CYCLIC LOAD TESTING OF WOOD-FRAMED, PLYWOOD SHEATHED SHEAR WALLS USING ASTM E564 AND THREE LOADING SEQUENCES

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ABSTRACT

The damage to wood-framed residential buildings in recent earthquakes has raised questions regarding the performance of shear wall assemblies when subjected to cyclic lateral loading. Historically shear wall performance has been evaluated on monotonic testing which has been used to develop model building code provisions for engineered shear walls. Presently no national or international standards for conducting cyclic lateral load testing of wood-framed assemblies are recognized. ASTM E 564, for example, does not specify a cyclic lateral load testing protocol.

This study applied ASTM E 564 to four identical sets of plywood shear wall assemblies using three different cyclic lateral load test sequences in order to investigate the effects of loading sequence on test results. The first sequence had a large number of cycles patterned after a sequentially phased displacement test procedure. The second sequence had only large excursions used to study the effects of large pulses in the near-field of an earthquake. The third sequence had a moderate number of cycles occurring in progressively increasing excursion increments.

Twenty-four 2.44 m x 2.44 m (8 foot x 8 foot) shear walls with 9.5 mm (3/8 inch) thick plywood panel sheathing were tested. Four different nail styles were used for the identically framed and sheathed samples. Two samples of each configuration were tested under each of the three loading sequences to obtain the load-displacement and load-capacity characteristics for each assembly. This information will assist in understanding the performance of wood-framed shear walls under cyclic lateral loads and the factors, which govern their performance.

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INTRODUCTION

Historically shear wall performance has been evaluated on monotonic testing which has been used to develop model building code provisions for engineered, timber shear walls. Presently no national or international standards for conducting cyclic lateral load testing of wood-framed assemblies are recognized. ASTM E 564 (1), for example, specifies some holdown connector requirements of the shear walls but does not provide for a cyclic lateral load testing protocol.

ASTM E 72 (2) was the test protocol that the American Plywood Association (APA) used from 1965 to 1993 to evaluate the performance of plywood shear walls (3). The strength values for plywood shear walls contained in model building codes are primarily based on these APA tests. In early 1996 the Structural Engineers Association of Southern California's (SEAOSC) Ad Hoc Committee on Testing Standards published a new test protocol (4), (5) for cyclic testing based on ASTM E 564.

This study applied SEAOSC's cyclic testing protocol based on ASTM E 564 to four identical sets of plywood shear wall assemblies using three different cyclic lateral loading sequences in order to investigate the effects of loading sequence on test results. All specimens were constructed with 9.5mm (3/8 inch) CDX plywood sheathing material with the only construction variable being nail type used to fasten the sheathing to the framing. Six samples used 8d hand-driven common nails (sample type A), six samples used 8d hand-driven galvanized box nails (sample type B), six samples used 8d pneumatically driven common nails (sample type C) and six samples used 8d pneumatically driven box nails (sample type D).

OBJECTIVE

The objective of these shear wall tests was to compare four identical sets of plywood shear wall assemblies, except for nail type, using three different cyclic lateral load test sequences in order to investigate the effects of loading sequence. The first set of tests followed the protocol developed by SEAOSC's Ad Hoc Committee on Testing Standards (4), (5) using the Sequentially Phased Displacement loading sequence (6). The second set of tests followed the same SEAOSC test protocol, except the first half of the loading sequence was removed to subject the test samples to large excursions as to simulate large pulses in the near-field of an earthquake. The third set of tests also followed SEAOSC's test protocol, except the final three cycles per displacement increment were removed to minimize nail fracture effects on the sheathing fasteners.

TEST SPECIMENS AND MATERIALS

Twenty-four samples were tested for the purposes of this study. Two test samples of each nail type were tested using each of the three loading sequences. All shear wall test samples were fabricated using a 2.44 m x 2.44 m (8 foot x 8 foot) wood frame with 51 mm x 102 mm (2 inch x 4 inch) nominal framing members using single sill plates, double top plates and adjoining panel edges. The posts at each end of the frames were 102 mm x 102 mm (4 inch x 4 inch).

Shear Wall Framing & Wall Sheathing

The lumber used for framing all shear walls was Douglas fir. As a rule the wall sheathing was fastened to the framing within 48 hours of each test to minimize any effects of moisture seasoning (drying) on the performance of the wall. CDX Plywood, 9.5 mm inch (3/8 inch) thick, was used for wall sheathing in the all tests. All plywood panels were manufactured in accordance with U.S. Product Standard PS 1-83, Construction and Industrial Plywood.

In all tests, wood structural panels were applied vertically to the framing members, with their face grain or strength axis parallel to the studs. To conform with APA recommendations for panel installation, the panel edges were spaced 3 mm (1/8 inch) apart along the vertical joint at the center stud in order to provide space for the panels to expand if subjected to moisture under on-site field conditions.

Fasteners & Holdown Connectors

The plywood was fastened to the framing with four different nail styles (sample types): hand-driven 8d common nails (sample type A), hand-driven 8d galvanized box nails (sample type B), pneumatically driven 8d common nails (sample type C) and pneumatically driven 8d box nails (sample type D).

Welded steel holdowns, fabricated from heavy 76mm (3 inch) channel, were used on both 102 mm x 102 mm (4 inch x 4 inch) end posts to resist wall uplift when subjected to in-plane lateral forces. The holdown design incorporated two 67 mm (2-5/8 inches) diameter steel shear plate connectors, designed and fabricated in accordance with the Uniform Building Code, to distribute bolt loads and minimize bolt deformation in the end posts. Additionally, 6 mm (1/4 inch) thick x 64 mm (2-1/2 inch) square steel plate washers were placed under the nuts used with the 19 mm (3/4 inch) diameter holdown bolts. This detail helped distribute the bolt loads to the end post without deforming the washer or crushing the wood.

Using tight-fitting shear plate connectors in the end posts minimized holdown slip. To minimize displacement in accordance with provisions in the National Design Specification for Wood Construction, the diameter of the bolt holes was limited to a maximum of 1.5 mm (1/16 inch) larger than the bolt diameter (19 mm (3/4 inch)).

TEST SET-UP AND PROCEDURE (6)

The test set-up (Figure 1) and procedure were based on the "Standard Method of Cyclic (Reserved) Load Test for Shear Resistance of Framed Walls for Building" as developed by SEAOSC's Ad Hoc Committee on Testing Standards and reported in references (4) and (5). The American Plywood Association work reported in its publication "Performance of Wood Structural Panel Shear Walls Under (Reversed) Loading" (7) used this test method.

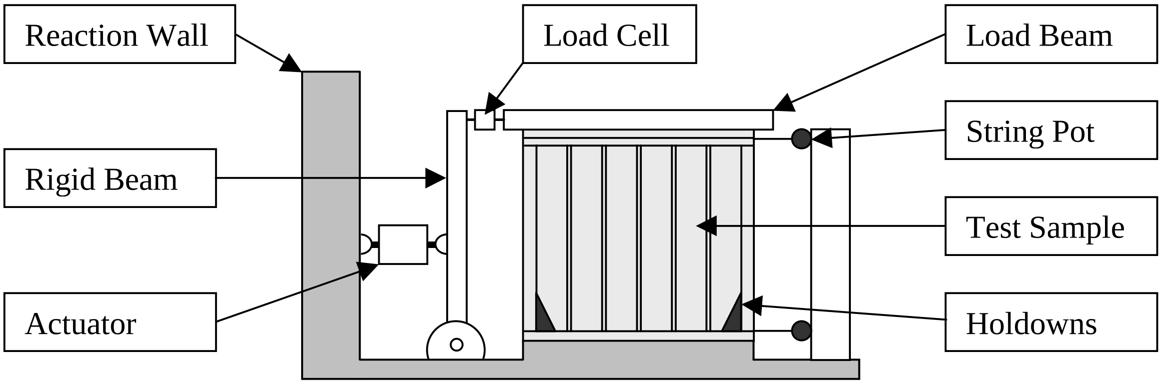

Figure 1: Test Set-up

The shear wall test samples were attached to the base of the test frame with four 16 mm (5/8 inch) diameter anchor bolts. Steel square plate washers, 6 mm (1/4 inch) thick x 64 mm (2-1/2 inches) square, were placed under the nuts for the bottom plate anchor bolts.

A 19 mm (3/4-inch) plywood spacer was placed on the top plate of the walls. The base of test fixture width equaled the sill plate width. These steps were taken so that panel sheathing was free to rotate without restraint (bearing) at the top and bottom edges. These conditions duplicate test configurations used by APA when wall bracing and shear wall tests are conducted monotonically in accordance with ASTM E72. Any bearing of the wall's sheathing panels at the top or bottom ends can increase shear wall stiffness and strength (8), since such bearing limits the displacement of the vertical panel edges relative to the framing at the end posts and the center stud.

Racking shear loads were applied to the shear wall test samples through a horizontal steel H-beam lag-screwed to the double top plate of the wall. The beam was placed on the plywood spacer, which was sandwiched between the beam and the double top plate.

The racking shear loads were applied horizontally to the top of the shear wall test samples. A 244.8 kN (55.0 kip) capacity, programmable, double-acting hydraulic actuator was bolted to a stiff vertical cantilever column hinged at the base to act as a lever arm. The hinged cantilever column arrangement allowed for displacements larger than the capacity of the actuator, which was limited to +/- 76mm (+/-3 inches) in either direction. The applied horizontal load at the top of the wall was measured with a load cell in the horizontal plane of the top plate and steel H-beam. A string potentiometer was used to measure panel drift.

LOADING SEQUENCES

The three loading sequences followed either the testing sequence adopted by SEAOSC Ad Hoc Committee on Testing Standards or were derivatives of this testing sequence.

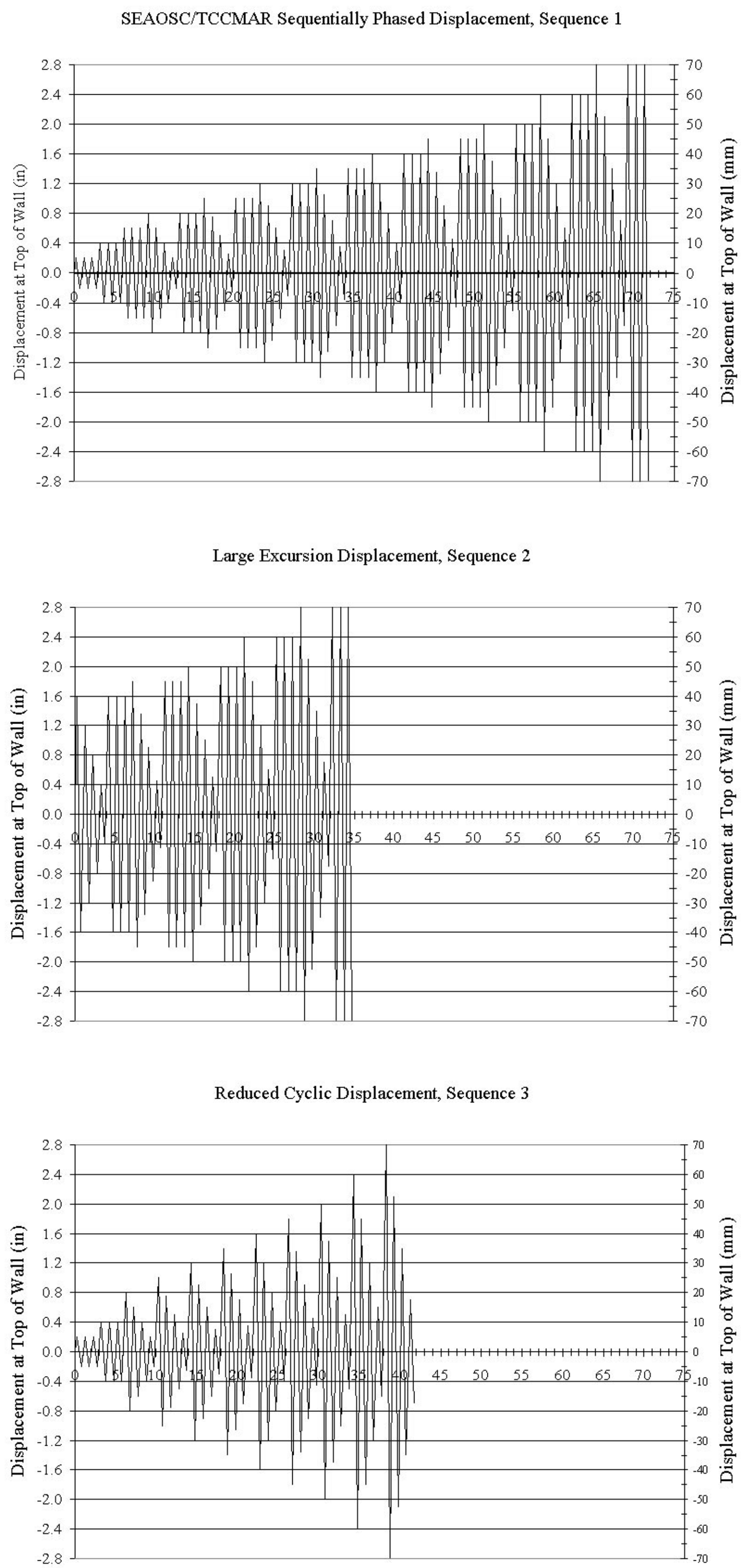

Figure 2. Three Different Loading Sequence Protocols

The first loading sequence, identified as Sequence 1, subjected test samples to displacements based on the TCCMAR sequential phased displacements procedure adopted by SEAOSC for the purpose of testing wood framed shear walls (4) and (5).

The TCCMAR procedure defines the concept of the First Major Event (FME) as the first significant limit state that occurs during the test. The FME occurs when the load capacity of the wall, upon recycling of load to the same wall displacement increment, first drops noticeably from the original load. The FME can be determined from preliminary cyclic load tests on an identical test sample. For the test samples in this series, the FME for all tests was estimated, based on prior cyclic tests, to occur at a displacement of about 20 mm (0.8 inch).

The TCCMAR procedure consists of applying three cycles of fully-reversing displacement, at increments representing 25%, 50% and 75% of the FME. Wall displacement is then increased for one cycle to 100% of the FME. Next, "decay" cycles of displacement for one cycle each at 75%, 50% and 25% of maximum displacement (100% of the FME) are applied, followed by three cycles of displacement at 100% of the FME. The next increment of increased displacement (125% of FME) is then applied, followed by similar decay and stabilization cycles of loading. This incremental cyclic load-displacement and decay sequence is continued to 150%, 175%, 200%, 250%, 300%, 350% and 400% of the FME, or until the wall exhibits a significant loss of capacity (in these tests, at about 350% to 400% of the FME).

The second loading sequence, identified as Sequence 2, is the Large Excursion Displacement Sequence. This sequence follows the TCCMAR incremental displacement guidelines but begins the test displacement at 200% of the FME.

The third loading sequence, identified as Sequence 3, is the Reduced Cyclic Displacement Sequence. This sequence also follows the TCCMAR guidelines but the three cycles of displacement at 100% of the FME following the decay cycles are removed within each displacement increment. These three cycles in each increment have been eliminated to decrease nail fracture effects.

Figure 2 contains plots of each of the three loading sequences. Note that since the load was applied at a cyclic frequency of approximately 0.5 Hz to 0.25 Hz (e.g., one cycle per 2 to 4 seconds), the abscissa values correspond to load cycles and not time. During later stages of the cyclic loading sequence, when the wall displacement exceeded 40mm (1.6 inches), the cyclic frequency was reduced with each displacement in order to maintain a constant maximum velocity. This was done to improve control and minimize inertial effects.

TEST RESULTS

Load points at 12.7 mm, 25.4 mm and 38.1 mm (0.5 inch, 1.0 inch and 1.5 inches) are summarized in Table 1. These values are chosen as comparison points for each of the four sample types. These points are similar to the points of comparison that the APA uses in its research (0.5%, 1.0% and 1.5% story drift) (7).

The load-displacement curve for the pneumatically driven common nails, sample type C, corresponding to each test sequence is shown in Figures 3, 4 and 5. These three plots are representative of each of the four sample types. Note that samples A (8d hand driven common nails), B (8d hand driven galvanized box nails) and D (8d pneumatically driven box nails) have results similar to the curves in Figures 3, 4 and 5.

Figure 6 presents the backbone curves developed from the six tests conducted with the hand driven 8d common nails (sample type A). Figures 7, 8 and 9 present the backbone curves for the tests conducted with each of the other three nail types (sample types B, C and D). Two samples of each nail type are plotted for each loading sequence. Refer to each chart's legend for the appropriate loading sequence. These plots show the overall effects of the three different loading sequences on each sample type.

Sample Type A
Hand Driven Common Nails

	Max. Load (kN) at Each Drift Level		
Sample	0.5% Drift	1.0% Drift	1.5% Drift
A-1-1	28.8	39.3	38.2
A-1-2	27.0	39.7	40.6
A-2-1	18.4	35.0	41.8
A-2-2	35.9	49.1	53.7
A-3-1	32.6	41.9	43.8
A-3-2	34.5	43.4	43.5

Sample Number (1 or 2)
Loading Sequence (1,2 or 3)
Sample Type (A,B,C or D)

Sample Type B
Hand Driven Galvanized Box Nails

	Max. Load (kN) at Each Drift Level		
Sample	0.5% Drift	1.0% Drift	1.5% Drift
B-1-1	24.0	38.4	41.2
B-1-2	28.2	38.1	40.7
B-2-1	28.5	40.8	46.8
B-2-2	28.1	43.5	51.9
B-3-1	32.6	43.3	46.5
B-3-2	32.7	44.4	47.3

Sample Type C
Pneumatically Driven Common Nails

	Max. Load (kN) at Each Drift Level		
Sample	0.5% Drift	1.0% Drift	1.5% Drift
C-1-1	26.4	35.8	36.7
C-1-2	26.4	39.0	41.7
C-2-1	30.8	43.9	50.0
C-2-2	32.3	46.7	52.7
C-3-1	31.3	42.5	46.1
C-3-2	31.2	41.4	44.6

Sample Type D
Pneumatically Driven Box Nails

	Max. Load (kN) at Each Drift Level		
Sample	0.5% Drift	1.0% Drift	1.5% Drift
D-1-1	26.4	37.3	40.4
D-1-2	25.6	37.7	40.9
D-2-1	26.7	42.2	48.4
D-2-2	30.4	41.9	47.3
D-3-1	31.8	41.2	44.5
D-3-2	30.8	41.3	45.2

Table 1. Load at Comparative Drift Levels for each Sample Type

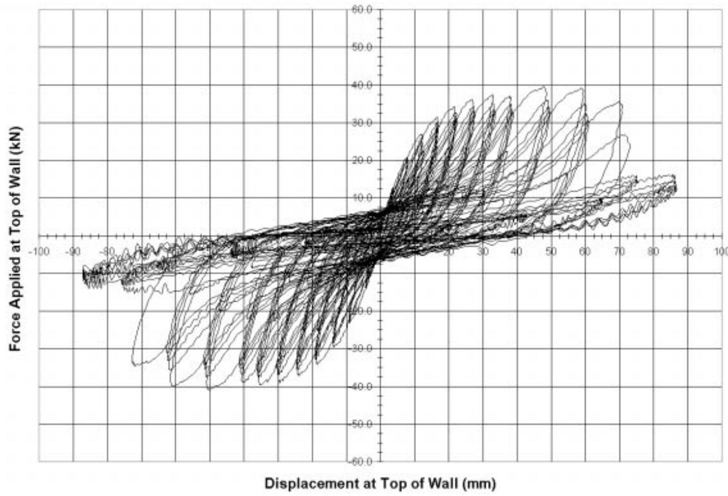

Figure 3: Sample Type C (Pneumatically Driven Common Nails) w/ Sequentially Phased Displacement, Sequence 1

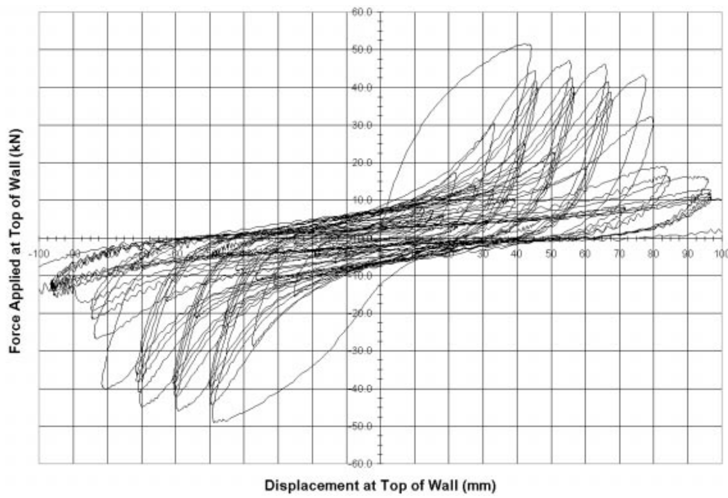

Figure 4: Sample Type C (Pneumatically Driven Common Nails) w/ Large Excursion Displacement, Sequence 2

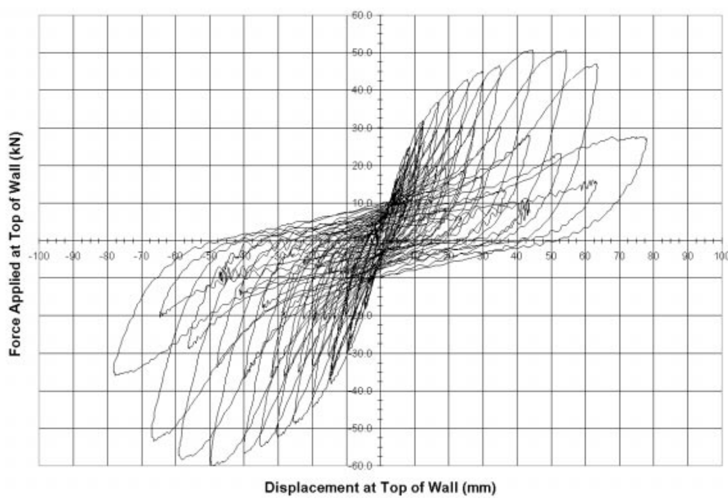

Figure 5: Sample Type C (Pneumatically Driven Common Nails) w/ Reduced Cyclic Displacement, Sequence 3

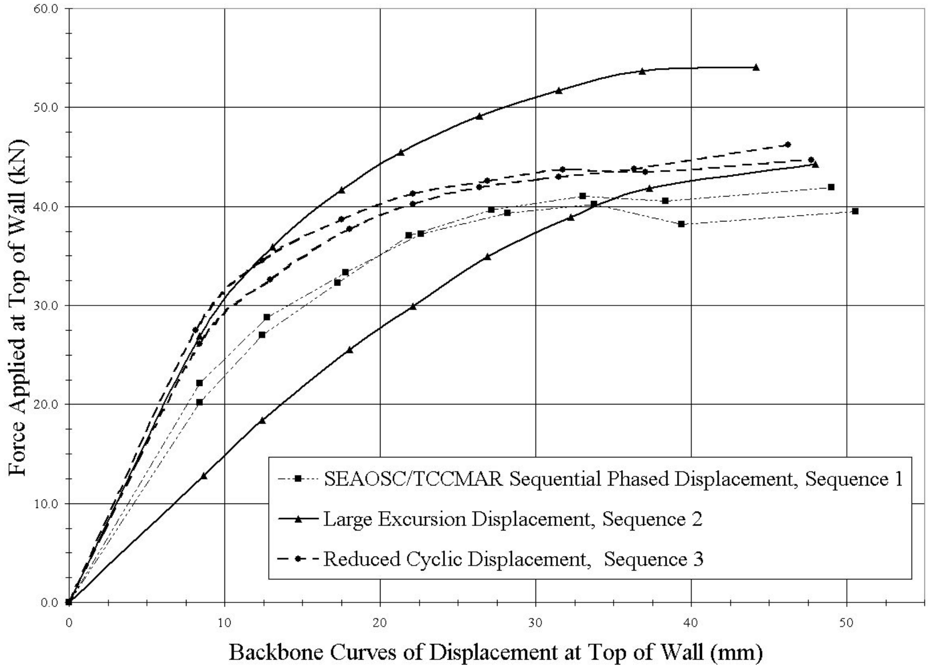

Figure 6: Backbone Curve of Sample Type A (Hand Driven 8d Common Nails)

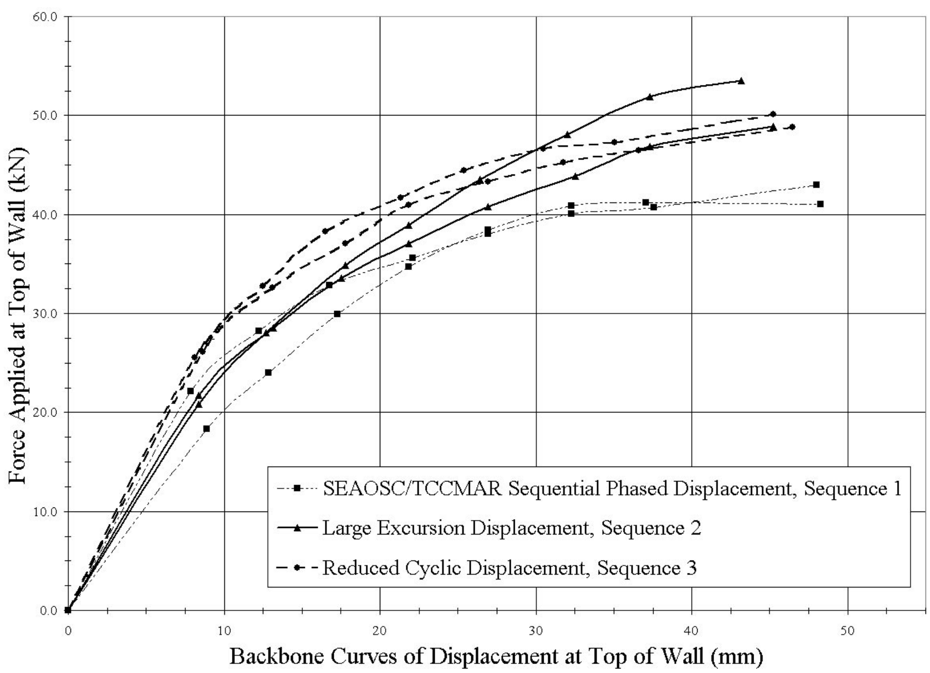

Figure 7: Backbone Curve of Sample Type B (Hand Driven 8d Galvanized Box Nails)

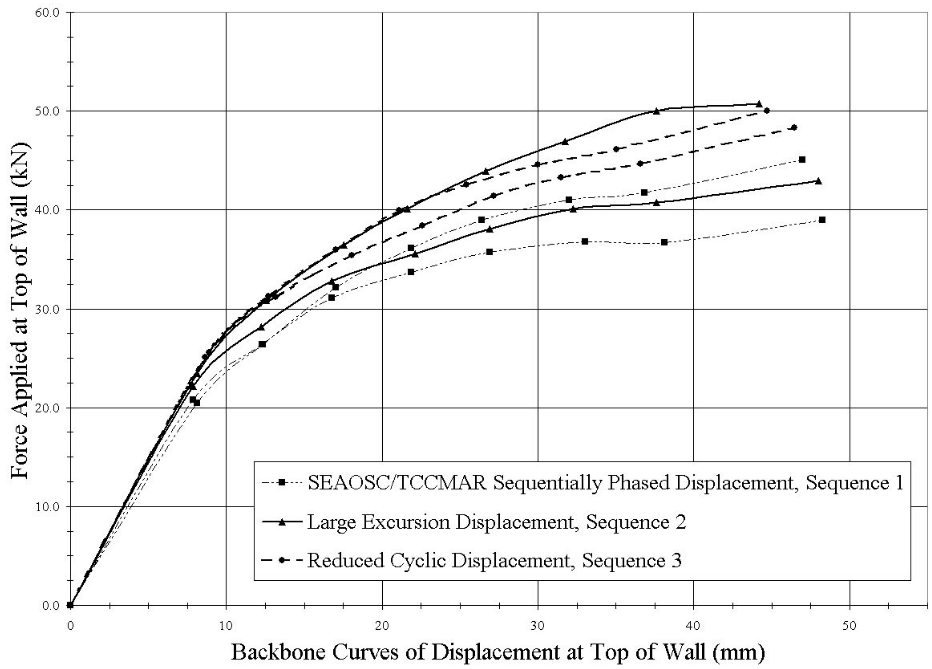

Figure 8: Backbone Curve of Sample Type C (Pneumatically Driven 8d Common Nails)

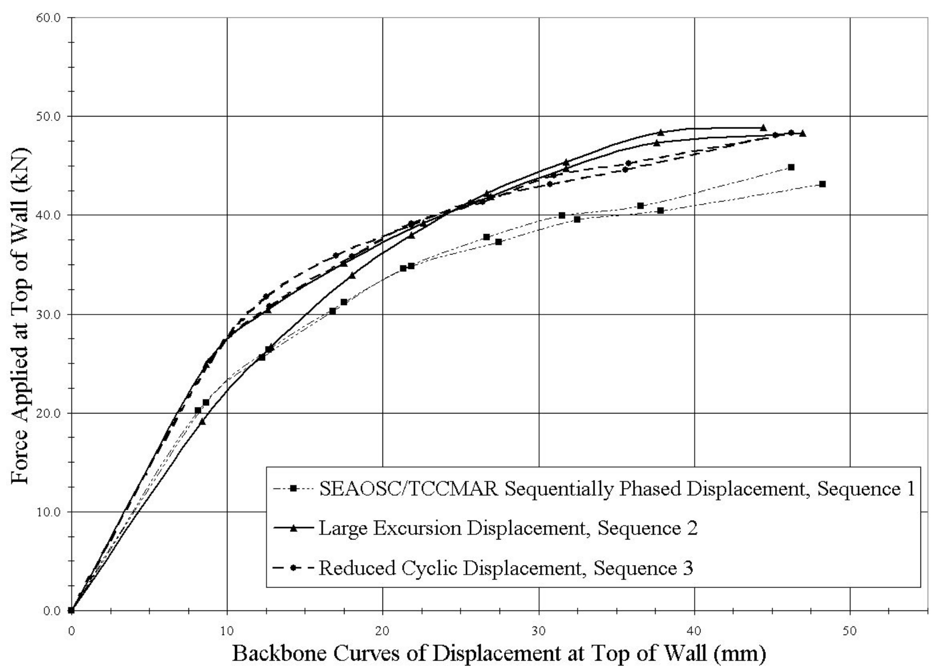

Figure 9: Backbone Curve of Sample Type D (Pneumatically Driven 8d Box Nails)

CONCLUSIONS

1. Sample ultimate strengths were lower for loading sequences having a greater number of preceding inelastic cycles and larger cumulative inelastic displacements (9).
   A. The initial cycle of the Large Excursion Displacement Sequence (Sequence 2) achieved the highest ultimate strength results for each sample type. This cycle is comparable to the monotonic tests where degradation effects of cyclic loading are not present. After this initial cycle, the strength of the sample degrades rapidly when exposed to larger subsequent cycles.
   B. The Low Fastener Fatigue Sequence (Sequence 3) achieved the next highest ultimate strength for each sample type. This sequence exposed the sample to a modest number of inelastic cycles prior to the sample achieving its ultimate strength.
   C. The TCCMAR Sequentially Phased Displacement Sequence (Sequence 1) had the lowest ultimate strength. This sequence exposed the sample to the greatest number of inelastic cycles prior to the sample achieving its ultimate strength.

2. The strength of the four sample types was substantially the same for a given test loading sequence. The average strengths achieved at 0.5%, 1.0% and 1.5% drift are listed below:

DRIFT	SAMPLE TYPE	Sequence 1	Sequence 2	Sequence 3
0.5%	H/D Common Nails	27.9 kN	27.2 kN	33.5 kN
	H/D Galvanized Box Nails	26.1 kN	28.3 kN	32.7 kN
	P/D Common Nails	26.4 kN	31.6 kN	31.2 kN
	P/D Box Nails	26.0 kN	28.6 kN	31.3 kN

DRIFT	SAMPLE TYPE	Sequence 1	Sequence 2	Sequence 3
1.0%	H/D Common Nails	39.5 kN	42.1 kN	42.7 kN
	H/D Galvanized Box Nails	38.3 kN	42.2 kN	43.9 kN
	P/D Common Nails	37.4 kN	45.3 kN	42.0 kN
	P/D Box Nails	37.5 kN	42.1 kN	41.3 kN

DRIFT	SAMPLE TYPE	Sequence 1	Sequence 2	Sequence 3
1.5%	H/D Common Nails	39.4 kN	47.8 kN	43.7 kN
	H/D Galvanized Box Nails	41.0 kN	49.4 kN	46.9 kN
	P/D Common Nails	39.2 kN	51.4 kN	45.4 kN
	P/D Box Nails	40.7 kN	47.9 kN	44.9 kN

3. The failure modes observed were nail fracture with necking, nail pull through and nail withdrawal. All three modes of failure suggest that plywood shear wall behavior is significantly influenced by tension forces in the fastener subassembly (plywood, nail head, nail shank and receiving member). Common nails (hand driven and pneumatically driven) failed most often by pulling through the plywood. Box nails (hand driven galvanized and pneumatically driven) failed more often by nail fracture. Since box nails have a larger net

area on the underside of the nail head as compared to common nails, box nails have greater resistance to failing by pulling through the plywood (10).

4. The ultimate displacement capacity of the samples tested did not appear to be significantly influenced by loading sequence. However, samples using pneumatically driven nails maintained their capacity to greater displacements than samples using hand driven nails.

REFERENCES

(1) ASTM, 1984. Standard Method of Static Load Test for Shear Resistance of Framed Walls for Buildings. ASTM E564-76 (1984). American Society for Testing and Materials, West Conshohocken, PA.

(2) ASTM, 1980. Standard Methods of Conducting Strength Tests of Panels for Building Construction (Sections 14 and 15). ASTM E72-80. American Society for Testing and Materials, West Conshohocken, PA.

(3) Tissell, John R., 1993. Structural Panel Shear Walls. APA Research Report 154. APA The Engineered Wood association, Tacoma, WA.

(4) Shepherd, R., “Standardized Experimental Testing Procedures For Mixed Material Structural Systems”, SEAOC Proceeding - 64th Annual Convention, Indian Wells, CA. 1995, pp. 299-308

(5) Shepherd, R., February 1996, Standardized Experimental Testing Procedures For Low-Rise Structures. Earthquake Spectra, Earthquake Engineering Research Institute, Oakland, CA.

(6) Porter, M.L., 1987. Sequential Phased Displacement (SPD) Procedure for TCCMAR Testing. Proceedings of Third Meeting of the Joint Technical coordinating Committee on Masonry Research, U.S. - Japan Coordinated Earthquake Research Program. Tomamu, Japan.

(7) Rose, John, November 1995, "Performance of Wood Structural Panel Shear Walls Under (Reversed) Loading", American Plywood Association.

(8) Adams, Noel R., May 1966, Plywood Shear Walls. APA Research Report 105. APA - The Engineered Wood Association, Tacoma, WA.

(9) Krawinkler, Helmut, February 1996, Cyclic Loading Hiostories for Experimentation on Structural Components. Earthquake Spectra, Earthquake Engineering Research Institute, Oakland, CA.

(10) Ficcadenti, S., Castle T., Sandercock, D., Kazanjy, R., Laboratory Testing to Investigate Pneumatically Driven Box Nails for the Edge Nailing of 3/8" Thick Plywood Shear Walls. SEAOC Proceeding - 64th Annual Convention, Indian Wells, CA. 1995, pp. 389-399