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Seismic retrofit of non-ductile concrete and masonry walls by steel-strips bracing

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ABSTRACT: Four concrete block masonry and two reinforced concrete walls of large scale 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. The first pair of masonry walls was unreinforced and the second pair was partially reinforced masonry. One wall from each pair was retrofitted using a steel strip system. The steel strip system consists of diagonal and vertical strips attached to the walls using through-thickness bolts. These tests show that the steel-strip system is most effective to significantly increase the in-plane strength and ductility of low-rise unreinforced and partially reinforced masonry walls, and lightly reinforced concrete walls.

1 INTRODUCTION

Many single-story buildings in North America (schools, shopping centers, hospitals, etc.) rely on masonry or concrete walls to resist both vertical and lateral loads. In many instances, these older walls may exhibit an insufficient in-plane strength and/or ductility to behave satisfactorily during earthquakes. These deficiencies can be corrected by one of the following techniques: Increasing the effectiveness of the existing walls using external coatings, filling existing windows or doors, constructing new shear walls or new steel braced frames inside or outside of the building. While the above upgrading techniques are effective, they require a great deal of work, and usually result in an increase in the mass of the structure. This paper proposes a retrofitting alternative that consists of adding diagonal and vertical strips of steel on both sides of walls, attached using through-thickness bolts. This type of strengthening strategy has the following advantages: Retrofitting can be conducted with minimal disruption to occupants and minimal architectural impact, as alterations on the existing walls do not result in loss of rentable floor space or changes to exterior appearance of the building. The minimal increase in wall thickness due to the steel strips also makes this an interesting alternative for existing walls close to mechanical equipment, such as in elevator cores.

This paper reports the results of tests conducted on such unretrofitted and retrofitted walls. The objective of these tests was to quantify the improvement in seismic resistance of non-ductile low-rise masonry and concrete shear walls provided by the steel-strips bracing retrofitting technique, and determine whether the resulting cyclic ultimate behavior is adequate. It is shown that this retrofitting system significantly increases the in-plane strength and ductility of low-rise masonry (unreinforced and partially reinforced) and reinforced concrete walls.

2 PRIOR INVESTIGATION

Numerous tests have been conducted around the world to examine the behavior 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 behavior of reinforced concrete elements and few studies were carried to improve shear behavior 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.

3 EXPERIMENTAL APPROACH

3.1 *Wall specimens*

Six large scale walls with rectangular cross sections were constructed and tested in this study. These specimens were labeled as Wall 9, Wall 9R, Wall 10, Wall 10R, Wall 11 and Wall 11R following the notation for 8 previously tested low-rise walls. The first and the second pairs of wall specimens were made of concrete masonry and the third pair of wall specimens were made of reinforced concrete. Letter R in specimen labels indicate retrofitting. Fig. 1 shows a typical layout of these walls. Four concrete block wall specimens were prepared using standard blocks with 200 mm nominal size. All masonry were face-shell beaded using type O mortar which represents the practice for walls built in the 1950's and 1960's. The masonry compressive strengths of ungrouted and grouted standard prisms were 12.5 MPa and 8.1 MPa respectively. Two identical walls with 100 mm thickness were built using relatively low strength (25 MPa) concrete, representing the construction practice of 1950's and 1960's. Details of reinforcement for PRM and RC walls are shown in Fig. 2.

3.2 *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 center 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.

3.3 *Test setup*

Fig. 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.

3.4 *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).

4 EXPERIMENTAL RESULTS

4.1 *Behavior 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. 12. 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. 6. 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. Despite, the low strength of this wall, which indicates a certain strength deficiency, its sliding friction and rocking behavior noticeably dissipated energy.

4.2 *Behavior of Wall 10 (partially reinforced masonry wall)*

Wall 10 exhibited symmetrical hysteretic force displacement relationship with relatively wide loops. This is shown in Fig. 12. However, it suffered shear failure, with progressive crushing of masonry diagonal struts (see Fig. 7), leading to early strength degradation and relatively low energy dissipation.

Vertical cracks that developed between grouted masonry cells and elsewhere in the wall suggest that the behavior 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 behavior 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 behavior of the wall.

4.3 *Behavior of Wall 11 (reinforced concrete wall)*

Wall 11 experienced symmetrical and stable hysteretic behavior, as shown by its force-displacement relationship in Fig. 13. These stable hysteresis loops also clearly show that Wall 11 experienced rocking behavior in later stages of testing, making it possible for this wall to maintain its strength up to 2.5 % drift.

Because this wall progressively developed a rigid-body rotation behavior, with reinforcing bars controlling the wall rotation, no inelasticity was introduced in the main body of the wall panel above the base (see Fig. 8). The wall ends severely crushed and the vertical re-bars elastically buckled. While the strains in the end bars were not large, the re-bars in the middle of the wall experienced extensive yielding and developed strain hardening at higher drifts. The wall did not experience any strength degradation until this middle reinforcement ruptured. At that stage, the wall was left to rely on pure rocking behavior to resist the lateral loads, much like the unreinforced masonry wall (Wall 9). Although, the performance of this wall can be considered to be satisfactory, in terms of ductility and energy dissipation, its lateral load resistance could be inadequate to resist earthquakes and may still require retrofit.

4.4 *Common behavior of retrofitted walls*

In general, all retrofitted wall specimens exhibited superior behavior when compared with that of unretrofitted wall specimens. 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 and R/C retrofitted walls, in which crushing was delayed until after the excessive yielding of vertical steel strips and re-bars occurred.

Generally, presence of the steel strip system prevented development of the rigid body rotation observed in the unreinforced wall. Furthermore, 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 deformation cycles were 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 a plastic hinge midway between the bolts during compression. 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 favorable anchor bolt configuration, they only exhibited limited buckling.

4.5 *Strength of retrofitted walls*

The absolute increases in all the retrofitted walls are within less than 15% difference among each other (355 kN, 456 kN and 499 kN respectively for Wall 9R, Wall 10R and Wall 11R). Note that the difference in increase in load resistance of Wall 10R and Wall 11R is only 2.4%. This implies 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 prevented it from developing the same increase in resistance attained by the other retrofitted walls.

4.6 *Comparison of hysteretic behavior*

Hysteretic relationships shown in Fig. 12 indicate that the retrofitted URM walls exhibit approximately symmetrical stable hysteretic behavior 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 behavior 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 behavior 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 also shown in Fig. 12. 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 behavior of Wall 10R is compared with that of Wall 9R, it is observed that Wall 10R exhibit somewhat better lateral load resistance, stiffness, ductility and energy dissipation. The presence of re-bars 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. 12); 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 behavior in Wall 10R at that point.

The hysteretic behavior of Wall 11R was superior to that of any other walls tested in the current investigation. The hysteresis loops, shown in Fig. 13, indicate high lateral load resistance, stiffness, ductility, and energy dispassion with no strength decay up to 2.0% lateral drift. The lateral load resistance dropped by 25% at a drift of 3.0%. However, the shape of these hysteresis loops still exhibited a lot of pinching, similar in shape to what is often observed in tension-only braced steel frames.

4.7 *Wall 10R and Wall 11R*

The presence of reinforcement bars in walls 10R and 11R increased their redundancy over Wall 9R, as described elsewhere Taghdi et al. (1998). The anchor bolts used to attach the vertical steel strips to the wall were also helpful in enhancing cyclic inelastic performance of walls as these bolts provided lateral support to re-bars against premature buckling. The anchor bolts used in Wall 11R also delayed premature buckling at higher drift levels by confining the concrete surrounding the end re-bars.

The torsional behavior observed in Wall 10R after the fracture of the weld, described earlier, was useful in demonstrating why steel strips must be on both sides of the wall. The symmetric arrangement helps avoid eccentric loading that may cause twisting of the retrofitted walls. It also provides additional redundancy to retrofitted walls and superior support against out-of-plane failures of walls, although not tested in this investigation.

4.8 *Behavior of steel strips*

The vertical steel strips used in retrofitted walls showed similar behavior. However, wall type played a major roll in delaying buckling of vertical strips. Wall 9R vertical strips experienced some mild local buckling during earlier drift cycles, as shown in Fig. 9. However, because the lateral support provided by the wall was lost after the crushing of masonry blocks at the ends, the vertical strips buckled in a more global way, as shown in Fig 10. As a result, Wall 9R exhibited strength decay as early as 0.8% drift. A better lateral support to vertical steel strips was provided in Wall 10R by the reinforced cells at the ends. Local buckling, shown in Fig. 11, dominated over global buckling, shown in Fig. 10. Consequently the wall kept its integrity and was able to sustain higher levels of drift without a significant strength decay. Fig. 14 shows Wall 11R at 1.0% drift. The behavior of vertical strips in Wall 11R was similar to that of Wall 10R because of the strong lateral support provided by concrete. Note that although local buckling prevented the vertical steel strip from sustaining its plastic capacity at large deformations, this local buckling has a lesser impact on the overall wall behavior than global buckling of the steel strips.

The above illustrates the importance of providing adequate lateral support to prevent global buckling of vertical steel strips. For that reason, even though Wall 9R showed a satisfactory behavior up to 1.5% drift, grouting of the end cells may delay their crushing and help attain higher drifts without any strength deterioration. However, this remains to be verified experimentally.

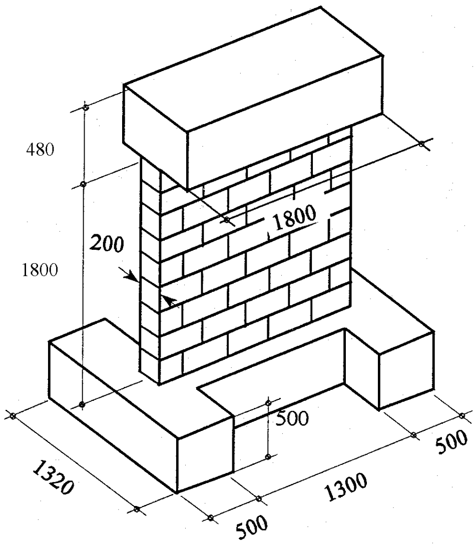


Figure 1a. Layout of masonry walls

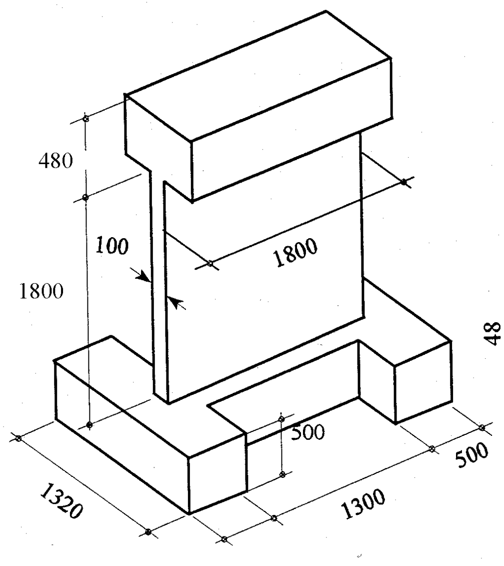


Figure 1b. Layout of concrete walls

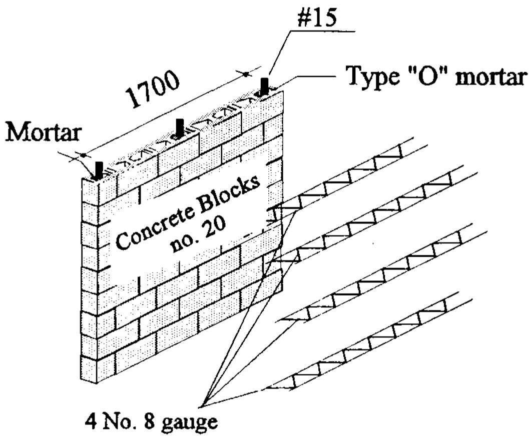


Figure 2a. Details of reinforcement for PRM walls

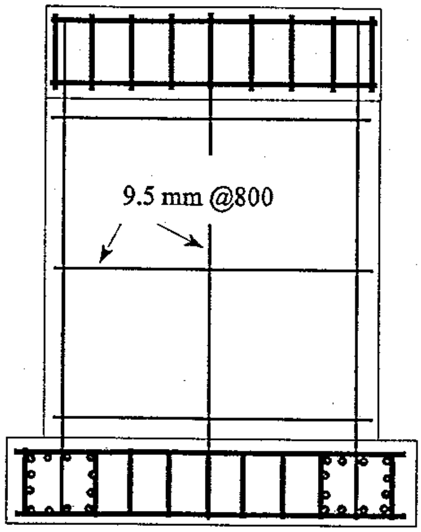
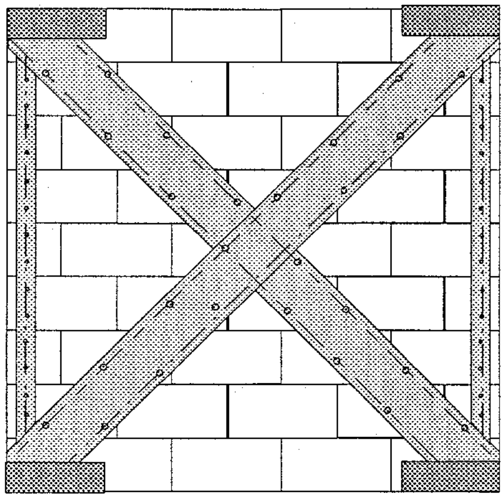


Figure 2b. Details of reinforcement for RC walls



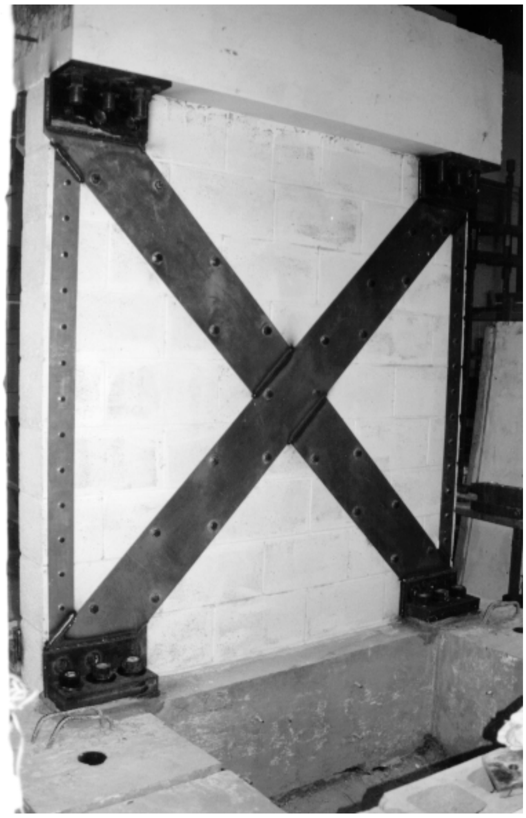


Figure 3a. Layout of Retrofitted wall

Figure 3b. Retrofitted wall before testing

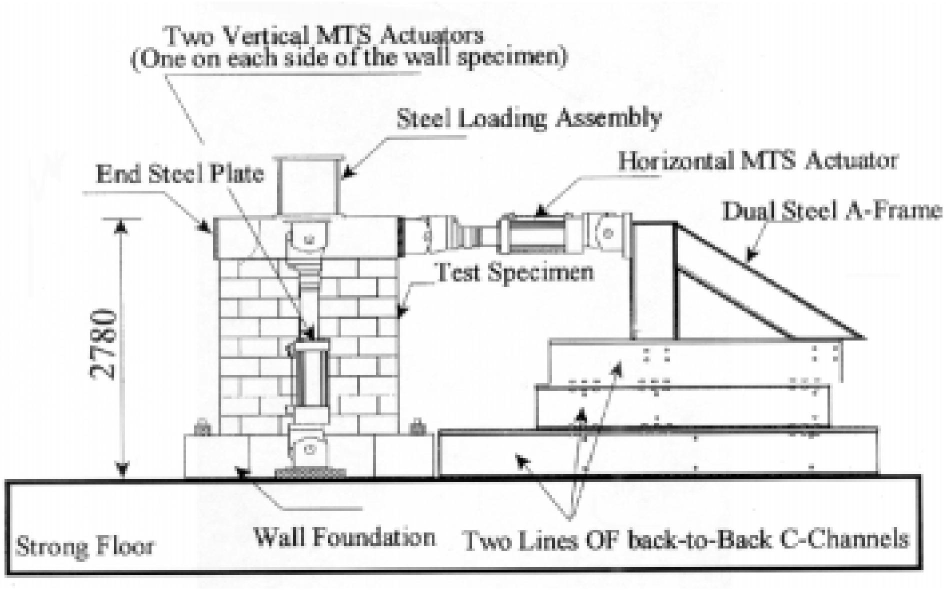


Figure 4. Test setup

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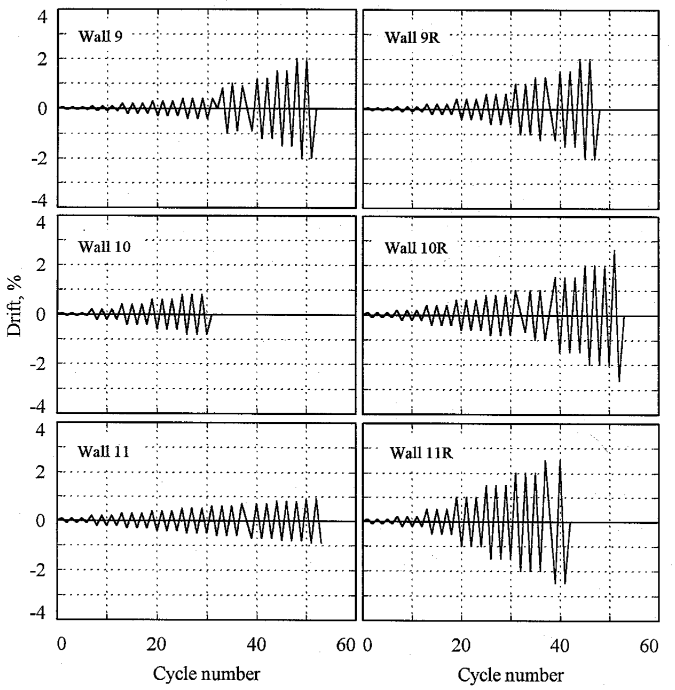

Figure 5. Load horizontal displacement history for all walls

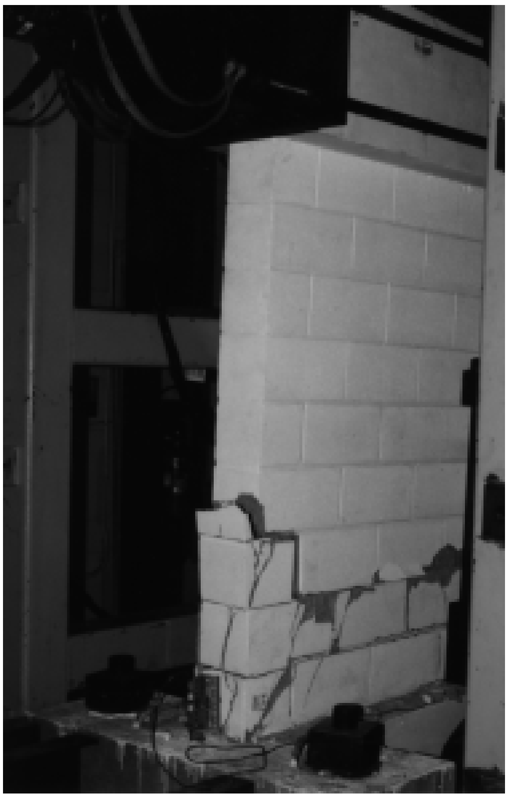

Figure 6. Wall 9 during testing

Figure 7. Wall 10: at 0.8% drift, diagonal crushing of masonry

Figure 8. Wall 11: at 2.0% drift, no inelasticity in the main body of the wall panel

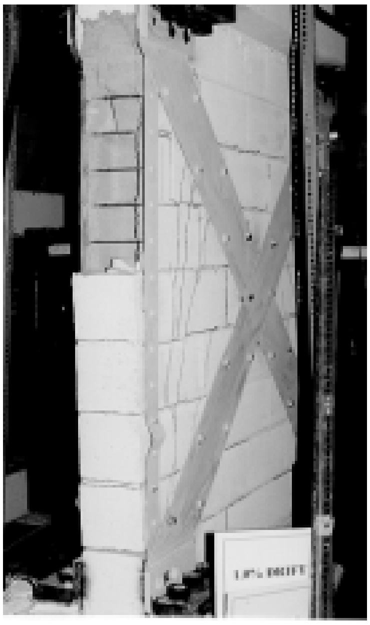

Fig. 9. Wall 9R: at 1.0% drift, local buckling of vertical steel strips

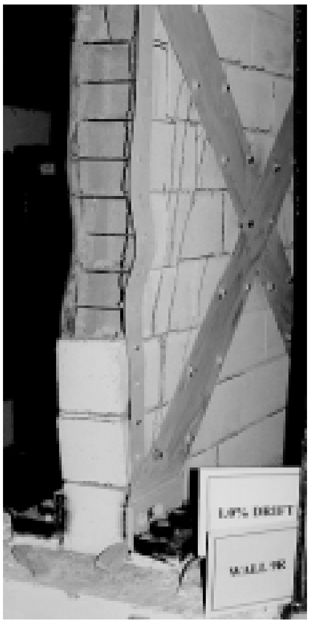

Fig. 10. Wall 9R: at the end of 1.0% drift, global buckling of vertical steel strips

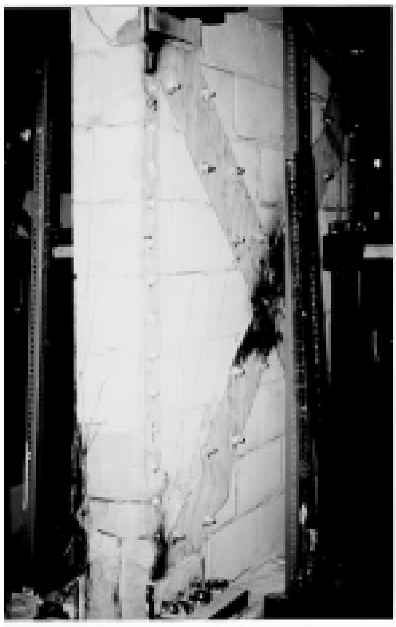

Fig.11. Wall 10R: at 1.5% drift, local buckling of vertical and diagonal steel strips as well as vertical re-bar

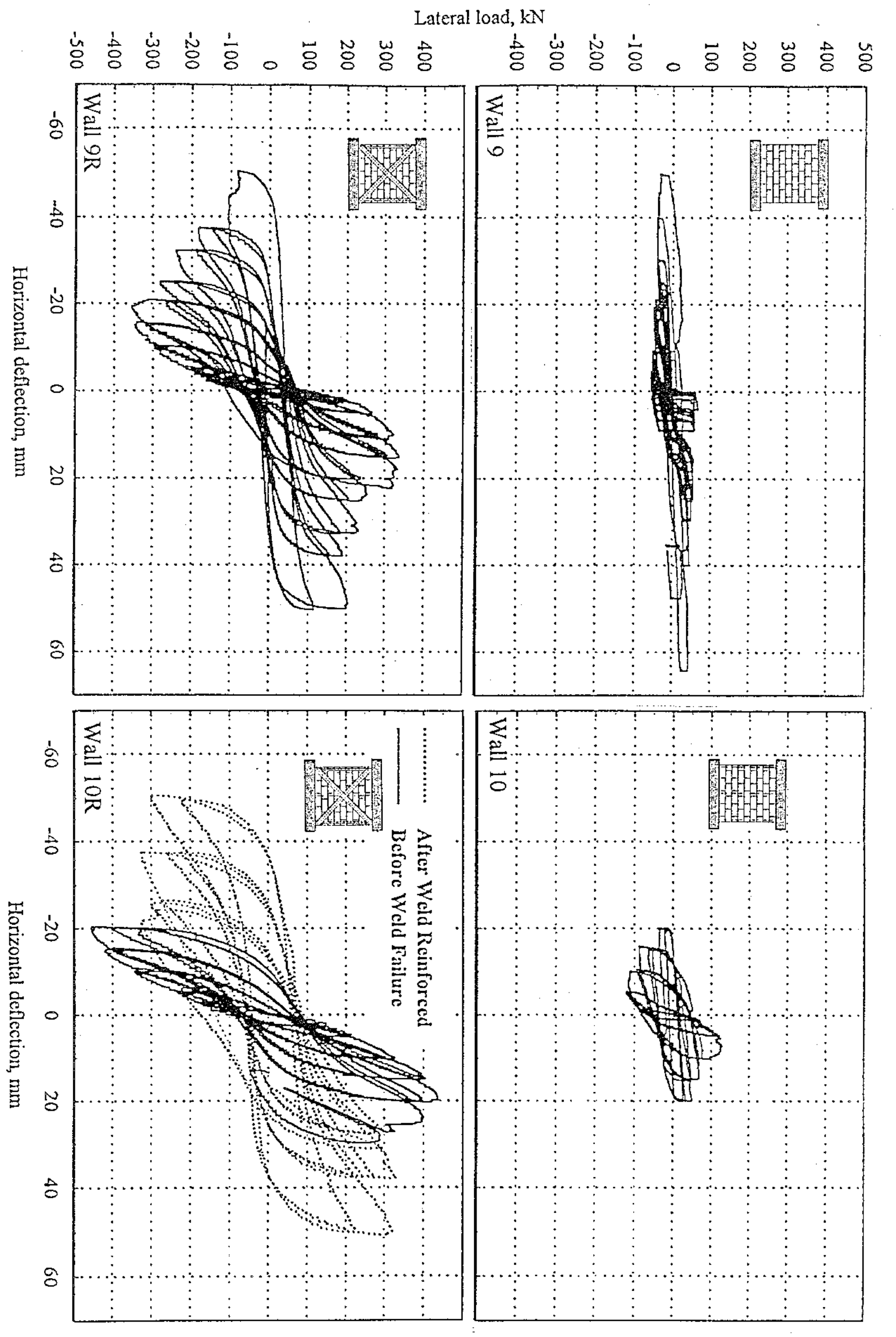

Figure 12. Comparison of hysteretic response of all masonry walls

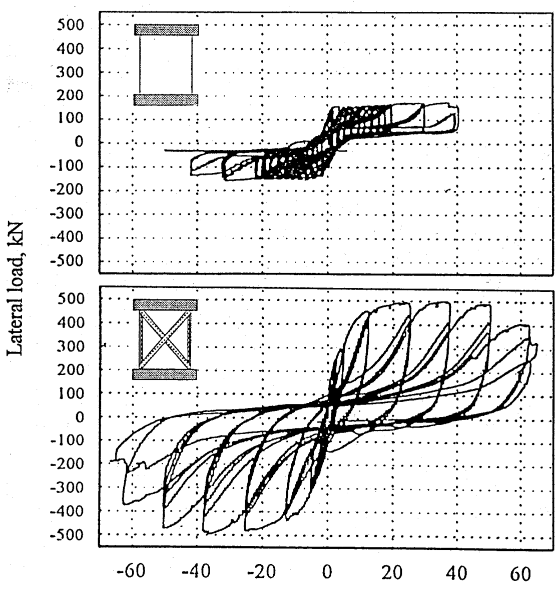

Figure 13. Comparison of hysteretic response of Unretrofitted concrete wall (top) and retrofitted concrete wall (bottom).

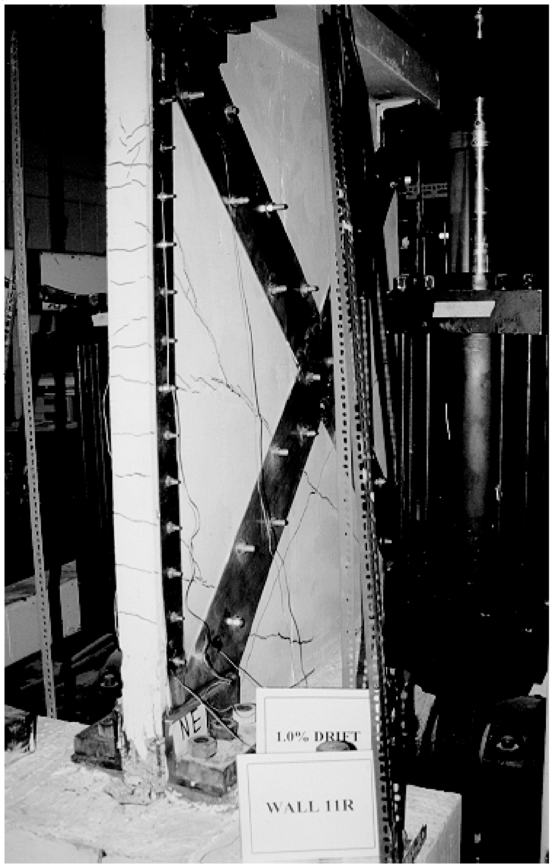

Figure 14. Wall 11R: at 1.0% drift.

5 CONCLUSIONS

Experiments conducted in this study show that the steel strip system, proposed to retrofit low-rise masonry and concrete walls, is most effective to significantly increase the in-plane strength, ductility and energy-dissipation capacity of these existing low-rise walls. For the particular specimens considered, addition of steel strips increased the lateral load resistance of each wall by approximately 300 kN. 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.

REFERENCE

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