10th Canadian Masonry Symposium, Banff, Alberta, June 8 – 12, 2005

EFFECTS OF CONFINEMENT REINFORCEMENT ON THE PERFORMANCE OF MASONRY SHEAR WALLS

Matthew Snook[1], David McLean[2], Cole McDaniel[3] and David Pollock[4]
[1]Graduate Student, [2]Professor, [3]Assistant Professor, [4]Associate Professor
Department of Civil and Environmental Engineering
Washington State University, Pullman, WA 99164-2910 USA

ABSTRACT

The research presented in this paper investigates the behavior of relatively heavily reinforced concrete masonry shear walls incorporating three types of confinement reinforcement, consisting of steel confinement plates or seismic reinforcement combs placed in the mortar joints or the use of polymer fibers mixed into the grout. The shear walls were tested as cantilever specimens subjected to cyclic lateral displacements under a constant axial load to represent seismic loading. The behavior of each wall specimen was evaluated with respect to failure mode, masonry and steel strains at failure, force displacement relationships, ductility, and the rate of strength degradation after maximum lateral loading. Test results show that all three confinement techniques moderately improve drift capacity and energy absorption. The addition of fibers in the grout provided the greatest improvement in performance.

KEY WORDS: shear walls, seismic, confinement, ductility

INTRODUCTION

Shear walls are the primary lateral load and axial load resisting elements in most masonry structures and therefore must perform satisfactorily under extreme loading events. Shear wall behavior is usually controlled by inelastic deformation mechanisms in shear and flexure. Shear behavior is characterized by diagonal cracking, and flexural behavior is typically characterized by reinforcement yielding prior to crushing of the masonry in compression.

The strength design provisions in the 2002 MSJC *Building Code Requirements for Masonry Structures* [1] establish maximum reinforcement limits for use in masonry structures. These limits on tensile reinforcement are based on material strain capacities and specified drift limits and are intended to provide ductile response. The effect of the new provisions has been to restrict the use of masonry systems for many traditional applications. Previous research has demonstrated that confinement reinforcement can be placed in the masonry mortar joints to increase the masonry compressive strain capacity and thereby improve ductility. The goal of the present research is to investigate the effectiveness of different confinement techniques for improving the ductility of masonry shear walls.

BACKGROUND AND PREVIOUS RESEARCH

Reinforced masonry shear walls are subjected to simultaneous in-plane loading, axial loading and overturning moment during a seismic event. The inelastic performance of the shear walls is influenced by several interacting factors, including axial load, aspect ratio, material strengths, and the amount of horizontal and vertical reinforcement. Past experimental and analytical studies [2, 3, 4, 5] have evaluated the performance of reinforced masonry shear walls as influenced by these factors. This past research has demonstrated that masonry shear walls may experience different failure mechanisms including shear, flexure, sliding, rocking and combinations thereof. However, most structural damage occurs from shear and flexure mechanisms since the other failure modes result in rigid body translation and rotation.

Shear failures, characterized by diagonal tensile cracking, generally result in the walls performing in a brittle fashion when loaded to the ultimate state in a seismic event. Thus, it is desirable in design of masonry shear walls to allow for the ultimate failure mechanism to be dominated by flexure yielding prior to the masonry crushing at the extreme compression fiber. However, the flexural performance of masonry shear walls can also be brittle if a majority of the tension reinforcement does not yield prior to the masonry reaching the maximum usable strains.

Shing et al [6] studied the influence of various forms of confinement reinforcement on masonry shear walls. Their research included the evaluation of a concrete masonry shear wall with seismic reinforcement combs placed within the mortar joints. The volumetric confinement ratio provided by the combs was 0.003. Their study concluded that the addition of the confinement reinforcement improved wall behavior. Envelopes of the wall hysteresis curves from this study are given in Figure 1.

Priestley [7] also conducted research on concrete masonry shear walls with the addition of confinement reinforcement. This research investigated the use of steel confinement plates that were placed in the critical toe regions. The plates provided a volumetric confinement ratio of approximately 0.008. This study concluded that the addition of plates significantly improved the wall flexure behavior. Wall envelopes from Priestley's study are also given in Figure 1.

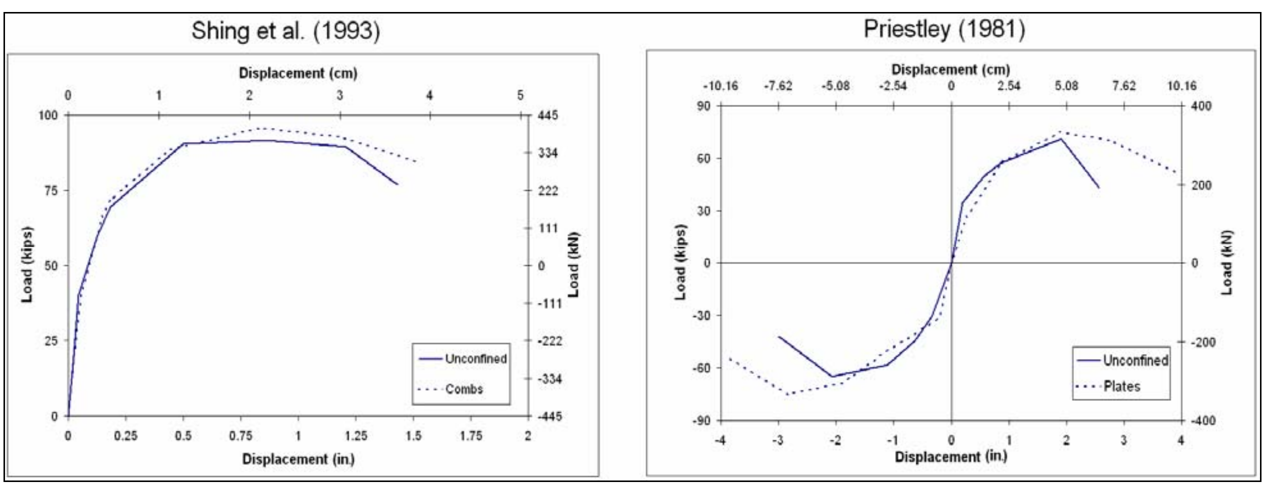

Figure 1 - Wall Envelopes from Shing et al [6] and Priestley [7]

WALL TESTING PROGRAM

Nine cantilever walls were tested to examine the effect of various types of confinement reinforcement on the behavior of reinforced concrete masonry shear walls with different aspect ratios. The wall specimens were constructed upon a heavily reinforced concrete footing that anchored the specimen to the laboratory strong floor and provided rigid support at the wall base. The walls were constructed of fully grouted concrete masonry in running bond and with a wall thickness of 19.4 cm (7.625 in.). The confinement reinforcement used in this research consisted of steel confinement plates, seismic reinforcement combs, or polymer fibers. The steel confinement plates were fabricated from ASTM A36 steel and had similar dimensions to those used in previous research [7]. The seismic reinforcement combs are a commercially-available product and confined the same area as the plates. Placement and details of the plates and combs are given in Figure 2. The polymer fibers are a commercially-available product used to reinforce concrete. Two different concentrations of fibers were used in this study based upon the weight of fibers per volume of grout. Fiber 1 had a concentration of 2.97 kg/m^3 (5 lbs/yd^3), and Fiber 2 had a concentration of 4.76 kg/m^3 (8 lbs/yd^3). All specimens had a uniformly distributed vertical reinforcement with a reinforcing ratio of 0.0055. Horizontal reinforcement was provided such that the nominal shear strength would exceed the flexural strength. Details for the wall specimens are given in Table 1.

Table 1 - Test Specimen Details

Wall Specimen	Height to Load cm (in.)	Wall Length cm (in.)	Height/Length Ratio	Confinement Method	Horiz. Reinf. # of Bars - Bar dia. @ o.c. spacing
1	132 (52)	141 (55.625)	0.93	Not Confined	5 - 16 mm @ 40 cm (#5 @16 in.)
2	132 (52)	141 (55.625)	0.93	Plates	5 - 16 mm @ 40 cm (#5 @16 in.)
3	132 (52)	141 (55.625)	0.93	Combs	5 - 16 mm @ 40 cm (#5 @16 in.)
4	132 (52)	141 (55.625)	0.93	Fiber 1	5 - 16 mm @ 40 cm (#5 @16 in.)
5	213 (84)	141 (55.625)	1.5	Not Confined	7 - 13 mm @ 40 cm (#4 @16 in.)
6	213 (84)	141 (55.625)	1.5	Plates	7 - 13 mm @ 40 cm (#4 @16 in.)
7	213 (84)	141 (55.625)	1.5	Combs	7 - 13 mm @ 40 cm (#4 @16 in.)
8	213 (84)	141 (55.625)	1.5	Fiber 1	7 - 13 mm @ 40 cm (#4 @16 in.)
9	213 (84)	141 (55.625)	1.5	Fiber 2	7 - 13 mm @ 40 cm (#4 @16 in.)

Material properties were as follows: masonry unit compressive strength = 20.7 MPa (2960 psi); mortar compressive strength = 25.8 MPa (3700 psi); grout compressive strength = 34.9 MPa (5000 psi); masonry prism compressive strength = 12.1 MPa (1730psi); and Grade 60 reinforcing steel.

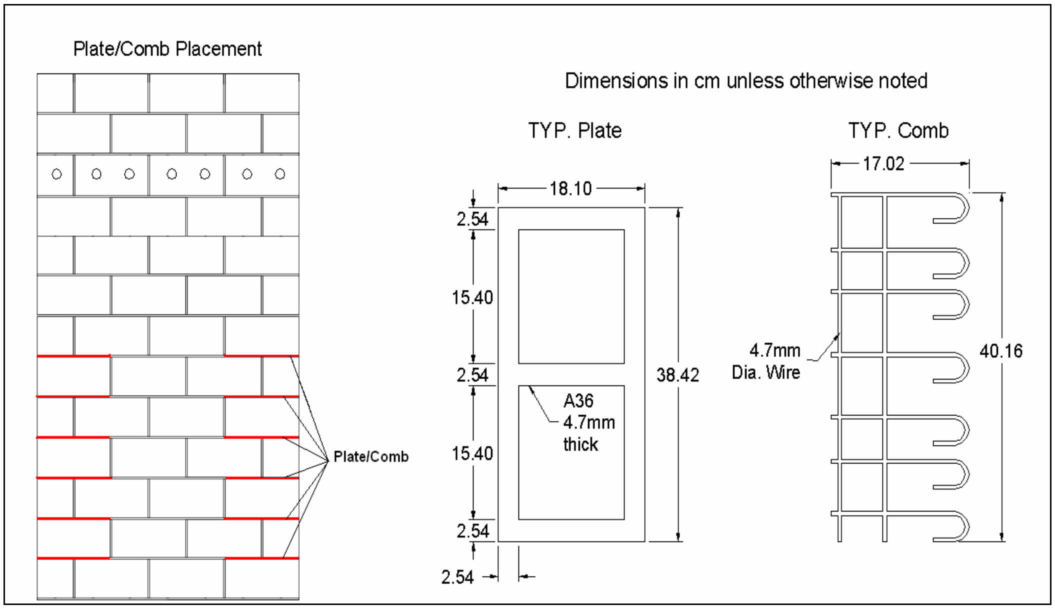

Figure 2 - Placement and Dimensions of Confinement Plates/Combs

Three hydraulic jacks, operated under pressure control, provided a constant vertical load to produce an axial stress at the wall base of approximately 0.24 MPa (35 psi) during testing. A hydraulic actuator applied in-plane lateral loading through two steel channels attached to the walls. Figure 3 shows a wall during testing. All walls were tested under displacement control. Displacement amplitudes were based on multiples of the theoretical displacement to cause first yield of the extreme tensile reinforcement bar in that wall. The loading pattern consisted of three cycles at a given displacement, and displacements were progressively increased until failure of the wall, defined as a 20% drop in peak applied load.

Figure 3 - Test Setup

TEST RESULTS

Nine shear wall specimens were tested in this study. For brevity, results from four of these tests are summarized here; detailed test results are given in Snook [8]. Limit states of interest included critical masonry strain, attainment of maximum load resistance, and 20% load degradation from maximum load resistance. These limits states were used to evaluate and compare wall behavior.

Wall 5 had an aspect ratio of 1.5 and contained no confinement reinforcement. The performance of this wall served as a baseline to which the performance of walls with the same aspect ratio and with the various confinement methods were compared. Wall 5 behavior was dominated by flexure with minimal shear cracking or evidence of sliding. A picture of Wall 5 after testing is given in Figure 4. Flexural damage spread throughout the bottom four courses of both the north and south toe regions. Small shear cracks developed over the full height of the wall. Load degradation occurred from the gradual crushing of both toe regions and buckling of the extreme flexural reinforcement over the bottom four courses. The total drift attained in Wall 5 at 20% load degradation was 2.76%. The load-displacement hysteresis curves for Wall 5 are shown in Figure 5.

Figure 4 - Wall 5 After Testing

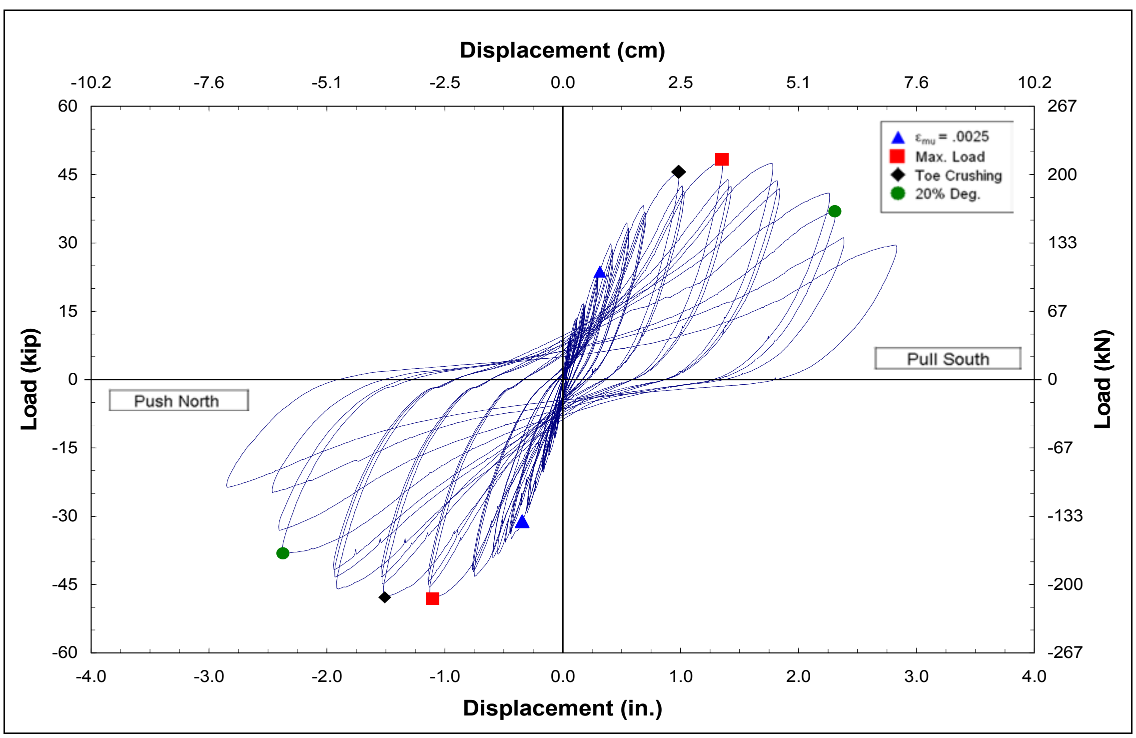

Figure 5 - Wall 5 Load-Displacement Hysteresis Curves

Wall 6 had an aspect ratio of 1.5 and contained steel confining plates in the bottom toe regions of the wall. The plates provided a volumetric confinement ratio of 0.010. Actual dimensions of the plates and placement within the wall are given Figure 2. Wall 6 behavior was dominated by flexure with minimal shear cracking and deformations. Wall sliding was insignificant. A picture of Wall 6 after testing is shown in Figure 6. Wall damage from flexure was localized in the bottom two courses. This differed from the control wall, which experienced flexure damage throughout the bottom four courses. Cracking from shear was primarily located in the bottom five courses. Load degradation occurred from the crushing of both toe regions at the bottom course and buckling followed by fracture of the extreme flexural reinforcement at the bottom course. Wall 6 achieved a total drift of 2.94% at 20% load degradation. The load-displacement hysteresis curves for Wall 6 are shown in Figure 7.

Figure 6 -Wall 6 After Testing

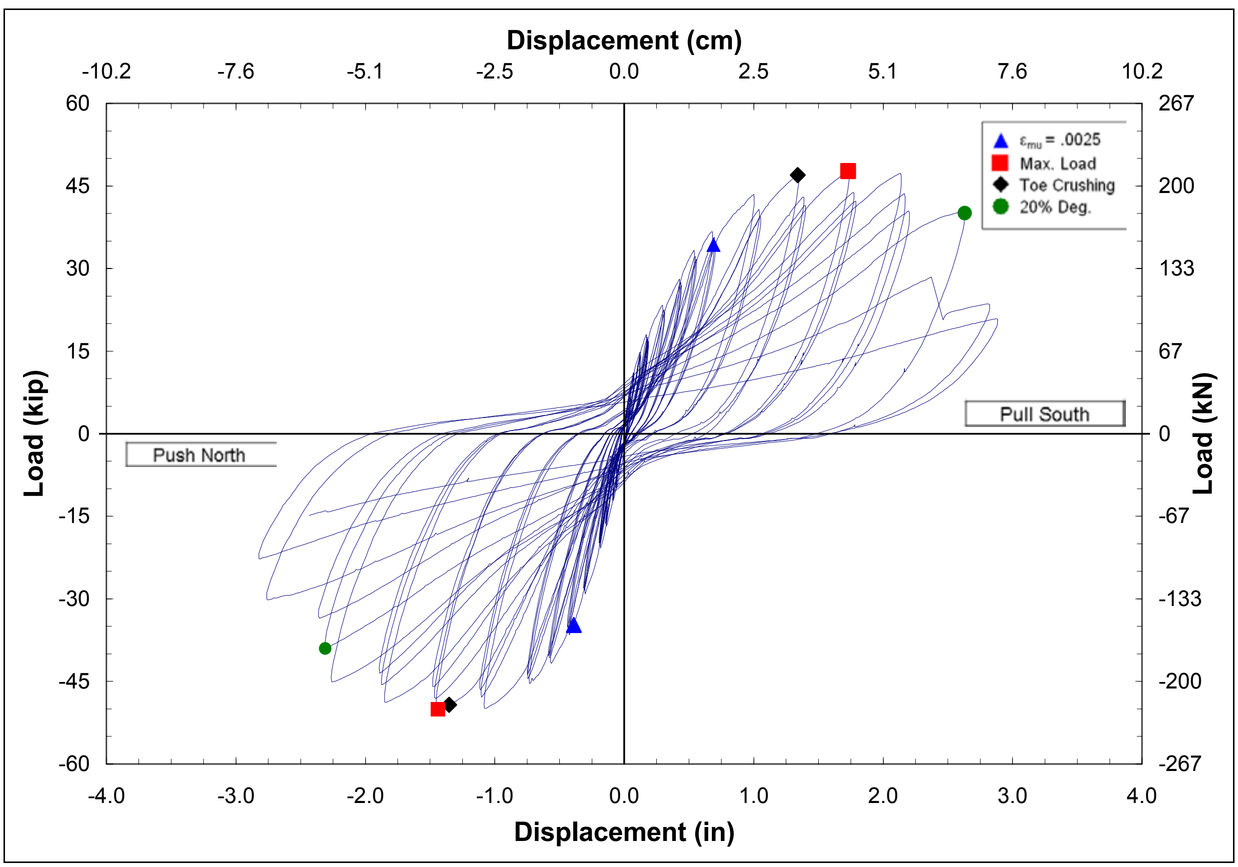

Figure 7 - Wall 6 Load-Displacement Hysteresis Curves

Wall 7 had an aspect ratio of 1.5 and contained seismic reinforcement combs in the bottom toe regions of the wall. The placement of the combs is given in Figure 2. The combs were cut to a length of 40.16 cm (15.81 in.) to confine the same area as the plates. The combs provided a volumetric confinement ratio of 0.003. Wall 7 behavior was dominated by flexure with small amounts of shear cracking and deformations. Wall sliding was insignificant. A picture of Wall 7 after testing is shown in Figure 8. Wall damage from flexure was localized to the bottom two courses of the south toe and only the bottom course of the north toe. This damage pattern was similar to the damage observed in the wall containing steel plates. Shear cracks were primarily located in the bottom four courses. Load degradation was caused by the crushing of both toe regions and buckling followed by fracture of the extreme flexural reinforcement. Total drift achieved at 20% load degradation was 2.83 %. The load-displacement hysteresis curves for Wall 7 are shown in Figure 9.

Figure 8 - Wall 7 After Testing

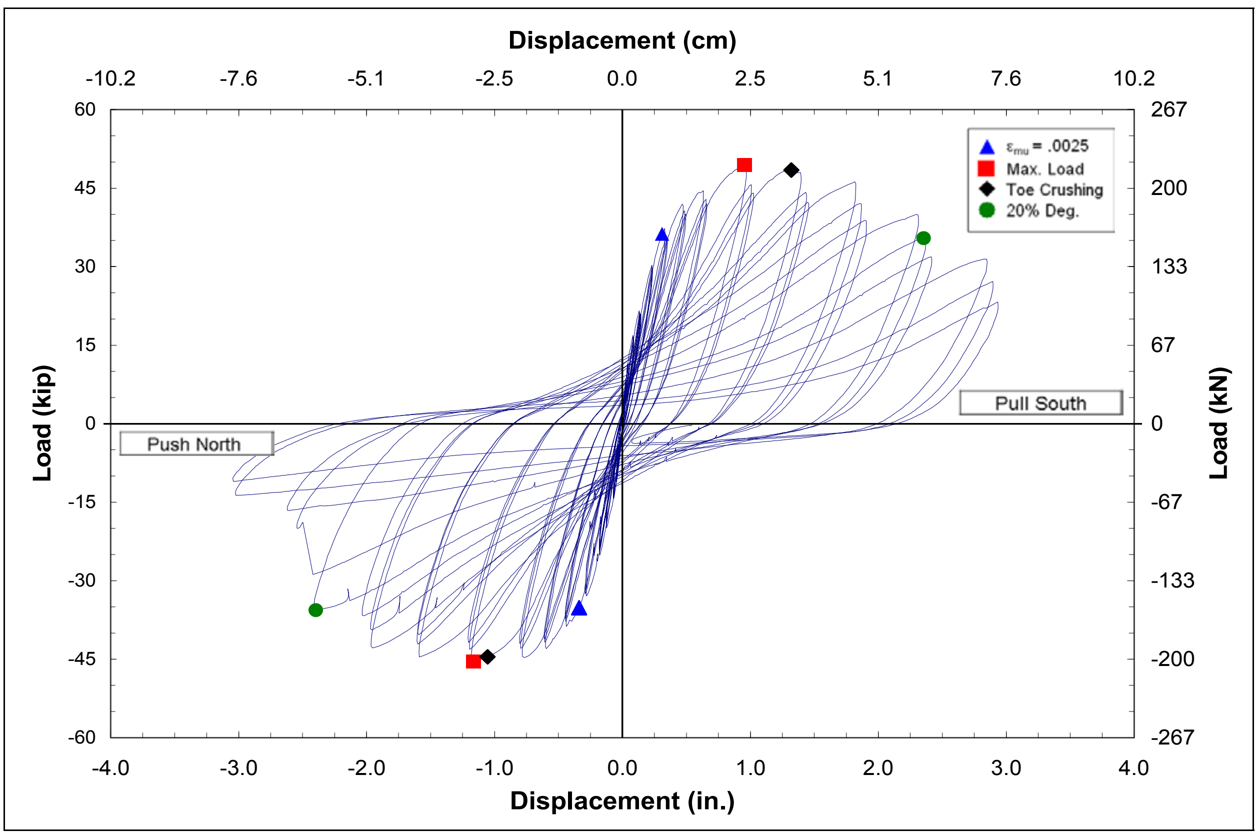

Figure 9 - Wall 7 Load-Displacement Hysteresis Curves

Wall 8 had an aspect ratio of 1.5 and contained polymer fibers that were mixed into grout, with a fiber concentration of 2.97 kg/m^3 (5 lbs/yd^3). Grout with fibers was placed in all cells within the wall. The behavior of Wall 8 was primarily flexural with small contributions from shear and sliding. A picture of Wall 8 after testing is shown in Figure 10. Wall damage from flexure spread throughout the bottom four courses of the north toe and throughout the bottom two courses of the south toe. Compared to behavior observed in the other specimens, the crushing damage was delayed during testing. Shear cracking was minimal, likely due to the additional shear strength provided by the fibers. Load degradation occurred from the gradual crushing of both toe regions and buckling of the extreme flexural reinforcement buckling. Total drift for Wall 8 was 2.76 % at 20% load degradation. The load-displacement hysteresis curves for Wall 8 are shown in Figure 11.

Figure 10 - Wall 8 After Testing

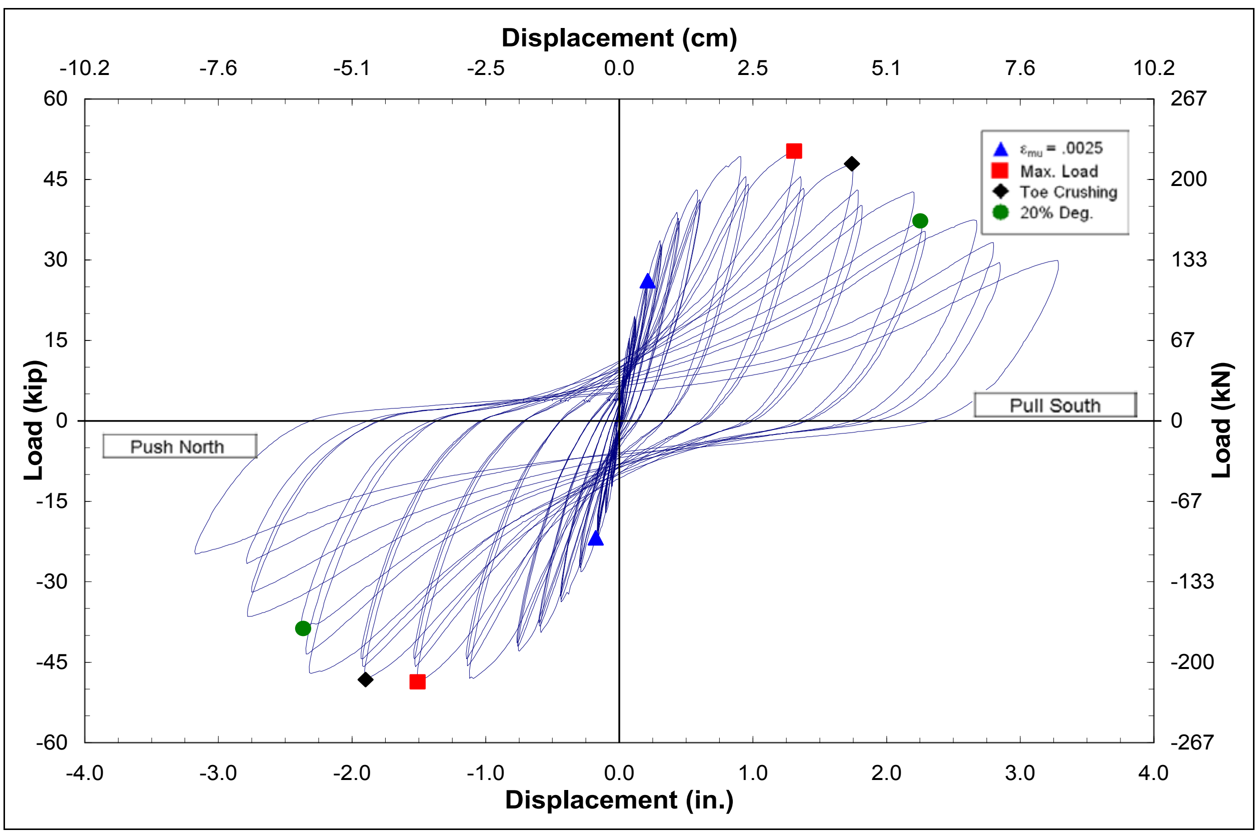

Figure 11 - Wall 8 Load-Displacement Hysteresis Curves

ANALYSIS OF RESULTS

A summary of total drift in each specimen at the three limit states is given in Table 2. Total drift consisted of measured drift due to flexural, shear and sliding deformations. The table shows that all of the investigated confinement methods only moderately improved the drift capacity of the tested shear walls. One confined specimen (Wall 2) actually failed to reach the same drift at 20% load degradation as the similar unconfined wall. Following testing of Wall 2, some evidence of construction irregularities was noted for this wall, including grout voids and slight variations in plate alignment.

Wall 4 achieved the highest total drift at 20% load degradation for the 0.93 aspect ratio walls. This wall showed a significant increase in performance compared to the similar unconfined wall. Shear damage and deformations in Wall 4 were considerably less than the other walls of the same aspect ratio, likely due to the added shear strength gained by the grout fiber reinforcement. For this aspect ratio, the total drifts for the fiber-reinforced walls were higher than those for walls with the other types of confinement reinforcement. A comparison of the load-displacement envelopes for all walls with 0.93 aspect ratio is given in Figure 12.

Table 2 - Summary of Total Wall Drift

Wall	Aspect Ratio	Confinement Reinforcement	Total Drift (%)		
			ε_{mu} =0.0025	Max. Load	20% Deg
1	0.93	none	0.34	1.47	2.26
2	0.93	Plates	0.37	1.11	2.05
3	0.93	Combs	0.41	1.27	2.40
4	0.93	Fiber 1	0.40	1.37	3.07
5	1.5	none	0.39	1.46	2.79
6	1.5	Plates	0.64	1.89	2.94
7	1.5	Combs	0.39	1.26	2.83
8	1.5	Fiber 1	0.50	1.68	2.76
9	1.5	Fiber 2	0.49	1.70	3.22

Wall 9, containing the larger amount of fibers in the grout, achieved the highest drift at 20% load degradation for the 1.5 aspect ratio walls. Wall 8 total drift at 20% load degradation was essentially the same as that obtained for the similar unconfined wall. A comparison of the load-displacement envelopes for all walls with 1.5 aspect ratio is given in Figure 12.

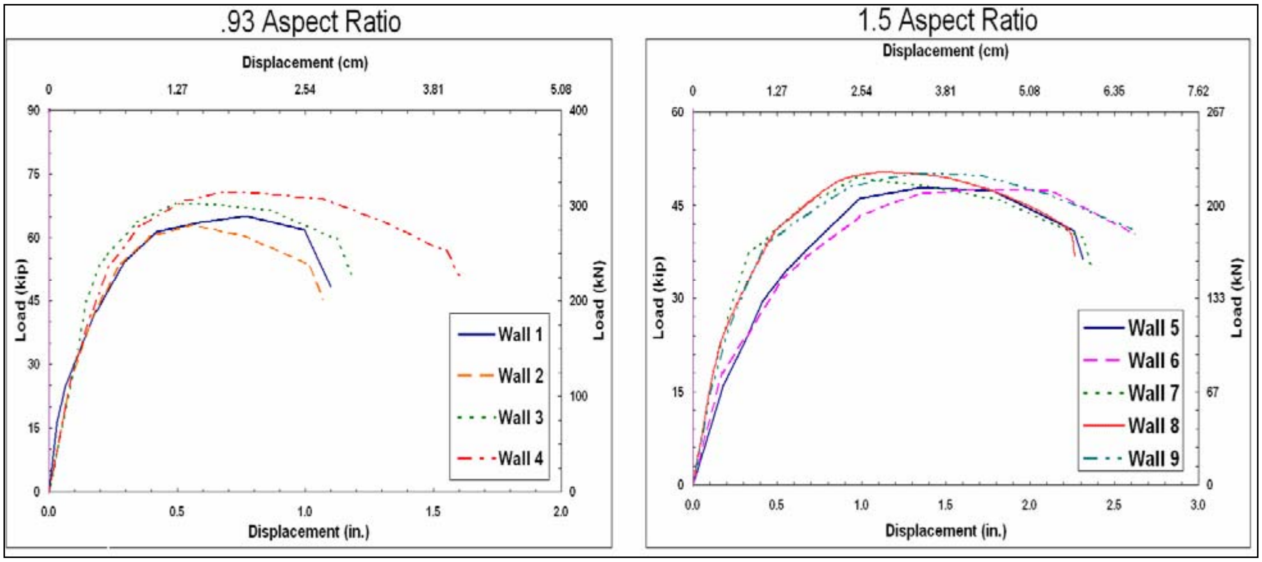

Figure 12. Load-Displacement Envelopes for 0.93 and 1.5 Aspect Ratio Walls

Total energy absorbed up to 20% load degradation, defined as the area contained with the load-displacement hysteresis curves, is given in Table 3. The energy values indicate that all confined walls, with the exception of Wall 2, absorbed more energy then the unconfined similar wall at each aspect ratio at 20% load degradation. Wall 4 absorbed the most energy for the 0.93 aspect ratio walls, and Wall 9 absorbed the most energy for the 1.5 aspect ratio walls.

Table 3 - Summary of Energy Absorbed

Wall	Aspect Ratio	Confinement Reinforcement	Energy Absorbed at 20% Load Deg. kN-m (k-ft)
1	0.93	None	645 (476)
2	0.93	Plates	505 (373)
3	0.93	Combs	700 (516)
4	0.93	Fiber 1	1119 (825)
5	1.5	None	955 (704)
6	1.5	Plates	1094 (807)
7	1.5	Combs	1137 (839)
8	1.5	Fiber 1	1144 (844)
9	1.5	Fiber 2	1413 (1042)

CONCLUSIONS

Results from these wall tests indicate that the addition of seismic comb reinforcement or confinement plate reinforcement in the flexural toe regions at the ends of a wall has a positive effect on the wall's overall performance. However, improvements in performance were relatively modest and, for the case of the plate reinforcement, less than was reported with previous research. The addition of fibers within the grout resulted in higher energy absorption and drift capacity when compared to results obtained for walls with the other confinement techniques. The fibers also appeared to provide additional shear strength to walls resulting in significantly less cracking due to shear. Additional research on walls with other forms of confinement is recommended, including the use of boundary elements at the ends of the walls containing conventional reinforcing ties.

ACKNOWLEDGEMENTS
The authors gratefully acknowledge the financial support provided by the Northwest Concrete Masonry Association, the Masonry Industry Promotion Group of Spokane Washington, the National Concrete Masonry Association, and the W.R. Grace & Co. - Conn. The first author also gratefully acknowledges the support received from the Bob Fraser Masonry Graduate Fellowship at Washington State University.

REFERENCES
1. Masonry Standards Joint Committee, *Building Code Requirements for Masonry Structures (ACI 530-02/ASCE 5-02/TMS 402-02)*, 2002.
2. Ibrahim, K.S and Suter G.T. (1999). "Ductility of Concrete Masonry Shear Walls Subjected to Cyclic Loading" *Proceedings of the Ninth North American Masonry Conference*, The Masonry Society, University of Texas, Austin, Texas.
3. Lieva, G. and Klingner, R.E. (1991). "In-plane Seismic resistance of Two-Story Concrete Masonry Shear Walls with Openings," *TCCMAR Report 3.1(c)-2, Report No. PMFSEL 91-*2, Phil M Ferguson Structural Engineering Laboratory, University of Texas, Austin, Texas.
4. Paulay T. Priestley, M.J.N. (1992). *Seismic Design of Reinforced Concrete and Masonry Buildings*, John Wiley & Sons, Inc., New York.
5. Shing, P.B., Noland, J.L, Klamerus, E., and Spaeh, H. (1989). "Inelastic Behavior of Concrete Masonry Shear Walls," *Journal of Structural Engineering,* ASCE, Vol. 115, No.9.
6. Shing, P.B., E.W Carter and J.L Noland (1993) ."Influence of Confining Steel on Flexural Response of Reinforced Masonry Shear Walls." *The Masonry Society Journal*, Vol. 11, No. 2 February.
7. Priestley, M.J.N. (1981). "Ductility of Confined and Unconfined Concrete Masonry Shear Walls," *The Masonry Society Journal*, Vol. 1, No. 2 July-December.
8. Snook, M., *Effects of Confinement Reinforcement on the Performance of Masonry Shear Walls,* M.S. Thesis, Department of Civil and Environmental Engineering, Washington State University, May 2005.