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SEISMIC RETROFITTING OF EXISTING LOW-RISE MASONRY WALLS BY STEEL STRIPS

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ABSTRACT

Four concrete block masonry walls were subjected to combined constant gravity load and incrementally increasing lateral deformation reversals. They were designed to simulate walls built using provisions in effect decades ago, before the enactment of earthquake-resistant design provisions. Two of these walls were of unreinforced masonry, the other two being partially reinforced. One wall from each pair was retrofitted using a steel strip system, consisting of diagonal and vertical strips attached to the walls using through-thickness bolts. Stiff steel angles and anchor bolts were used to connect the steel strips to the foundation and the top loading beam. These tests show that the steel-strip system significantly increases the in-plane strength and ductility of low-rise unreinforced and partially reinforced masonry walls.

INTRODUCTION

Single-story buildings are very common in North America (schools, shopping centres, hospitals, etc.) and many of them rely on walls to resist both vertical and lateral loads. Because of the high risk of earthquake damage to older masonry shear walls and the potential for a great loss of life, particularly since the earthquake-resistant design requirements only started to appear in Canadian building codes in the late 1950's, research on the seismic behaviour of these non-ductile members is important.

In many instances, these older masonry shear walls may exhibit an insufficient in-plane strength and/or ductility to behave satisfactorily during earthquakes. The new retrofitting alternative proposed here can be used to corrected these deficiencies. This retrofit method consist of adding diagonal and vertical strips of steel on both sides of masonry walls, attached to the walls using through-thickness bolts. This paper reports the results of tests conducted on such unretrofitted and retrofitted walls. The objective of these tests was to experimentally validate this retrofit strategy and to qualitatively and quantitatively assess the adequacy of the proposed retrofit procedure. It is shown that the steel-strip system significantly increases the in-plane strength and ductility of low-rise unreinforced and partially reinforced masonry walls. The development of rocking in the unreinforced wall was also of particular interest.

PRIOR INVESTIGATION

Existing low-rise unreinforced or partially reinforced concrete masonry walls

While many tests of masonry walls designed and reinforced in compliance with various seismic provisions are reported in the literature, only a few cyclic tests have conducted to investigate the in-plane behaviour of existing unreinforced masonry (URM) and partially reinforced concrete masonry (PRM) walls of the type constructed prior to the enactment of seismic provisions. These are reviewed by Taghdi et al. (1998). The aspect ratios, reinforcement, and expected behaviour resulting from the loading conditions considered here have not been studied. In particular, unreinforced masonry walls have not been tested in conditions that may lead to a rocking type of failure in the past, contrary to brick masonry walls.

Retrofitting of low-rise walls

Numerous tests have been conducted around the world to examine the behaviour of columns, beams and slabs strengthened by the addition of steel plates. Generally these tests showed that this method of strengthening is an effective and convenient method to improve member strength and/or ductility. However, only a limited amount of this research is relevant to walls. Moreover, most of that previous research was conducted mainly to improve the flexural behaviour of reinforced concrete elements and few studies were carried to improve shear behaviour of masonry structures. Likewise, very few of these studies were done in the perspective of seismic retrofitting. In most experimental studies reported, the structural elements tested were only subjected to monotonic loading. Finally, while steel plates have been added to retrofit walls in a few existing buildings, there is no evidence of any experimental work done on this subject.

EXPERIMENTAL APPROACH

Wall Specimens

Four large scale concrete masonry walls of rectangular cross sections were constructed and tested in this study. These specimens were labelled as Wall 9, Wall 9R, Wall 10, Wall 10R following the notation started with a series of previously tested low-rise reinforced concrete walls. Letter R in specimen labels indicate retrofitting. These walls were prepared using standard blocks with 200 mm nominal size. Figure 1 shows a typical layout of these masonry walls. All masonry were face-shell beaded using type O mortar which represents the practice of walls built in the 1950's and 1960's. The cells containing reinforcement in the PRM walls were filled with the same mortar. Details of reinforcement are shown in Fig. 2.

Retrofitting Details

Companion wall specimens were upgraded by adding two 220x3.81 mm diagonal steel strips on each side of the walls as shown in Fig. 3. The diagonal steel strips were 9 gauge (3.81 mm) thick. The strip width was chosen to ensure yielding of steel in tension prior to net-section fracture at bolt locations. The specified yield strength of the diagonal strips in both retrofitted walls as well as in the vertical strips of Wall 9R was 227 MPa. The vertical strips of Wall 10R had a specified yield strength of 248 MPa.

Through-wall anchor bolts of A325-3/8 in (9.5mm) and A325-5/8 in (15.9 mm) were used to fasten vertical and diagonal steel strips to the walls, respectively. The spacing between these bolts was chosen to prevent elastic buckling. The steel strips were also connected to the concrete footing and top beam using eight 150x100x16 mm angles of 300 mm length. The steel strips were welded together at the centre of the wall, where they meet, and to the steel angles at the top and bottom. The steel angles were connected to the top and bottom concrete beams using 400 mm long high-strength anchor bolts. In addition to the above diagonal steel strips, two 80x3.81 mm vertical steel strips were added on each side of the walls as boundary elements, as shown in Fig. 3. Steel angles and anchor bolts were used to connect steel strips to the foundation and top loading beam.

Test Setup

Figure 4 illustrates the test setup. It consists of three 1000 kN capacity servo-controlled actuators, two of which are positioned vertically to apply axial compression, and the third one positioned horizontally and supported by a frame to apply horizontal deformation reversals. Identical axial loads were applied to all specimens of this research study. A realistic axial load of 100 kN was chosen to simulate service gravity loads that typically act on walls of some single-story buildings.

Loading History, Instrumentation and Data Acquisition System

Fig. 5 shows the load horizontal displacements history followed for each wall. The specimens were instrumented for displacement, rotation and strain measurements. The displacement measurements were taken with respect to the foundation of the wall to exclude any effect of sliding or uplift of the foundation on the laboratory strong floor. Instrumentation and data acquisition details of all wall specimens are presented elsewhere (Taghdi et al. 1998).

EXPERIMENTAL RESULTS

Behaviour of Wall 9 (Unreinforced Masonry Wall)

This wall behaved in a combination of rocking and sliding, as evidenced by the unsymmetric hysteresis loops of Fig. 6. The sliding developed in one direction, at an ultimate force of 64.5 kN, while the rigid-body rocking (with some small amount of sliding) developed in the other direction, at an ultimate force of -58.5 kN. The wall exhibited relatively large deformations with minor strength decay before failure. Rocking and sliding could only develop as a consequence of cracking along the bed joint. In this test, cracking did extend along the length of the wall, but, the path followed by the crack was unusual. Cracking did not occur at the base, nor at the first bed joint above the base, but in the bed joint above the second course of masonry, as indicated in Fig. 7. Another crack of a shorter length also appeared in the third bed joint above the base. After cracking, drift in both directions increased without any significant increase in lateral loading.

In hindsight, even though calculations prior to testing predicted that rocking would develop at a lateral load of 46 kN, assuming cracking along the base of the wall, cracking above the base joint should not be surprising. Examination of the base joint revealed a fully mortared joint as normally done in practice. Obviously, the tensile resistance of this joint was large enough to force the crack to occur in the above weaker joints, rather than at the base. However, the reason for cracking above the second course of masonry instead of the first is unclear at this time. The non-symmetric behaviour up to drift of 0.8% is explained in detail elsewhere Taghdi et al. (1998). Despite, the low strength of this wall, which indicates a certain strength deficiency, its sliding friction and rocking behaviour noticeably dissipated energy.

Behaviour of Wall 10 (Partially Reinforced Masonry Wall)

Cracks appeared along vertical and horizontal mortar joints, corner to corner of the wall, in a stair-step pattern at about 50% of the wall ultimate strength. The number of diagonal cracks increased with increasing load, and the cracks started to propagate through the blocks. This lead to the formation of diagonal struts, and the wall developed a truss behaviour. At this stage of loading, the wall exhibited its maximum strength. However, because the diagonal struts could not withstand large compressive stresses, the wall rapidly suffered loss of strength and stiffness. Yielding of vertical reinforcement at the base of the wall was not observed prior to the formation of diagonal struts. The rapid loss of strength in diagonal compression struts also precluded the attainment of flexural strength. The vertical cracks between grouted masonry cells and elsewhere in the wall suggest that the behaviour changed into that of an infilled frame with the ungrouted cells of the wall playing the role of the infill, and the grouted cells forming the columns of the frame. This mode of behaviour further contributed to the generation of large compressive forces at wall corners where the grouted masonry cells are located, leading to local buckling of vertical reinforcement and crushing and spalling of masonry and mortar. Horizontal reinforcement did not appear to contribute significantly to the overall behaviour of the wall.

Wall 10 exhibited symmetrical hysteretic force displacement relationship with relatively wide loops. This is shown in Fig. 8. However, it suffered shear failure, with progressive crushing of masonry diagonal struts (see Fig. 9), leading to early strength degradation and relatively low energy dissipation.

Common Behaviour of Retrofitted Walls

In general, the retrofitted walls exhibited superior behaviour when compared with that of unretrofitted walls (see Fig. 11). For Wall 9R, the retrofitted URM wall, cyclic loading of progressively increasing magnitude lead to some uniform cracking of the masonry, followed by yielding of the steel strips, and eventually inelastic-buckling of the strips. This inelastic-buckling led to the crushing of masonry. Better performance was observed in the PRM retrofitted wall, in which crushing was delayed until after the excessive yielding of vertical steel strips and re-bars occurred. Fig. 10 shows Wall 9R and Wall 10R at 1.0% drift.

First, presence of the steel strip system prevented development of the rigid body rotation observed in the unreinforced wall. Second, as the vertical and the diagonal strips yielded, cracks spread more evenly over the entire wall. Crack widths were controlled by the vertical steel strips.

As the applied deformations increased, the steel strips between the bolts were subjected to large tension and compression strains. Yielding of the steel strips in tension produced permanent plastic elongations that could not be fully recovered in compression. Accumulated tensile plastic strains eventually triggered buckling, and a plastic hinge developed midway between the bolts at the buckle locations. The diagonal steel strips yielded shortly after the vertical steel strips, which experienced similar strain characteristics. Because the diagonal strips were wider and had a more favourable anchor bolt configuration, they only exhibited limited buckling.

Strength of Retrofitted Walls

Comparison between the ultimate lateral load resistance of the unretrofitted and retrofitted walls is presented in Table 1. This table also compares the retrofitted walls among each other. The absolute increases in both retrofitted walls are within less than 15% difference among each other (355 kN and 456 kN respectively for Wall 9R and Wall 10R). Note that the increase in lateral load resistance provided by the addition of steel strips is approximately the same. It is believed that the early crushing of the masonry at the ends of Wall 9R and the slight difference in the yield strength of the vertical steel strips prevented it from developing the same increase in resistance attained by the other retrofitted wall.

Comparison of Hysteretic Behaviour

The two hysteretic relationships shown in Fig.11 indicate that the retrofitted URM walls exhibit approximately symmetrical stable hysteretic behaviour with significant increase in ductility, stiffness and dissipation of energy. They also indicate that Wall 9R experienced a lateral load resistance 4.5 times that of Wall 9, up to drifts of 1.0 %. The hysteresis loops of Wall 9R showed noticeable pinching. This pinching is attributed to bolt slippage prior to the development of composite action at low drift levels, and buckling of steel strips at a drift of 0.4%. Crushing of the masonry at both ends of the wall (i.e. the compression zone), contributed to the pinching of the loops. After 1.0% drift, the hysteresis loops showed 25% strength drop with further pinching due to excessive crushing of masonry and global buckling of vertical steel strips. In spite of this, the hysteretic behaviour of Wall 9R, beyond 1.0% drift, was superior to that of Wall 9 in terms of strength, stiffness, ductility and dissipation of energy.

After the retrofitted URM wall lost its end masonry, its hysteretic behaviour resembled that of a tension-only braced steel frame where the buckled compression members contributed little to lateral resistance. The loss of strength of the retrofitted wall during the first cycle at 1.25% drift was also caused by the loss of masonry blocks at the ends. Although, Wall 9R showed a 25% drop in lateral load resistance, its strength remained much higher than that of Wall 9 during these large drift cycles.

The hysteretic lateral load versus top horizontal displacement relationships of the retrofitted and unretrofitted PRM walls are shown in Fig. 11. It is clear that the hysteresis loops of the retrofitted PRM wall demonstrate good strength, stiffness, ductility and overall energy dissipation, compared to those of the unretrofitted PRM wall. When the hysteretic behaviour of Wall 10R is compared with that of Wall 9R, it is observed that Wall 10R exhibit somewhat better lateral load resistance (as discussed earlier), stiffness, ductility and energy dissipation. The presence of rebars and grouted cells in Wall 10R helped delay the global buckling of the steel strips. Note that some welds with poor workmanship fractured during testing (Fig. 11); testing resumed after strengthening of all welds.

Wall 10R showed a less than 7.0% drop in its lateral load resistance up to about 1.0% drift, whereas the lateral load resistance of the unretrofitted wall had fallen by more than 50% of wall maximum lateral load resistance at 0.8% drift. However, once Wall 10R lost the masonry at its ends, the shape of the hysteresis loops became similar to that of Wall 9R. A slight difference was observed because the re-bars were still contributing to the overall hysteretic behaviour in Wall 10R at that point.

CONCLUSIONS

Experiments conducted in this study show that the steel strip system, proposed to retrofit low-rise masonry walls, is most effective to significantly increase their in-plane strength, ductility and energy-dissipation capacity. The details and connections used to ensure continuity between the steel strip system and the foundation and the top beam also enhanced the sliding friction resistance.

Tests of the non-retrofitted walls, beyond providing a comparison basis to assess the behaviour of the retrofitted walls, also made possible some valuable observations. In particular, the stable in-plane rocking mode of failure reported earlier experiments on brick walls by other researchers, was observed to also develop in unreinforced concrete block walls tested here. The tests conducted by the authors also suggest that partially reinforced masonry walls tend to behave in manner similar to infill frames.

REFERENCES

Taghdi, M., Bruneau, M., and Saatcioglu, M. 1998. "Seismic Retrofitting of Existing Low-Rise Masonry and Concrete Walls by Steel Strips", Ottawa Carleton Earthquake Engineering Research Centre report OCEERC 98-21, Ottawa, Ontario.

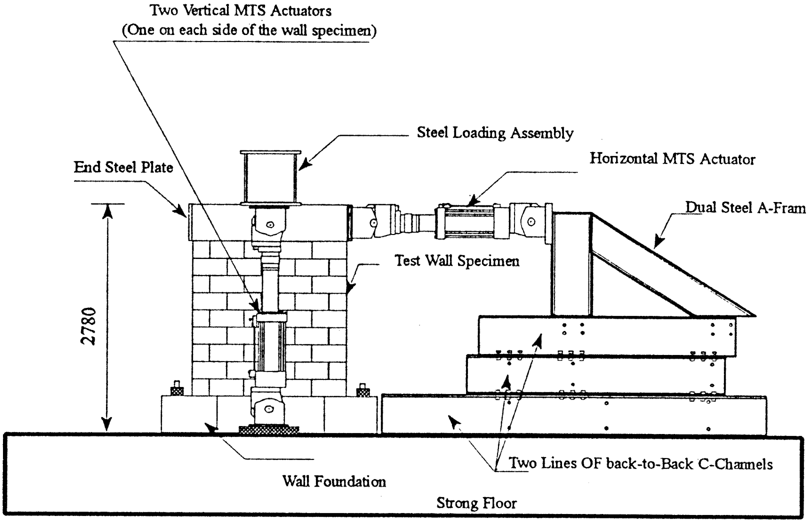


Figure 4 Test setup

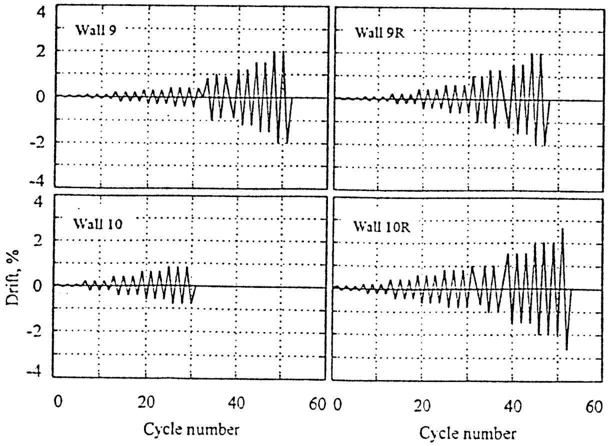
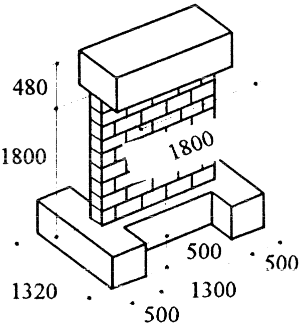


Figure 5 Loading history for each wall

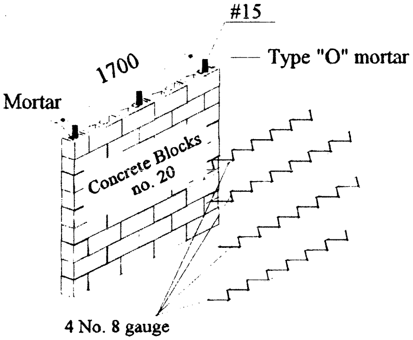
Table 1 Strength increase in retrofitted walls

Wall Label	V_u, kN (Unretrofitted)	V_{ur}, kN (Retrofitted)	ΔV_u, kN (Increase)	$\Delta V_u / V_u$, % (Increase)
9R	64.5	355	290.5	450
10R	120	456	336	280



Masonry prism compressive strength
(ungrouted):12.5 MPa
(grouted):8.1 MPa

Figure 1 Layout of masonry walls



Yield strength of steel re-bar (#15): 400MPa

Figure 2 Reinforcement detail, PRM walls

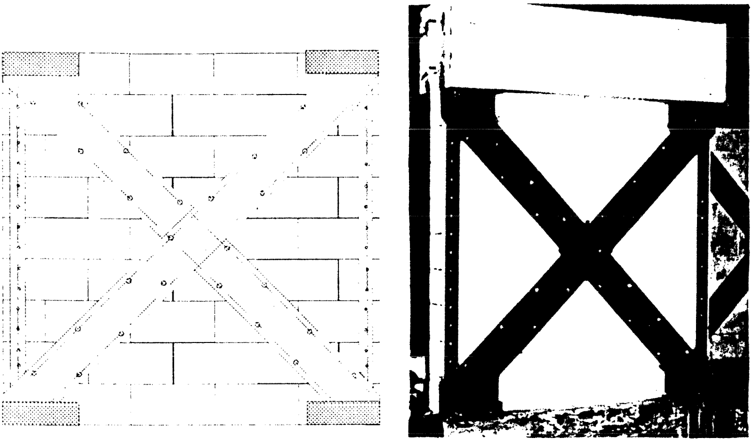


Figure 3 Retrofitting masonry wall

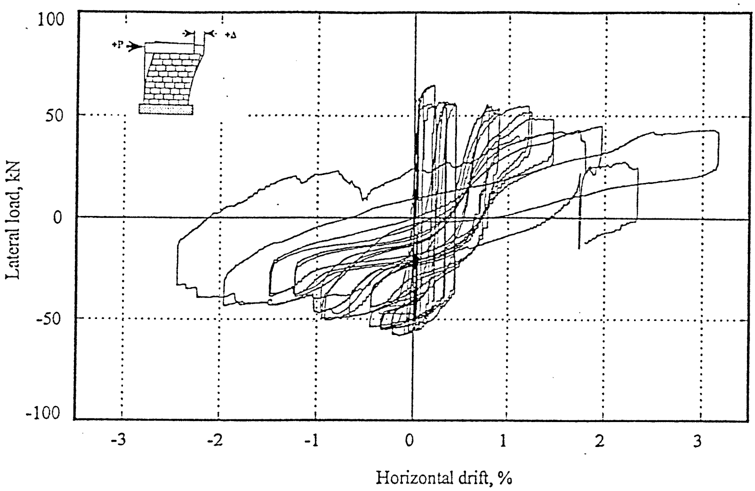
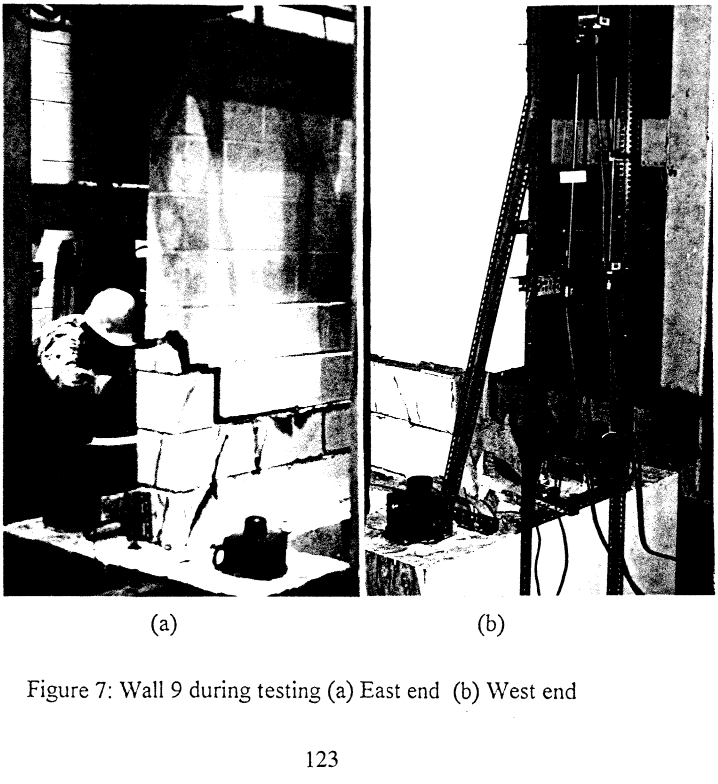


Figure 6: Hysteretic lateral load-displacement of Wall 9



(a)

(b)

Figure 7: Wall 9 during testing (a) East end (b) West end

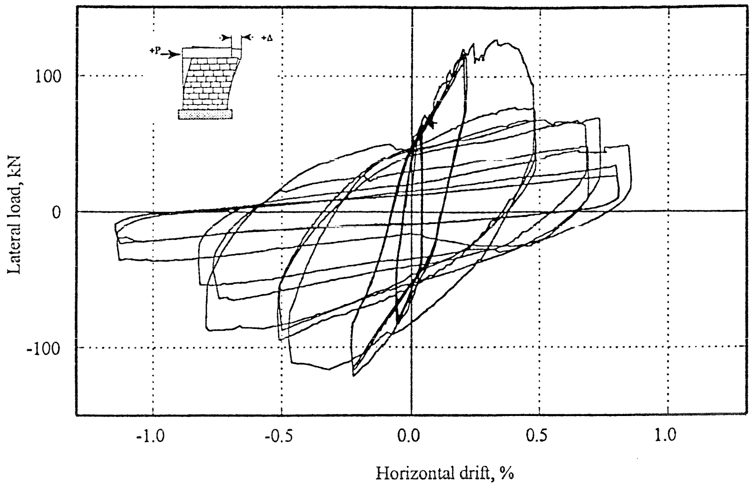


Figure 8: Hysteretic lateral load-displacement of Wall 10

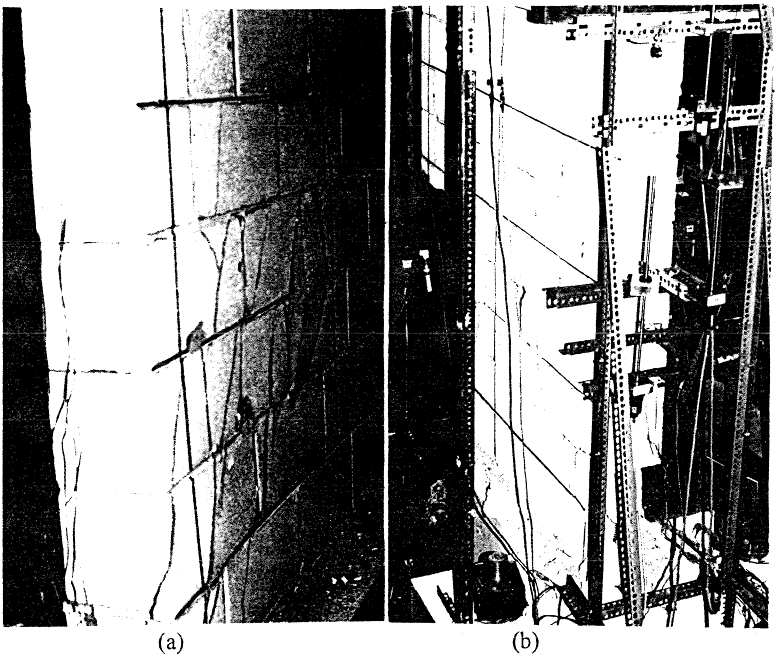
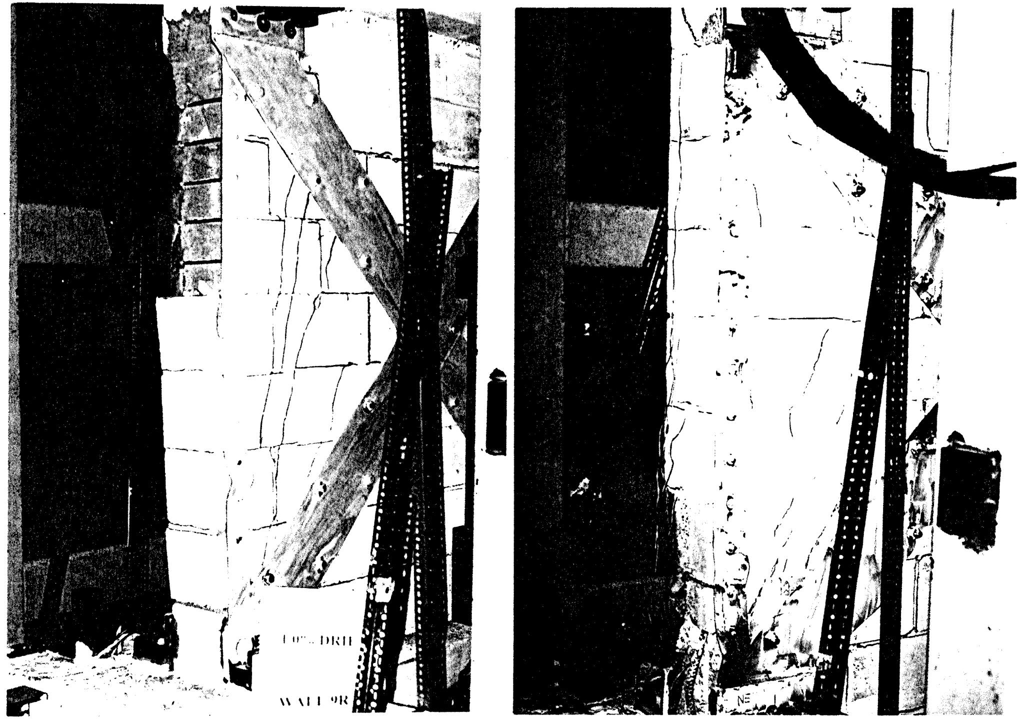

(a)
(b)

Figure 9: Wall 10 during testing (a) East end. (b) West end



Wall 9R

Wall 10R

Figure 10: Retrofitted walls at drift of 1.0%

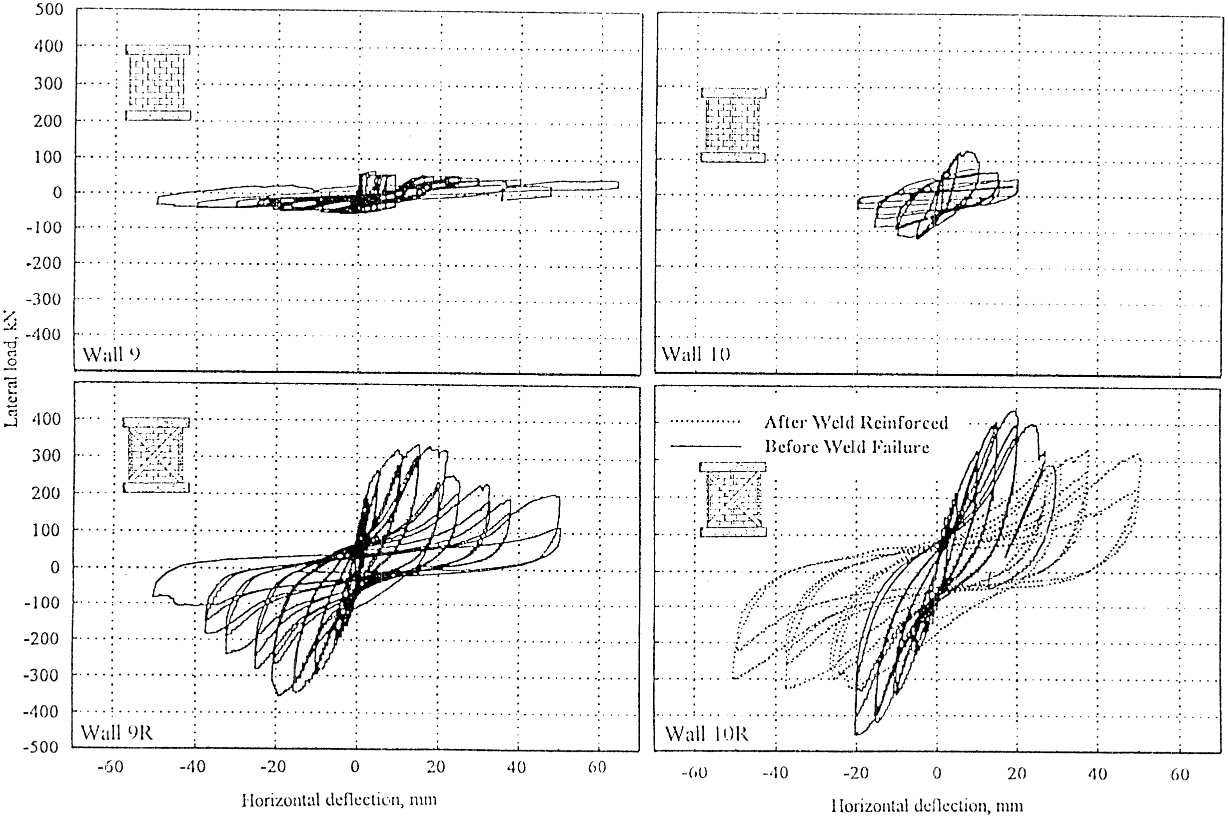


Figure 11 Comparison of hysteretic response of all walls