Realistic Modelling of Cold-Formed Steel in Domestic Constructions for Performance Based Design

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Abstract

The actual behaviour of cold-formed steel bracing walls in as-built conditions cannot be fully modelled by general purpose computer package for structural analysis. This is partly because of the complex interactions of the studs with the connected sheathing material. This paper discusses the shear load-deflection behaviour of connections between cold-formed steel members and fibre cement sheathing based on experimental monotonic and cyclic tests. Test results show sensitivity of the strength, and mode of failure, to the edge distance of the fasteners amongst other design parameters. Cyclic test results show a highly pinched hysteresis response associated with significant stiffness and strength degradations at higher displacement amplitude, which is typical in such bracing walls. The load-deflection curves for the connections enable full scale finite element models to be developed for predicting the performance of such bracing walls under seismic actions.

Keywords: Load-deflection behaviour, connections, cold-formed steel members, fibre cement sheathing, fasteners, pinched hysteresis

1. INTRODUCTION

Cold-formed structural steel is gaining momentum in domestic low-rise buildings in industrialized countries including Australia. Resistance against lateral loads (due to wind or earthquake) in this type of construction is provided by bracing wall panels. Lateral load is transferred from framing members to a bracing material by the connecting fasteners. Indeed, the load deflection behaviour of the bracing wall panel under in-plane lateral loading is highly governed by the connections between these elements. Peterman and Schafer (2013) conducted the series of experiments using oriented standard board and gypsum board with cold-formed steel studs screw connections. Test results showed a significant reduction in stiffness as the displacement is increased. This is because of the pinching phenomenon which usually develops in the system due to gaps and residual displacements.

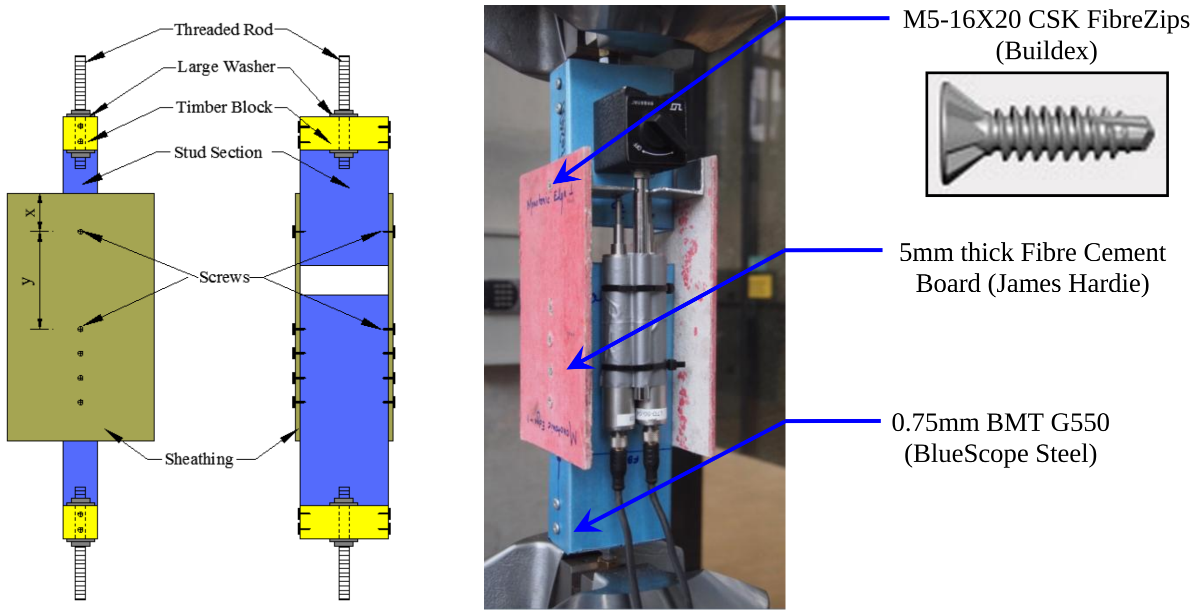
This study presents the experimental work on the behaviour of the connections between cold-formed steel members and fibre cement board sheathing. A number of small-scale tests of these connections were conducted under monotonic and cyclic loads. The study is a companion to full-scale wall tests; thus the stud type, the sheathing type, the fastener type, the fastener spacing as well as the distance of fastener from edge of the sheathing were kept similar to the full-scale test. The objective of the connection tests is to determine the hysteretic response of the stud-fastener-sheathing connections for computational modelling of steel framed shear wall panels.

2. TEST METHODOLOGY

2.1 Test Set Up

There is no standard method for testing stud-fastener-sheathing connections in shear. A number of attempts were made to achieve the most realistic configuration. A typical set up for the connection test is illustrated in Figure 1. In this test, a pair of sheathing board segments is connected to each side of the stud flange by a single screw on one stud and four screws on the other stud. The reason for using four screws in the second stud is to apply the load through the second segment of the specimen without risking connection failure. Since there are two connecting screws (two segments of board) at each side of the stud flange, the resulting load needs to be divided by a factor of two to determine the results for one screw. A pair of board segments is used to have a symmetrical specimen thus avoiding premature failure caused by eccentric loads. Since it is not practical to grip the board by the jaw of universal testing machine, loading was done via threaded rods provided at each end of the specimen. Threaded rods were inserted and bolted to timber blocks (hole was drilled through the centre of the timber block) from both ends which were connected to stud flanges by using two screws per flange (Figure 1). Large washer was used while bolting threaded screws to timber block in order to avoid failure of timber block prior to stud-connection-sheathing failure. Connections between timber block and stud flanges should be strong enough to withstand and transfer applied loads before failure of stud-fastener-sheathing connections.

Distance (x) in Figure 1(a) is dependent on whether the test specimen is ‘edge’ connection or ‘field’ connection. If distance x is set to 15mm, then it refers to the stud-fastener-sheathing connection along the edges of wall panel. Similarly if distance x is set to higher value (say 50mm), then it refers to the stud-fastener-sheathing connection at field (i.e. away from the edges). Spacing between screws is represented by distance (y). In order to demonstrate the edge connection failure, more specimens were tested by setting the edge distance at 12 (minimum limit), 15, 20 and 25mm.



(a) (b) (c)

Figure 1 (a) Side view of specimen (b) Back view of specimen (c) Photograph of loaded specimen showing position of instrumentation (2 LDTs)

2.2 Loading

Two types of loading conditions were applied for the connection tests; monotonic and cyclic loads. Monotonic loading was performed prior to the cyclic tests to determine the displacement control parameter (Δ_M) which is a key parameter required for cyclic loading protocol (Shahi *et al.* 2013, shown in Figure 2). The protocol is based on conditions of low-moderate ground shaking consistent with the level of seismic hazard stipulated by the current Australian Standard AS1170.4, 2007. Displacement control parameter (Δ_M) refers to the displacement corresponding to 90% of the peak strength at the declining portion of the monotonic load deflection curve. Loading was applied at the rate of 1 to 2mm/min for monotonic test and 10 to 20mm/min for cyclic test.

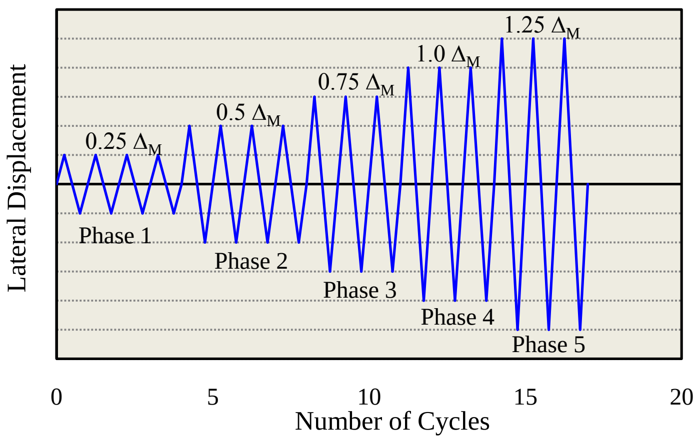


Figure 2 Cyclic loading protocol (Shahi *et al.* 2013)

2.3 Test Specimen and Instrumentation

There are large number of variables that may affect the performance of the stud-fastener-sheathing connection such as over-driven screws, screws not driven perpendicular to the board, screws not driven along the alignment of loading to be applied. A number of tests have been performed to ensure consistent and representative results. A basic matrix of test specimens is shown in Table 1. Two identical specimens were tested for edge and field screws under monotonic and cyclic loadings. Two lateral displacement transducers (one on each side of the board as shown in Figure 1(c)) were used to measure the relative movement of the fastener between the stud and the sheathing material.

Table 1 Basic test matrix for characterising fastener response in shear

Connection Type	Loading	Number of Specimens	Fastener Distance from Board Edge (x)	Specimen
Edge	Monotonic	2	12	Monotonic Edge-12mm-1 & 2
	Cyclic	2	12	Cyclic Edge-12mm-1 & 2
Edge	Monotonic	2	15	Monotonic Edge-15mm-1 & 2
	Cyclic	2	15	Cyclic Edge-15mm-1 & 2
Edge	Monotonic	2	20	Monotonic Edge-20mm-1 & 2
	Cyclic	2	20	Cyclic Edge-20mm-1 & 2
Edge	Monotonic	2	25	Monotonic Edge-25mm-1 & 2
Field	Monotonic	2	50	Monotonic Field-1 & 2
	Cyclic	2	50	Cyclic Field-1 & 2

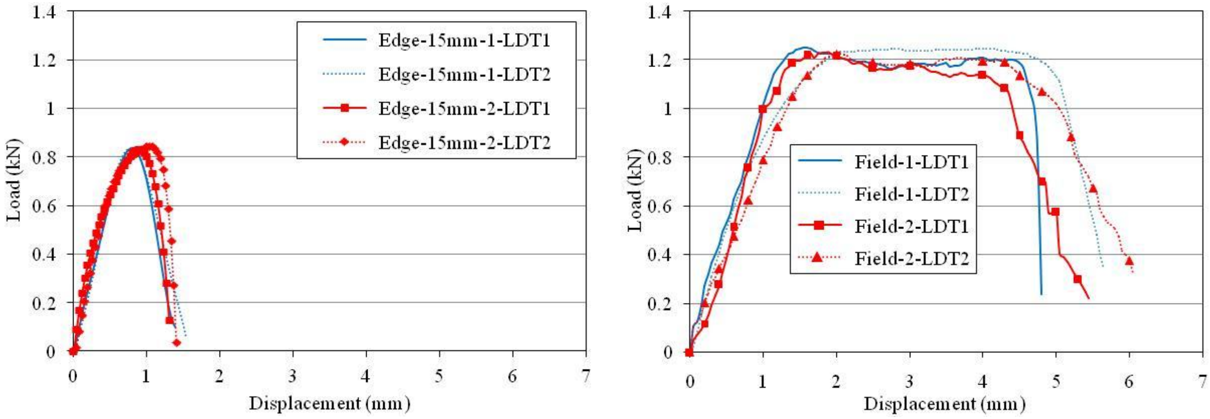
*Notes: Material Used in Stud-Fastener-Sheathing Connection Test

1. Stud: 0.75mm BMT G550 (BlueScope Steel)
2. Fastener: M5-16X20 CSK FibreZips (Buildex)
3. Sheathing: 5mm thick Fibre Cement Board (James Hardie, Australia)

3. RESULTS AND DISCUSSION

3.1 Monotonic test results

Load-deflection results of identical specimens for edge (Edge-15mm) and field connections under monotonic loading are provided in Figures 3(a) and 3(b) respectively. Scatter in the test results is due to inconsistent construction quality as described in section 2.3 which is non-trivial. The failure mode for edge connections was tearing out of the sheathing material from its edge (shown in Figure 4(a)) with limited or no ductility except for specimen Edge-25mm where bearing failure was observed. Similarly, field connection screw showed a failure mode with screw tilting and its head piercing down the sheathing material (Figure 4(b)) with high level of ductility (approximately equals to 3) which is herein termed as 'bearing failure'. Although significant scatter exists in the test results but some basic findings are immediately clear: such as initial stiffness of both edge and field connections are similar whereas capacity of edge connection (in terms of load and displacement) is lower than that of field connection. Mean values of load and deflection from identical specimens are plotted in Figure 5 which demonstrates a brittle failure mode (tearing of board) for specimens with edge distances of 12, 15 and 20mm and of ductile failure mode (board bearing and screw tilting) for specimens with edge distances of 25 and 50mm. Important parameters (mean values obtained from each load-deflection curves) such as tangent and secant stiffness (refer Figure 6), peak strength, deflection at peak strength, deflection at 90% of peak strength (Δ_M to be utilised in cyclic test) are provided in Table 2.



(a) Monotonic Edge-15mm connections (b) Monotonic Field connections

Figure 3 Load-deflection behaviour of stud-fastener-sheathing connections under monotonic loading (for one screw)

(a) Monotonic Edge-15mm-1 (b) Monotonic Field-1

Figure 4 Failure mode of stud-fastener-sheathing connections under monotonic loading

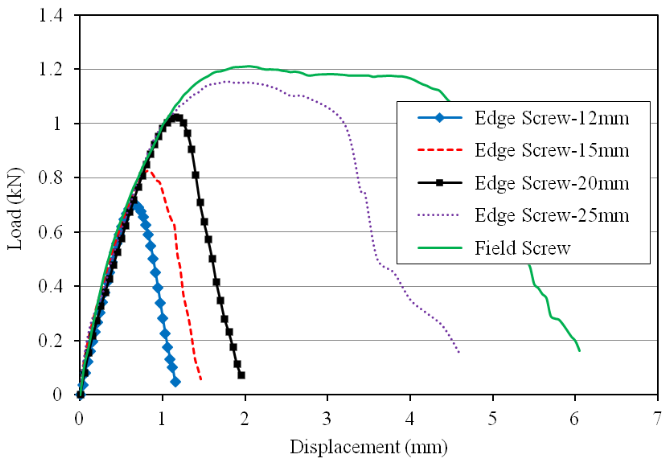


Figure 5 Load-deflection behaviour of stud-fastener-sheathing connections under monotonic loading (mean values obtained for one screw)

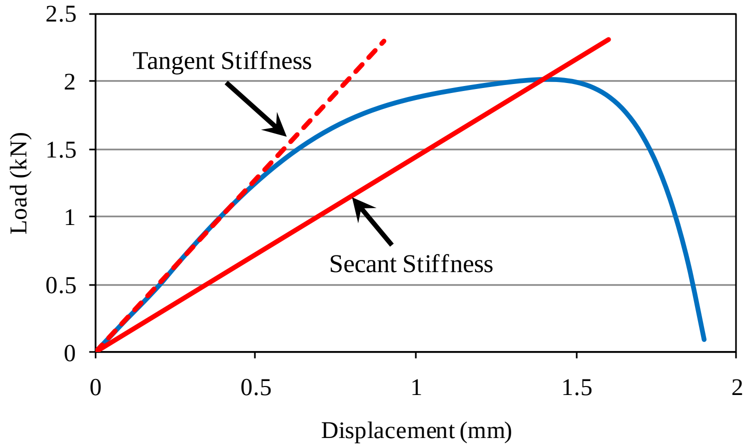


Figure 6 Definition of the tangent and the secant stiffness for monotonic test

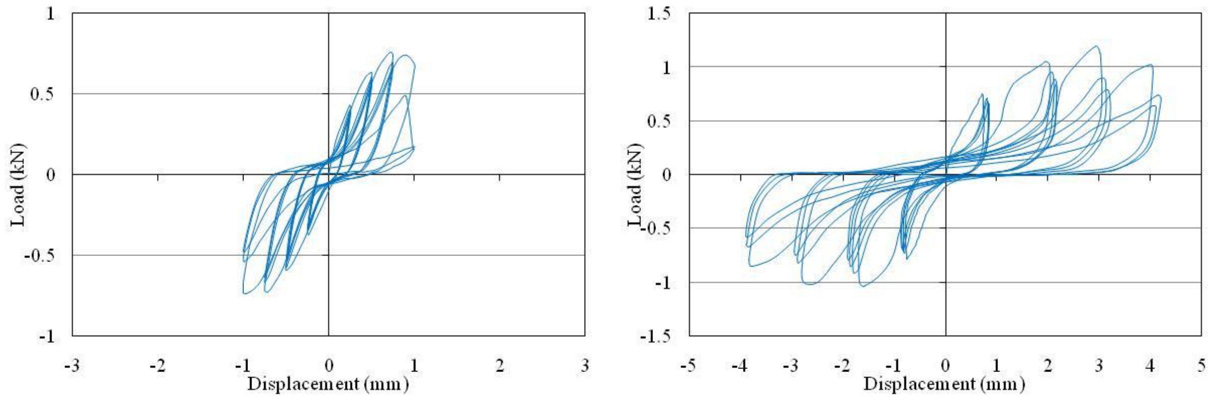
Table 2 Summary of monotonic test results (mean values obtained for one screw)

Specimen	Edge Distance (mm)	Displacement Control Parameter Δ_M (mm)	Peak Load (kN)	Displacement at Peak Load (mm)	Tangent Stiffness (kN/mm)	Secant Stiffness (kN/mm)	Failure Mode
Monotonic Edge-12mm	12	0.79	0.70	0.65	1.28	1.08	Board Tearing
Monotonic Edge-15mm	15	1.00	0.83	0.82	1.25	1.00	Board Tearing
Monotonic Edge-20mm	20	1.34	1.02	1.15	1.21	0.89	Board Tearing
Monotonic Edge-25mm	25	2.75	1.15	1.80	1.30	0.64	Bearing and tilting of screw
Monotonic Field	50	4.45	1.21	2.05	1.44	0.59	Bearing and tilting of screw

3.2 Cyclic test results

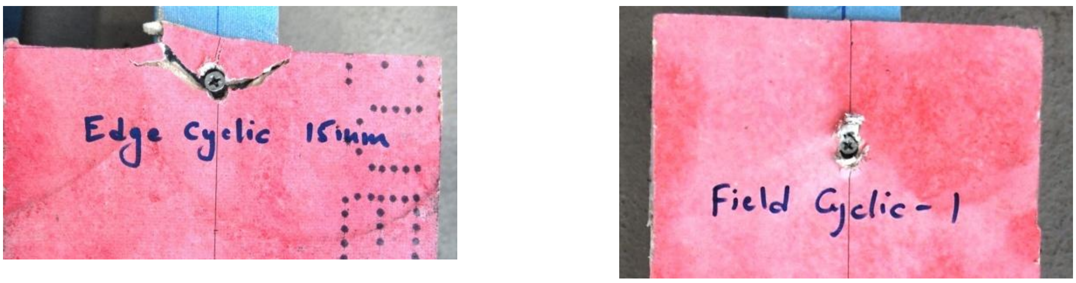
Load-deflection results for specimens Cyclic Edge-15mm-1 and Cyclic Field-1 are provided in Figures 7(a) and 7(b) respectively. The failure modes for edge and field connections during cyclic tests (shown in Figures 8(a) and (b)) were observed to be similar as in the cases of monotonic tests described in Section 3.1. Load-deflection responses for both edge and field connections showed severely pinched hysteresis loops with large residual displacement (displacement at zero load). This reflects that bearing of the fastener into the sheathing material is the primary mode of resistance. Important parameters such as maximum load, residual displacement (displacement corresponding to zero load while unloading) and stiffness are obtained at virgin and last cycles of loadings at each loading phases and the mean of identical specimens are provided in Table 3. These parameters are obtained from positive (tensile) hysteresis loops for edge connections (specimen loaded in tension direction reflects edge connection failure whereas compressive loading reflects bearing failure which is not of primary interest for edge connection screw); and both positive and negative hysteresis loops for field connections. Load is degraded from virgin cycle to last cycle of loading at the same displacement amplitude which is referred as load degradation. Edge connection tests showed a maximum load degradation of 13% at displacement amplitude of nearly 1mm whereas 50% of the load was degraded at 4mm displacement amplitude in field connection tests. This is due to increasing deterioration of sheathing material around the fastener. As per Herbert and King (1998, Vol2), the residual (displacement at zero load) after each cycle is a function of the maximum displacement at that cycle. Results shown in Table 3 show a reasonably constant residual displacement ratio for all loading cycles up to peak load.

Two approaches were used to calculate stiffness; effective stiffness and secant stiffness as illustrated in Figure 9. The effective stiffness and secant stiffness for identical specimens at virgin and last cycles of each loading phase is shown in Table 3. Both of the stiffnesses were found to be similar at lower displacement amplitude of 0.25mm whereas secant stiffness was substantially lower than effective stiffness with increasing displacement amplitudes (about 2 times at displacement amplitude of 1 to 2mm and 4 times at the displacement amplitude of 3 to 4mm). This is due to the fact that the fastener around its surface deteriorated the sheathing material leaving a slot around the fastener head. On reloading, little or no resistance is provided before the fastener reached the edge of the slot (i.e. uncrushed sheathing material) thereby reducing the secant stiffness value. Test results showed a higher rate of stiffness degradation (both effective and secant stiffness) with increasing amplitude of loading and these values are plotted in Figure 10. There was little or no effective stiffness degradation with increasing displacement amplitude up to 2mm whereas the rate of degradation was rapid (about 40%) between displacement amplitudes of 2 to 4mm. However, secant stiffness degradation was observed even at lower displacement amplitude (about 40% between 0.25 to 1mm amplitude) and the rate of degradation was much higher at large displacement amplitude (about 70% between 1 to 4mm amplitude).



(a) Cyclic Edge-15mm-1 (b) Cyclic Field-1

Figure 7 Load-deflection behaviour of stud-fastener-sheathing connections under cyclic loading (for one screw)



(a) Cyclic Edge-15mm-1 (b) Cyclic Field-1

Figure 8 Failure mode of stud-fastener-sheathing connections under cyclic loading

Table 3 Summary of cyclic test results (mean values obtained for one screw)

Specimen	Hysteresis Loop	Loading Phase	Displacement Amplitude Δ (mm)	Max Load (kN)		Load Degradation	Residual Δ_r (mm)	Δ_r/Δ	Effective Stiffness (kN/mm)		Secant Stiffness (kN/mm)	
				Virgin Cycle	Final Cycle				Virgin Cycle	Final Cycle	Virgin Cycle	Final Cycle
Edge-12mm	Positive	1	0.25	0.43	0.42	2%	0.08	0.32	1.80	1.78	1.72	1.68
		2	0.50	0.69	0.62	11%	0.19	0.38	1.50	1.45	1.38	1.23
		3	0.75	0.70	Fail	--	0.52	0.69	0.98	--	0.93	--
Edge-15mm	Positive	1	0.25	0.43	0.40	11%	0.08	0.32	1.75	1.72	1.70	1.60
		2	0.50	0.63	0.56	11%	0.19	0.38	1.56	1.51	1.26	1.12
		3	0.75	0.76	0.66	13%	0.29	0.39	1.52	1.46	1.01	0.88
		4	1.00	0.74	Fail	--	0.48	0.48	1.35	--	0.74	--
Edge-20mm	Positive	1	0.38	0.53	0.47	12%	0.12	0.32	1.90	1.87	1.42	1.24
		2	0.75	0.78	0.68	12%	0.29	0.39	1.36	1.33	1.04	0.91
		3	1.13	0.93	0.81	13%	0.42	0.37	1.13	1.09	0.83	0.72
		4	1.50	0.90	Fail	--	0.70	0.47	1.07	--	0.60	--
Field	Positive	1	1	0.83	0.72	13%	0.38	0.38	1.46	1.41	0.83	0.72
		2	2	1.11	0.85	24%	0.95	0.48	1.40	1.34	0.55	0.42
		3	3	1.20	0.79	34%	1.70	0.57	1.19	1.08	0.40	0.26
		4	4	1.01	0.49	51%	3.05	0.76	0.96	0.81	0.25	0.12
	Negative	1	1	0.83	0.73	12%	0.44	0.44	1.25	1.22	0.83	0.73
		2	2	1.11	0.90	19%	1.04	0.52	1.15	1.11	0.56	0.45
		3	3	1.08	0.81	24%	1.87	0.62	0.95	0.89	0.36	0.27
		4	4	0.83	0.53	36%	2.95	0.74	0.79	0.68	0.21	0.13
	Average of Positive and Negative	1	1	0.83	0.72	13%	0.39	0.39	1.35	1.32	0.83	0.72
		2	2	1.11	0.86	23%	0.98	0.49	1.27	1.23	0.56	0.44
		3	3	1.17	0.79	32%	1.74	0.58	1.07	0.99	0.38	0.27
		4	4	0.96	0.50	48%	3.02	0.76	0.88	0.75	0.23	0.13

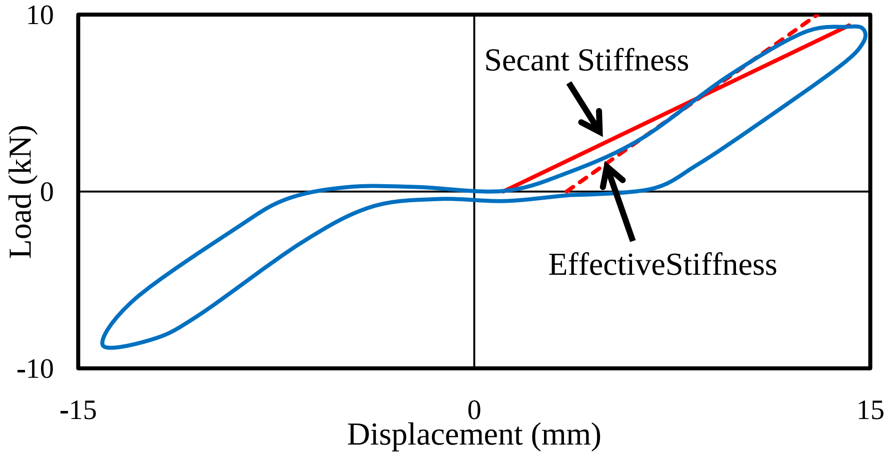
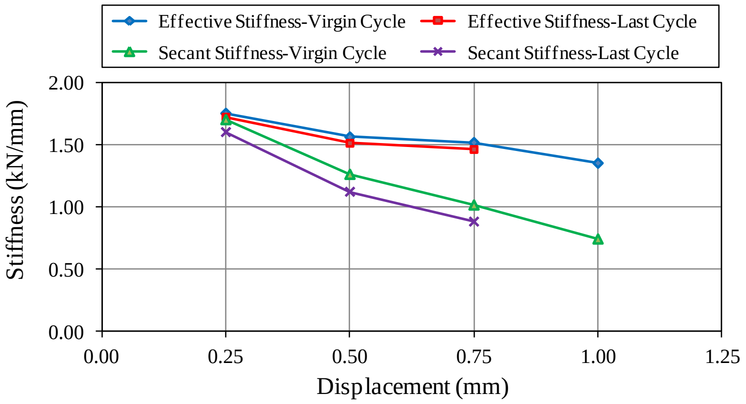
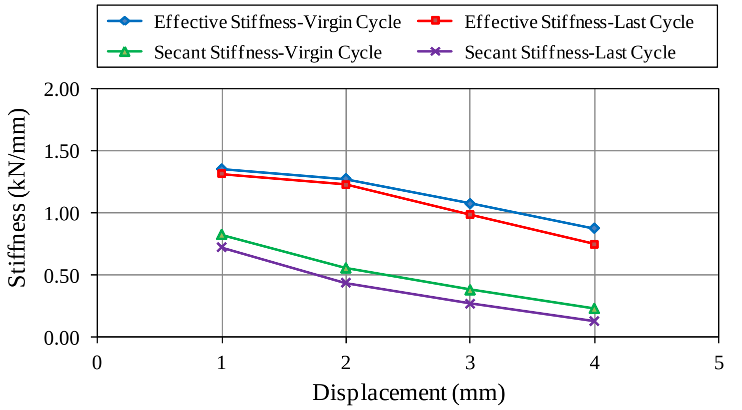


Figure 9 Definition of the effective and the secant stiffness for cyclic test (Gad *et al.* 1999)



(a) Cyclic Edge-15mm



(b) Cyclic Field

Figure 10 Stiffness degradation under cyclic loading (mean values obtained for one screw)

4. CONCLUDING REMARKS

Screw connections between cold-formed steel and fibre cement board were tested in shear under monotonic and cyclic loadings. Various edge distances (distance of fastener from edge of board) ranging from 12mm to 50mm were considered to examine connection capacities and failure modes. Based on the monotonic tests, it was found that screws located up to 20mm from the edge of the board exhibit tear out failure with limited or no ductility. For screws located further than 20mm from the edge, the failure mode was bearing failure of the board with high level of ductility. As expected the screws closer to the edge also had lower strength. The change of failure mode appears to occur at an edge distance of 25mm based on the tests performed to date. The cyclic test results showed similar type of failure modes as observed in the monotonic tests. Screws connected up to 20mm from the board edge showed a maximum load degradation of 13% at nearly 1mm displacement amplitude whereas 50% load degradation was observed at displacement amplitude of 4mm with screws fastened at 50mm from the board edge. With increasing amplitude of loading, secant stiffness degraded up to 40% for screws located up to 20mm from the board edge whereas 70% of the stiffness was degraded for screws located 50mm far from the board edge. Results obtained from this test will be utilised in finite element model to predict full wall panel behaviour. This study has been conducted using specific fasteners, sheathing board and studs which is a companion to full-scale wall test, hence hysteretic response and failure modes of the connections shall vary with different types of fasteners, board type and thickness, and/or stud thickness.

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