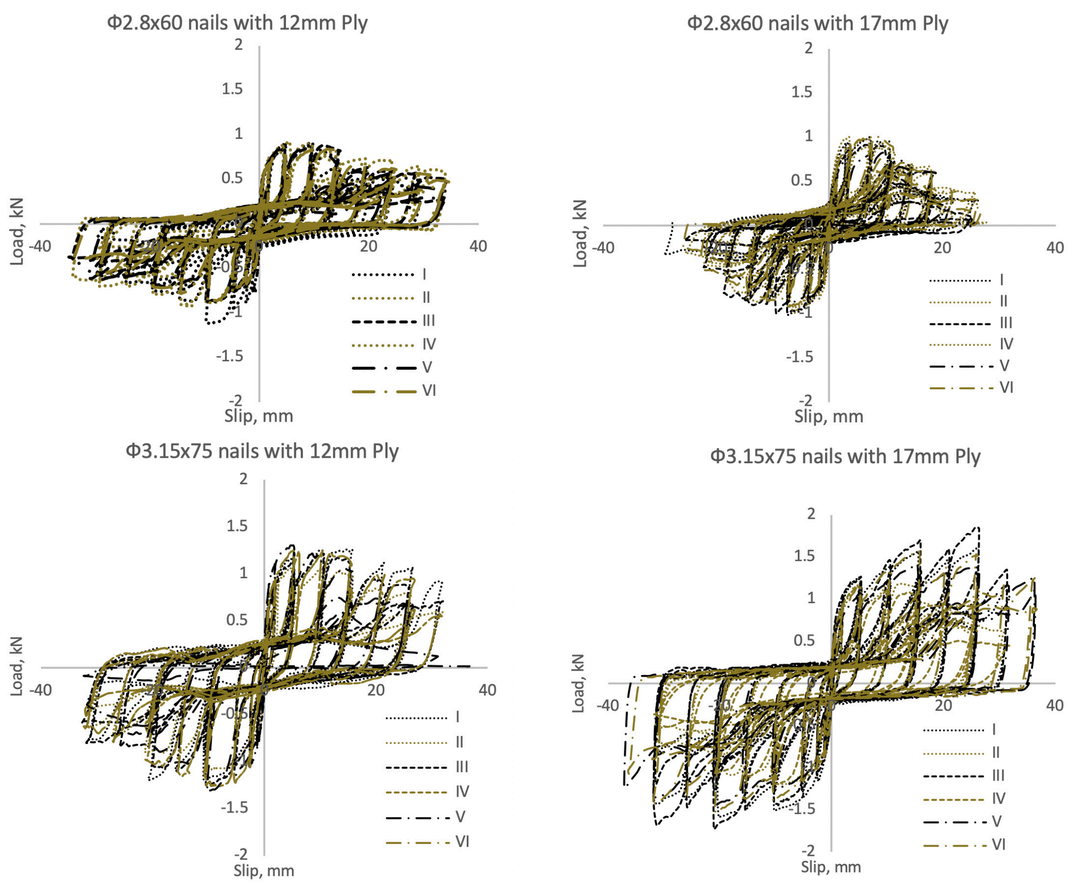

Figure 10: *Load-slip hysteresis of three nail sizes with various plywood thicknesses (loaded along parallel to grain direction)*

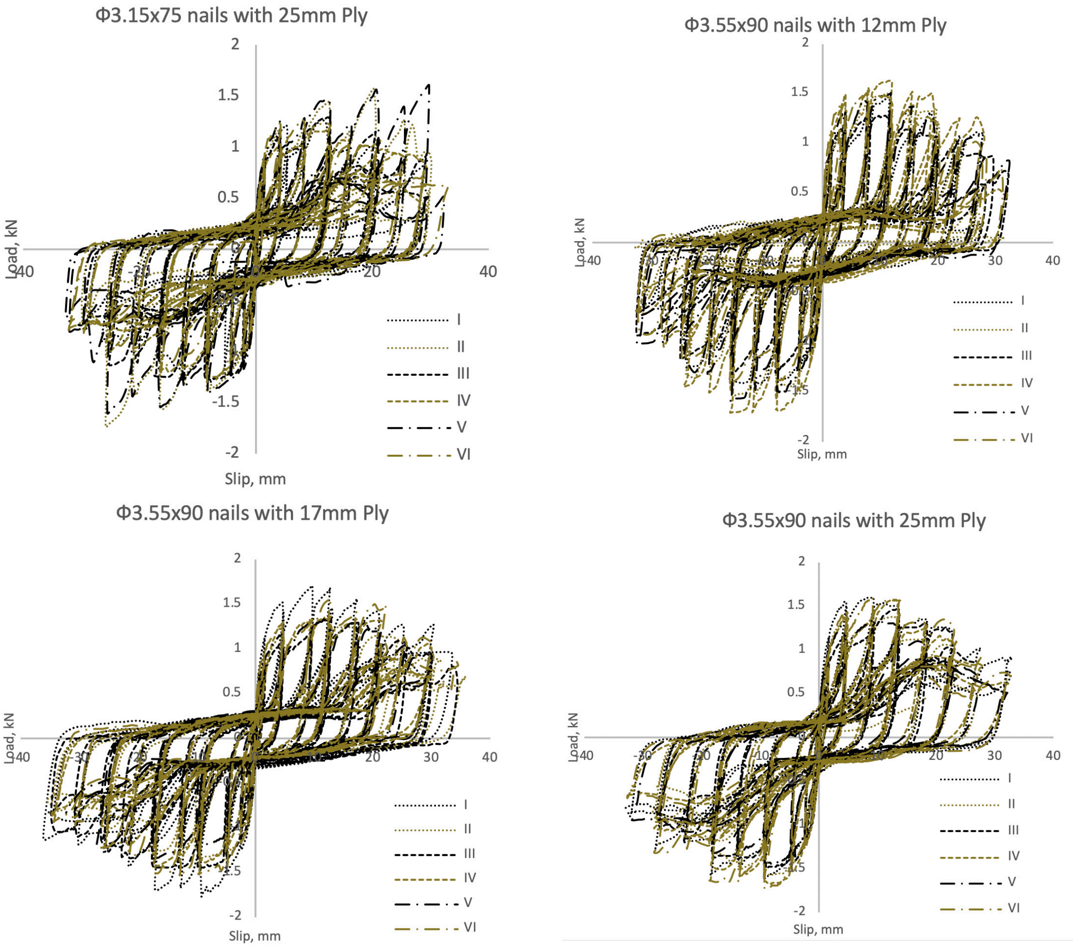

Figure 10 cont'd: *Load-slip hysteresis of three nail sizes with various plywood thicknesses (loaded along parallel to grain direction)*

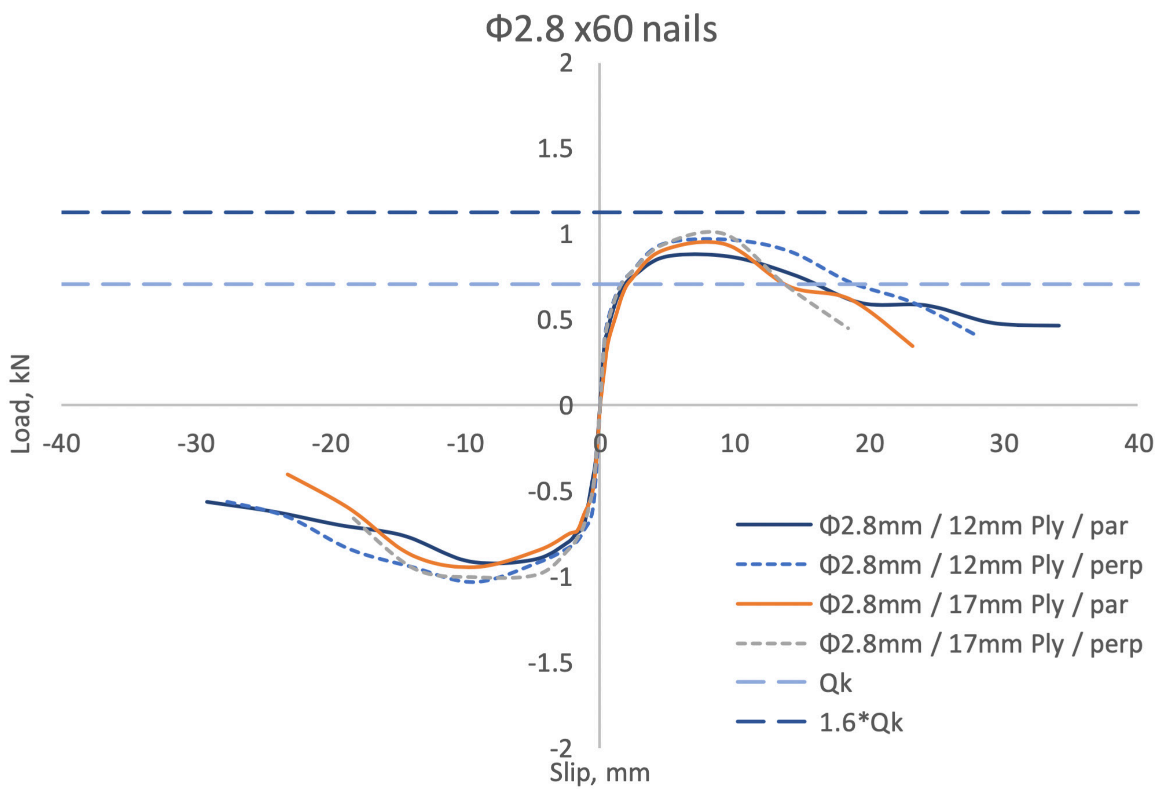

Figure 11: *Average backbones of ø2.8x60 nails (with characteristic strength and overstrength)*

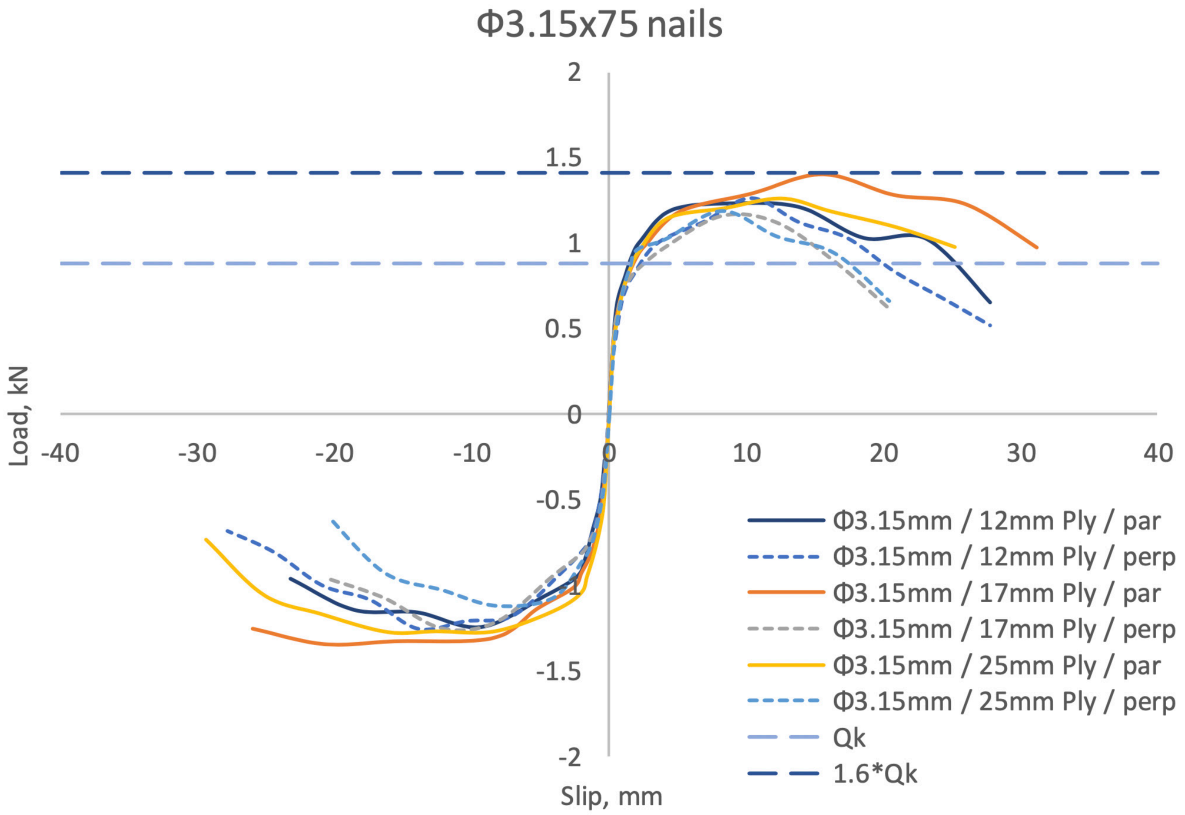

Figure 12: *Average backbones of ø3.15x75 nails (with characteristic strength and overstrength)*

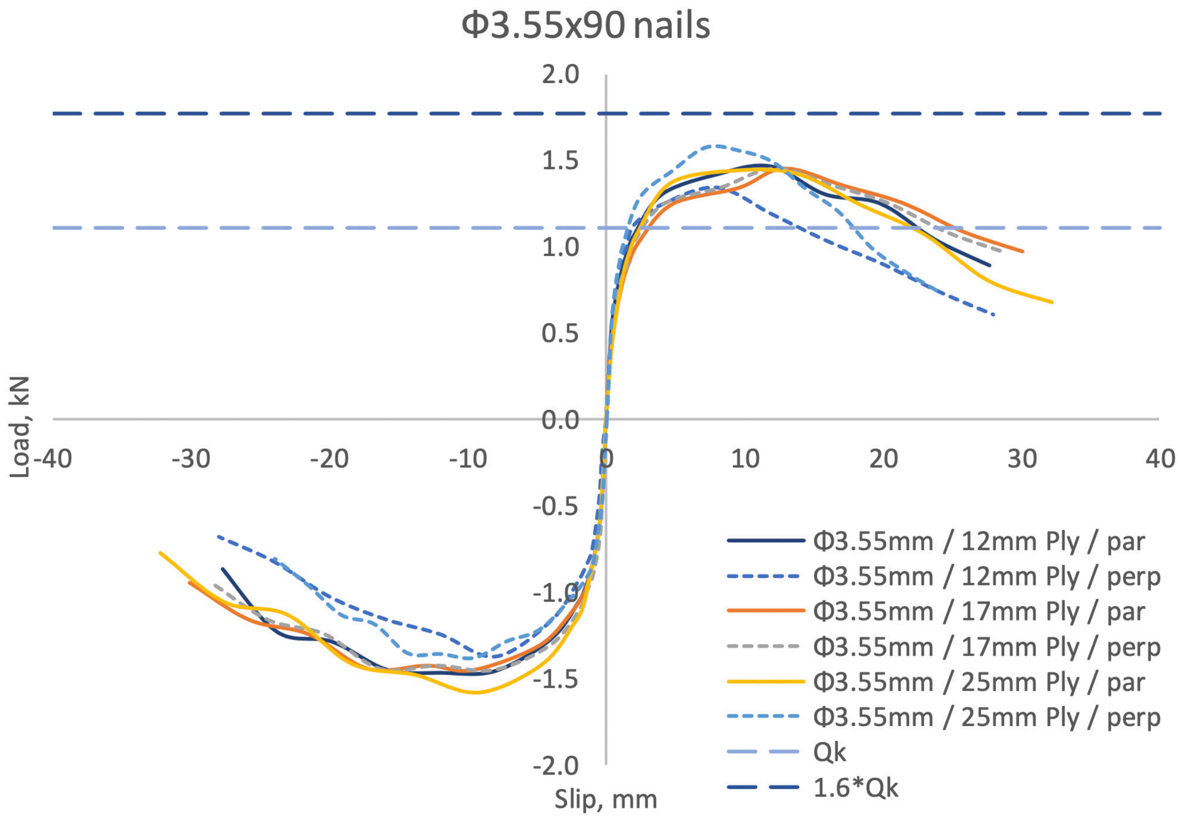

Figure 13: *Average backbones of ø3.55x90 nails (with characteristic strength and overstrength)*

in plywood shear walls. It should be noted that the high ductility ratios were partially caused by the high initial stiffness and low yield displacement derived according to EN 12512 (2001).

The average capacity of all the connections loaded perpendicular to grain (including monotonic and cyclic loading) was only 2.8% higher than that of all the connections loaded parallel to grain. This indicates that load-grain direction did not significantly affect the connection capacity, which agrees with previous research findings. However, the connections loaded perpendicular to grain had significantly lower ultimate displacements due to the tendency of wood splitting, thus leading to much lower average ductility (μ=14.4) compared with the average ductility of the connections loaded parallel to grain (μ=20.1).

Under cyclic loading, the average capacity of the connections loaded parallel to grain is almost the same as that under monotonic loading. However, for the connections loaded perpendicular to grain, the average capacity under cyclic loading was about 9% lower than that under monotonic loading. Cyclic loading also significantly reduced the connection ductility compared with monotonic loading. The average cyclic ductility of all connections was about 30% lower than the average monotonic ductility. Cyclic loading also caused significant strength degradation under repeated loading cycles. The peak load of the 2nd cycles of the cycle groups was 8-21% lower than the peak load of the 1st cycles. And the peak load of the 3rd cycles was 16-41% lower than the peak load of the 1st cycles.

As expected, nail size had a significant impact on the connection behaviour. Larger nails had increased connection capacity and stiffness regardless of the plywood thickness. The influence of plywood thickness on connection capacity was found not significant. However, thicker plywood caused a slight increase of the initial stiffness of the connections. On average, the connections with 17mm plywood had a 10% higher initial stiffness than the connections with 12 mm plywood.

4 CONCLUSIONS

Timber-plywood connections with three nail sizes and three plywood thicknesses were experimentally tested to evaluate the connection strength, stiffness, and ductility, etc. The influence of load-grain directions and loading scheme (monotonic vs. cyclic) on the connection behaviour was also evaluated. The experimental results showed very ductile connection behaviour. As expected, nail size was found to significantly affect the connection behaviour. For the connections with relatively thick plywood (12mm, 17mm and 25mm), the influence of plywood thickness on connection capacity seemed to be not so significant, although previous research on the connections

Table 4: Summary of average connection properties of ø2.8×60 nails

ø2.8x60 nails	12mm Ply				17mm Ply			
	Para		Perp		Para		Perp	
	Mono	Cyclic	Mono	Cyclic	Mono	Cyclic	Mono	Cyclic
k_i (kN/mm)	1.09	0.9	0.9	1.2	1.07	1.25	1.06	0.91
F_y (kN)	0.66	0.65	0.6	0.68	0.58	0.66	0.57	0.58
F_{max} (kN)	1.15	0.91	1.22	1.09	1.14	0.96	1.04	1.1
F_{ult} (kN)	0.88	0.73	1	0.87	0.91	0.76	0.83	0.88
Δ_y (mm)	0.9	1.3	0.8	1.2	0.8	1.3	0.9	1
Δ_{max} (mm)	14.2	10.4	11.7	8.5	10.8	8.3	6.7	8.2
Δ_{ult} (mm)	27.7	19.4	20.5	16.9	20.3	13.3	13.4	14.8
μ	30.8	14.9	25.6	14.1	25.4	10.2	14.9	14.8
$F_{(1-3)}$	-	21-46%	-	20-36%	-	12-33%	-	6-14%

Note: k_i = initial stiffness;
F_y = yield strength;
F_{max} = maximum strength;
F_{ult} = ultimate load;
Δ_y = yield displacement;
Δ_{max} = displacement at maximum strength
Δ_{ult} = displacement at ultimate load
μ = ductility ratio
$F_{(1-3)}$ = strength degradation factor

Table 5: Summary of average connection properties of ø3.15×75 nails

ø3.15 x75 nails	12mm Ply				17mm Ply				25mm Ply			
	Para		Perp		Para		Perp		Para		Perp	
	Mono	Cyc	Mono	Cyc	Mono	Cyc	Mono	Cyc	Mono	Cyc	Mono	Cyc
k_i (kN/mm)	0.92	1.04	1.18	0.89	1.02	1.07	1.06	1.42	0.92	1.42	0.96	1.63
F_y (kN)	0.65	0.86	0.85	0.73	0.77	0.81	0.87	0.73	0.91	0.91	0.87	0.85
F_{max} (kN)	1.19	1.34	1.41	1.28	1.32	1.46	1.45	1.28	1.34	1.39	1.37	1.22
F_{ult} (kN)	0.85	1.07	1.13	1.03	1.06	1.17	1.12	1.03	1.07	1.11	1.1	0.98
Δ_y (mm)	1.1	2.2	1.1	1.2	1.2	1.2	1.3	1.2	1.7	1.3	1.3	1.5
Δ_{max} (mm)	11.5	12.7	10.4	11.6	12.7	15.2	9.3	10.5	15.4	12.7	7.9	8.8
Δ_{ult} (mm)	32.4	22.1	18.4	18.4	31.1	28.4	18.2	16.3	32.5	23.2	14.8	15.4
μ	29.5	10.0	16.7	15.3	25.9	23.7	14.0	13.6	19.1	17.8	11.4	10.3
$F_{(1-3)}$	-	22-45%	-	18-30%	-	20-31%	-	15-31%	-	22-36%	-	15-30%

Table 6: Summary of average connection properties of ø3.55×90 nails

ø3.55 x90 nails	12mm Ply				17mm Ply				25mm Ply			
	Para		Perp		Para		Perp		Para		Perp	
	Mono	Cyc	Mono	Cyc	Mono	Cyc	Mono	Cyc	Mono	Cyc	Mono	Cyc
k_i (kN/mm)	1.12	0.74	1.3	1.61	1.44	1.22	1.58	1.17	1.24	1.21	1.4	1.66
F_y (kN)	0.84	0.95	0.98	0.97	0.88	0.93	0.9	0.95	0.91	1	1.01	1.05
F_{max} (kN)	1.46	1.49	1.73	1.41	1.33	1.46	1.46	1.36	1.61	1.54	1.72	1.54
F_{ult} (kN)	1.11	1.19	1.38	1.12	1.14	1.17	1.15	1.09	1.29	1.23	1.37	1.23
Δ_y (mm)	0.9	1.2	1.5	1.9	1	1.5	1.1	1.4	1.4	1.6	1.2	1.8
Δ_{max} (mm)	10.5	11.6	10	9.1	10.3	12.5	10.3	9.5	14.2	10	11.1	9.9
Δ_{ult} (mm)	22.5	22.6	21.1	16.9	23	24	21.3	17.2	25.7	20.3	18	18.2
μ	25.0	18.8	14.1	8.9	23.0	16.0	19.4	12.3	18.4	12.7	15.0	10.1
$F_{(1-3)}$	-	14-33 %	-	14-28%	-	13-24%	-	12-24%	-	8-15%	-	8-16%

Table 7: Summary of average connection properties for eight connection types

	ø2.8x60 nails		ø3.15x75 nails			ø3.55x90 nails		
	12mm ply	17mm ply	12mm ply	17mm ply	25mm ply	12mm ply	17mm ply	25mm ply
k_i (kN/mm)	1.02	1.07	1.01	1.14	1.23	1.19	1.35	1.38
F_y (kN)	0.65	0.60	0.77	0.80	0.89	0.94	0.92	0.99
F_{max} (kN)	1.09	1.06	1.31	1.38	1.33	1.52	1.40	1.60
F_{max} (kN) [a] avg	1.08		1.34			1.51		
1.6*Q_k (kN)	1.13		1.41			1.77		
F_{ult} (kN)	0.87	0.85	1.02	0.91	1.07	1.20	1.14	1.28
Δ_y (mm)	1.1	1.0	1.4	1.2	1.5	1.4	1.3	1.5
Δ_{max} (mm)	11.2	8.5	11.6	10.4	11.2	10.3	10.7	11.3
Δ_{ult} (mm)	21.1	15.5	22.8	19.8	21.5	20.8	21.4	20.6
μ	20.1	15.5	16.3	17.2	14.8	15.1	17.1	13.7
$F_{(1-3)}$	21-41%	9-24%	20-38%	18-31%	19-33%	14-31%	13-24%	8-16%

with relatively thin plywood (7.5mm, 9mm, 12mm) showed significant influence of plywood thickness on connection capacity. The connections of ø2.8x60 nails with 12mm plywood, ø3.15x75mm nails with 17mm plywood and ø3.55x90mm nails with 25mm plywood had higher capacities than the connections with the same nail size but with other plywood thicknesses. The connection ductility under cyclic loading was significantly lower than that under monotonic loading. Therefore, it is recommended to use cyclic testing to derive connection properties for seismic design. The overstrength factor of 1.6 provided in NZS 3603 was also applicable for these nailed connections with relatively thick plywood panels as the majority of the connections had lower ultimate strength than the code specified characteristic strength Q_k multiplied by the overstrength factor.

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