Evaluation of the Seismic Performance of Brick Walls Retrofitted and Repaired by Expansive Epoxy Injection

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Epoxy materials have been used in the past in the preservation of old masonry systems including brick masonry buildings. For the most part, the traditional technique consists of applying epoxy to seal the porosity of the masonry units or to make the masonry more watertight and therefore more resistant to the effects of the environment. To a lesser extent epoxy has been used to restore the strength of masonry systems. In the project reported herein, a new type of epoxy formulation was tested to determine its potential for structural retrofitting and strengthening of existing brick masonry buildings.

The expansive epoxy is a monolithic complex composite. This composite material, when injected into a void area within the walls of buildings, as shown in Figure 1, has the potential to increase the ductility, damping and strength of these walls.

This report presents the results from the laboratory testing of four brick walls in the structural lab of California State University, Fresno. The walls are fabricated using two layers of aged brick and masonry mortar to simulate the conditions existing in many old brick buildings. The size of walls is 10 ft by 10 ft by 10 inches (3.05 m x 3.05 m 254 mm) thickness with 2 inches (50.8 mm) void in between the two layers of brick. Two walls were loaded directly as plain, un-reinforced brick walls and results were obtained. The other two walls, identical to the first ones, were first injected with the expansive epoxy material into the 2 inch (50.8 mm) void, allowed to cure for seven days and then tested under similar support and loading conditions. After the plain walls were loaded beyond their full cracked state, they were also repaired with the expansive epoxy material and re-tested. The results of the tests demonstrate the feasibility and potential of the technique to restore the type of structures and demonstrate the potential for earthquake retrofitting or strengthening.

HISTORICAL BACKGROUND

A considerable number of un-reinforced brick masonry buildings were built throughout the world in the past and now they constitute an irreplaceable historical asset for civilization. These structures were built following construction techniques different from the current ones and were built to minimal or no construction codes. In the west coast of the United States, a good number of these types of buildings were built during the 18th and 19th centuries following the techniques of the time. Coincidentally, the great majority of these structures are on, or near zones of high seismic activity. That many have survived the numerous earthquakes since their construction is a proof of the quality of workmanship with which they were built. However, so many of these historical buildings are of incalculable aesthetic and historical value and it is not appropriate to leave their preservation dependent on their good luck. Various strengthening and retrofitting techniques have been used through the years, including more recently the use of high strength fiber composite materials [*Hamid et al.* (1993), *Bhende and Ovadia* (1994), *Keheo* (1996), *Ehsani and Saadatmsnesh* (1996), *Velazquez-Dimas et al.* (1999)]. Also, epoxy injection and consolidation started to be used in the 1960's in Poland [*Domaslowsy and Strzelczyk* (1986)] and 1970's in the United States [*Gauri and Madiraju* (1978)]. Although the main focus of epoxy repair or conservation has been geared towards the sealing of the porosity or cracks in stone, brick, and mortar materials, to protect them against the weather effects, there has always been a desire to provide also structural enhancement with the epoxy.

In 1971, the expansive epoxy technology was developed specifically for the rehabilitation of the Los Angeles City Hall building, which was severely damaged in the 1971 San Fernando earthquake. The original expansive epoxy product would be chemically irreproducible after 1976 due to the use of Freon as the foaming agent. This technology is now chemically reformulated by using CO_2 instead of Freon, which is a

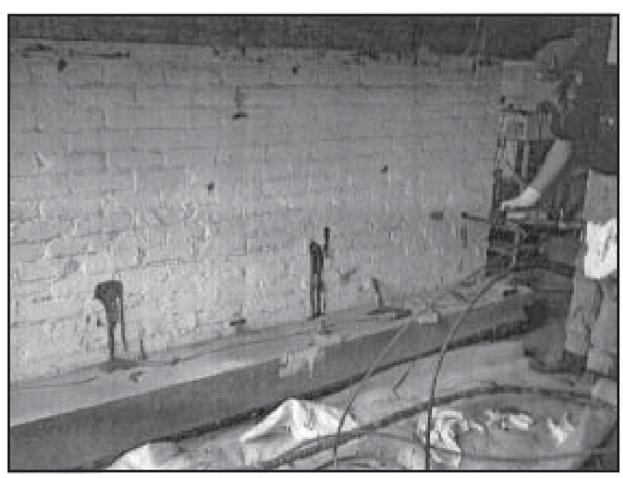

Figure 1—Pumping of Expansive Epoxy in the Wall

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non-regulated method of chemical expansion. The Los Angeles City Hall rehabilitation report [*Galletti*, (1972)] outlines extensively the application, building condition, and other methods considered. The expansive epoxy method, when compared to other types of restoration methods including base isolation technology, is both cost effective and time tested. The expansive epoxy has also been utilized in three applications other than the Los Angeles City Hall, which are Ventura City Hall, Alameda City Hall, and Mayflower Presbyterian Church in Pacific Grove, California in 1999. The Mayflower Presbyterian Church application was unique. The church is a single load-bearing wall structure. The approximately 1-2 inch (25.4 - 50 .8 mm) of void area to be filled with the expansive epoxy was created many years ago with the use of common plywood and drywall. This application, although altering the interior face of the wall, shows that seismic upgrading can be accomplished with the use of a manufactured confinement area between the actual wall and the added plywood. The application was accepted and now church services have resumed. Void areas may vary and may also be rubble filled. Rubble filled walls may pose the need for extra attention. The Los Angeles City Hall was a rubble-fill-wall application.

INJECTION PROCEDURE

One type of construction of brick walls of historical buildings consists of two layers of brick with 2-inch gap in between to provide insulation. To retrofit this kind of construction, holes are drilled in the outside bricklayer to reach to the 2-inch (50.8 mm) gap to pump the expansive epoxy in a liquid form. The holes are drilled in a diamond shape distribution with 2 feet (610 mm) spacing on center. Expansive epoxy is pumped at about 70°F (21°C) temperature in the lowest row of holes till it leaks out from neighbor holes showing that this particular section of the wall is full of epoxy as shown in Figure 1. Then after a few minutes, the expansive epoxy starts to expand and hardens to fill the two-inch gap in the entire wall. The expansion ratio, which is the ratio of the epoxy volume after and before expansion, varies depending on thermal characteristics and confinement of the surrounding. In this test, the expansion ratio for all walls is estimated to be 1:3.8. The necessary time for the expansive epoxy to cure is seven days. The method can also be implemented for brick walls with single layer of brick. The approximately 2 inches (50.8 mm) of void area can be created by the use of common plywood and drywall.

The brick used to build the four walls tested in the project reported here was obtained from the 1900 vintage era. It came from demolished historical buildings. Each wall was built using two layers of brick with 2 inches (50.8 mm) of void area in between. It should be noted that in actual historical buildings, the mortar has deteriorated to the level that it can be easily removed by a pocketknife. In addition, due to the lack of quality control at the time of construction of these buildings, the variability of the strength of both the brick and the mortar is high.

TEST SET-UP

Four walls were built in the structural testing laboratory at California State University, Fresno. The main goal in this procedure is to test the plain walls without any expansive epoxy and establish this as a reference line against which repaired and retrofitted walls are compared. This has clearly pointed out the improved mechanical properties due to the use of expansive epoxy. Two walls were subjected to out-of-plane loading and the other two were subjected to in-plane horizontal shear load, as shown in Figures 2 and 3, respectively. In the out-of-plane loaded walls, the axial loading is limited to the weight of the concrete header beam on the top, the weight of the two steel beams in the middle and the additional weight due to the weight of the actuator. This adds 3,500 lb (15.6 kN) of additional weight to the wall. This represents the worst-case scenario because increasing the axial

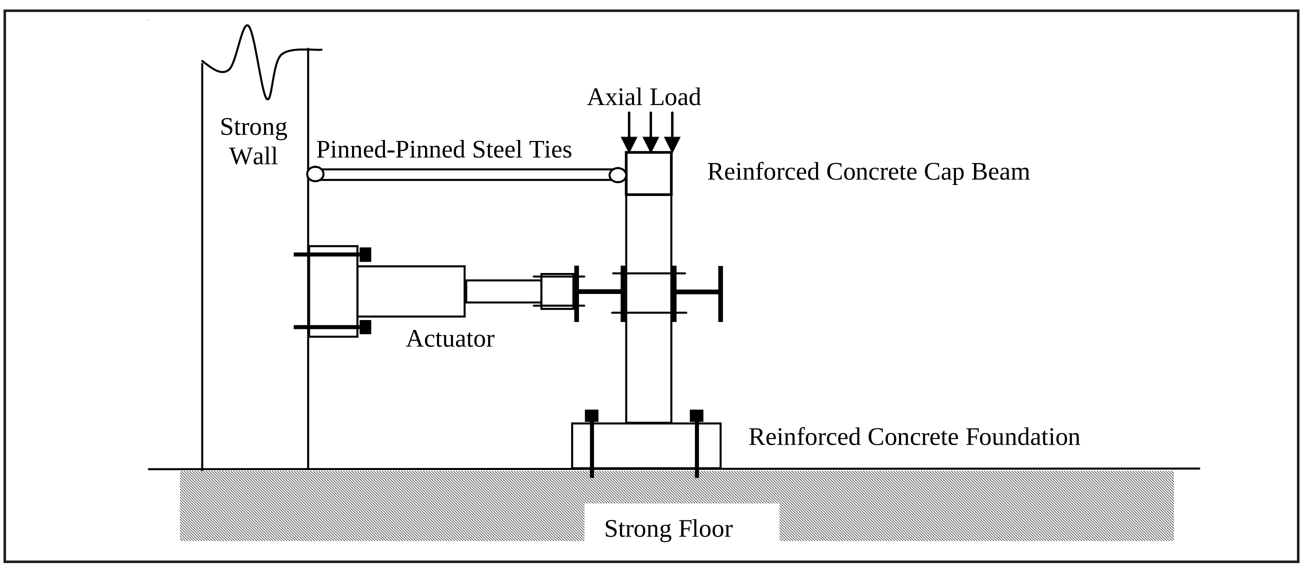

Figure 2—Out-of-Plane Bending Test Set-up

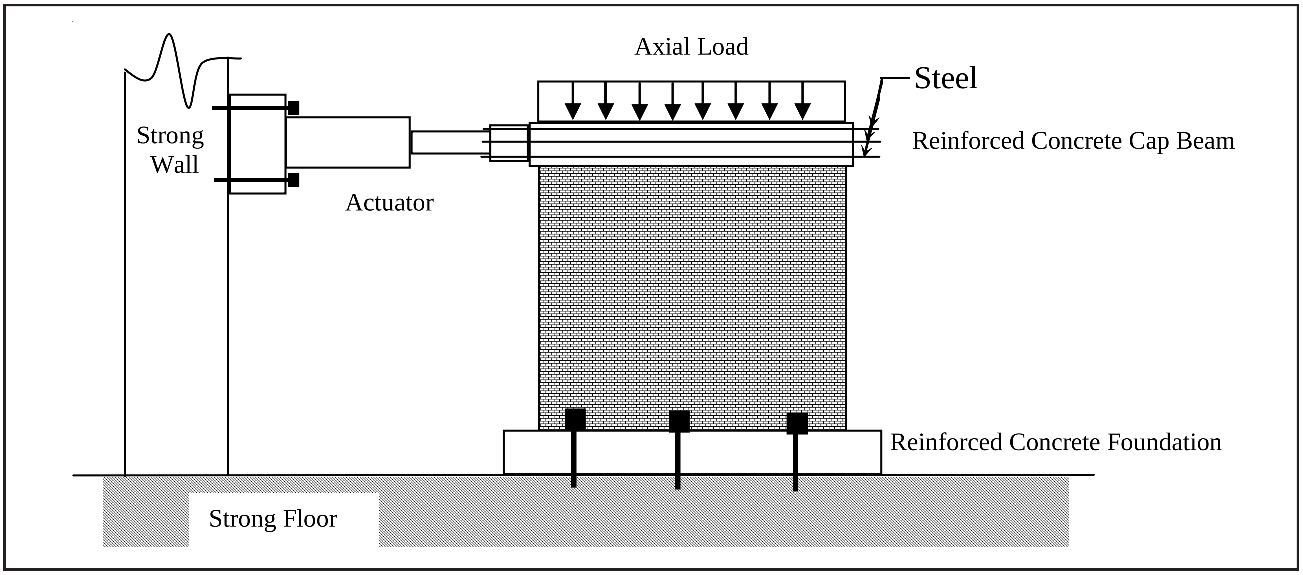

Figure 3—In-Plane Shear Test Set-up

load to certain extent is expected to increase the flexural capacity of the wall. This is attributed to the fact that the wall is much stronger in compression than in tension. The axial load acts like a pre-stressing load where it increases the initial axial compression stress on the wall causing the tension crack to develop at a much higher load.

In the case of in-plane loaded walls, the axial load in the test of the third wall was made of the weight of the concrete header beam and the weight of the actuator, which is 1,900 lb (8.5 kN). Such axial load represents the worst-case scenario where a brick wall is supporting one light roof. In the test of the fourth wall, the axial load was increased by adding two concrete blocks carried by steel beams from the bottom. The axial load in this case adds up to 11,000 lb (48.9 kN). The objective of this is to explore the change in wall mechanical properties in case of the wall supporting heavier roofs or multiple floors.

RESULTS OF TESTED WALLS IN THE OUT-OF-PLANE LOADING CONDITION

Test of the First Wall without Expansive Epoxy

The walls were subjected to a cyclic load under displacement-controlled conditions with gradual increase in the displacement. The initial cycle consisted of ±0.01(0.25 mm) inch displacement followed by increments of ±0.01 inch (0.25 mm) each cycle and at a frequency of 0.1 cycles per second.

The load deflection curve Figure 4 shows typical hysteresis loops with expected stiffness degradation. The ultimate capacity of the plain brick wall was 3,000 lbs (13.3 kN). The wall started to crack at about 2,000 lbs (8.9 kN)

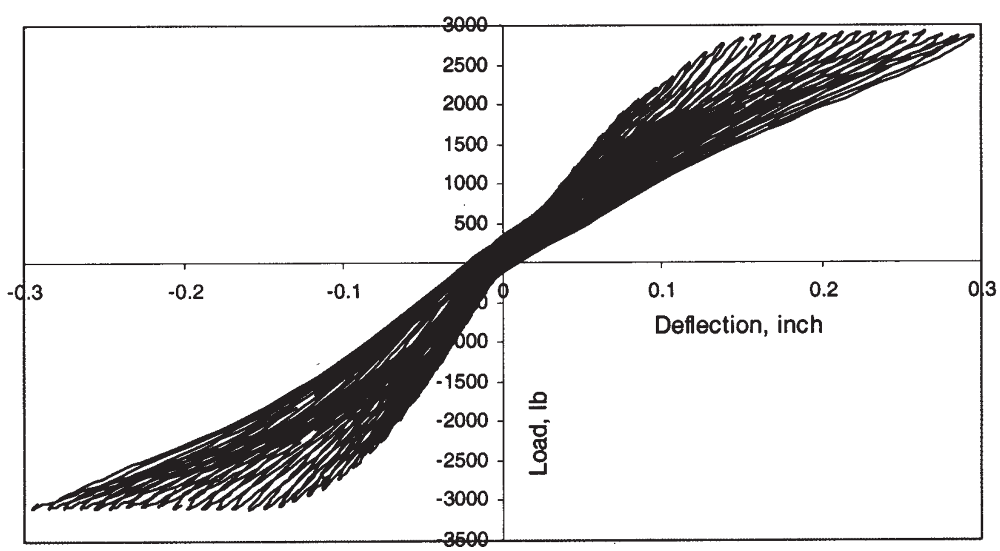

Figure 4—Load-Deflection Curve for Out-of-Plane Loading of Un-Injected Wall

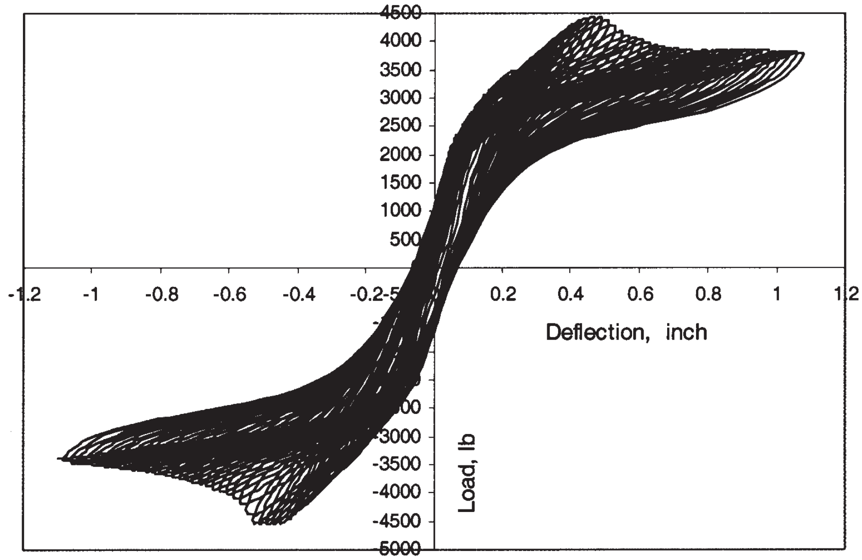

Figure 5—Load-Deflection Curve of the Out-of-Plane Repaired Wall – Phase I: Up to 1 in. (25 mm) Deflection (1 in. = 25.4 mm, 1 lb = 4.448 N)

and 0.1-inch (0.25 mm) deflection. The wall became fully cracked at 0.15 inch (3.81 mm) deflection. Increasing the displacement more than 0.15 (3.81 mm) inch caused the wall to deform in a rocking mode where the cracks will simply open and close without providing any resistance. As the deflection started to approach a value of 0.3 inch (7.62 mm), the wall showed signs of collapsing. The test was then stopped to prevent the wall from going into catastrophic failure where the bottom of the brick wall would slide out of the plane of the wall and the entire wall could then collapse. It was intended from the beginning to just crack the wall, to repair it, and then test it again. Two horizontal cracks were observed: one right above the horizontal steel beam connected to the actuator and the other at the bottom of the wall near the foundation. These two cracks separate the wall into three separate pieces; one below the bottom crack, the second between the bottom and middle cracks and the third above the middle crack. The wall could have slid out of its plane along these two cracks causing a catastrophic brittle failure.

Test of the First Wall After Being Repaired with Expansive Epoxy

The plain wall that was broken in the previous test was then repaired by expansive epoxy injection to fill the two-inch gap in the entire wall as described in section 3. It was then tested under cyclic displacement control condition. The period of the cycles was 10 seconds. The amplitude of the first cycle was 0.02 inches (0.508 mm) and then was increased by 0.02 inch (0.508 mm) per cycle. This test was done in two phases. In phase I, the wall was pushed to a total deflection of one inch. In phase II, the wall was pushed to the full stroke range of actuator (±5 inch (127 mm)).

Figures 5 and 6 show hysteresis loops for both phases. The wall has reached to a deflection of five inches in both directions without catastrophic failure as shown in Figure 7. Two horizontal cracks were observed: one right above the horizontal steel beam connected to the actuator and the other at the bottom of the wall near the foundation. At each horizontal crack, a plastic hinge was formed with a length equal to the length of the wall. Such ductile plastic hinges were not possible to form without the expansive epoxy. In addition, the maximum load observed has increased from 3,000 lb (13.3 kN) in the plain wall to 4,500 lb (17.8 kN) in the expansive epoxy-repaired wall, which is 24% increase. This indicates that the injection of the expansive epoxy not only restored the strength of the cracked wall by sealing all previous cracks, but also increased the strength by 50%.

Test of the Second Wall After Being Retrofitted with Expansive Epoxy

This test consisted of applying a cyclic out-of-plane load in a new brick wall that was not broken before and treated with the expansive epoxy injection prior to the test. The load was tested by applying a similar cyclic load as the previous out of plane tests, but with initial amplitude of 0.01 inch (0.25 mm). The amplitude increased gradually at a rate of 0.01 inch (0.25 mm) per cycle to reach to total of 1.0 inch (25.4 mm) after 100 cycles. Then the amplitude was increased 0.05 inch (1.27 mm) per cycle from there on. The period was maintained at 10 seconds as in the previous tests. Figure 8 shows typical hysteresis loops with expected stiffness degradation. The ultimate capacity of the retrofitted wall is 4,000 lbs (17.8 kN). The wall cracked at a section right above the horizontal steel beam connected to the actuator. After cracking, the walls started to deform in a rocking mode where the cracks will simply open and

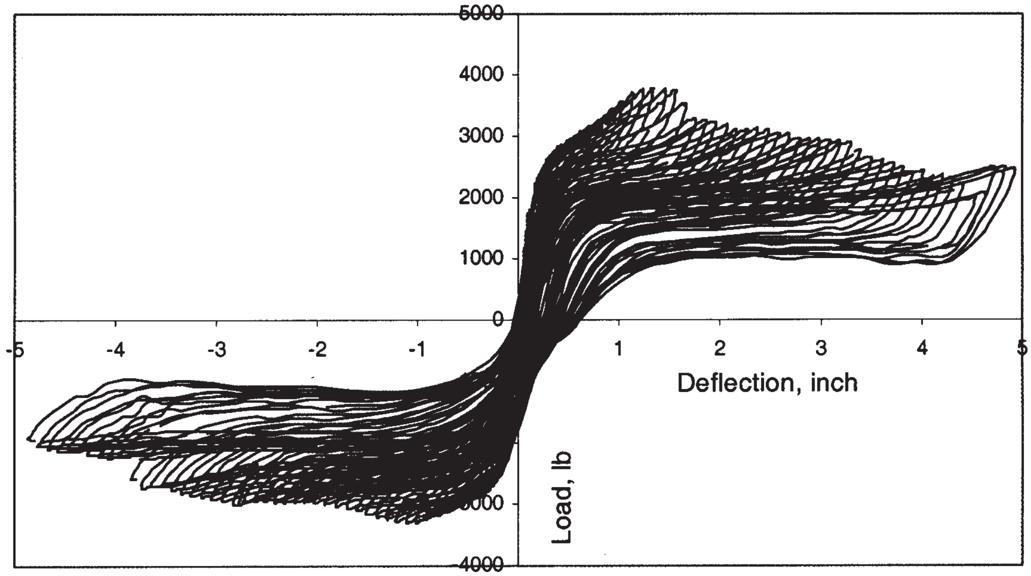

Figure 6—Load-Deflection Curve of the Out-of-Plane Repaired Wall – Phase II: Full Deflection Range (1 in. = 25.4 mm, 1 lb = 4.448 N)

close as shown in Figure 9. This rocking mechanism was similar to the mechanism developed in the repaired walls.

Comparison of Results from Walls Injected with Expansive Epoxy with Results from Plain Brick Walls

Figure 5 shows the ultimate strength of the repaired wall at a value of 4,500 lbs (20 kN), which is 1,500 lbs (6.7 kN) more than the plain brick wall. Figure 6 shows that the wall is very ductile because it took a deflection up to five inches without collapsing. This ductility is attributed to the formation of the plastic hinges in the middle and at the bottom of the wall. One may argue that the wall was prevented from catastrophic failure because the actuator laterally braced it. Such an argument is not valid because the load did not reverse sign. In other words, if the wall is prevented from collapsing by the actuator, then the force in the actuator will be tension instead of compression in one direction, or compression instead of tension in the other. But the shown load deflection

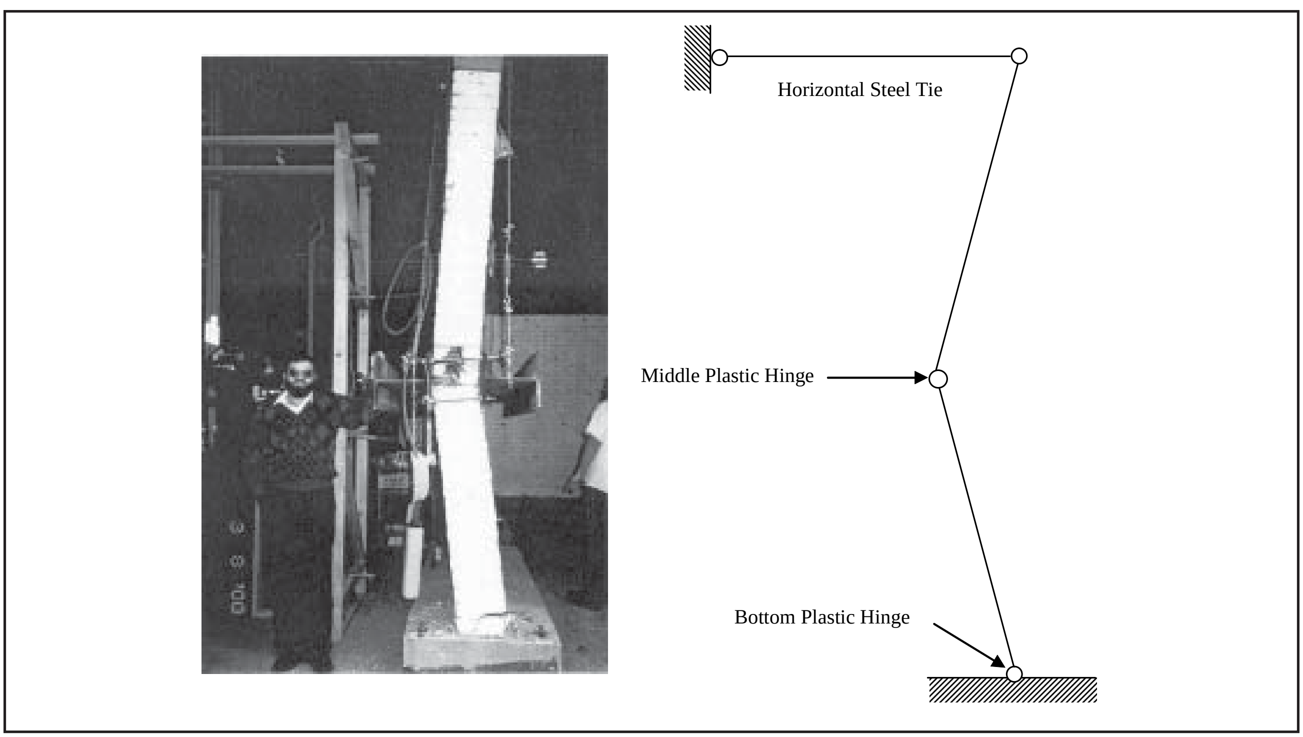

Figure 7—Failure Mechanism of the Out-of-Plane Repaired Wall

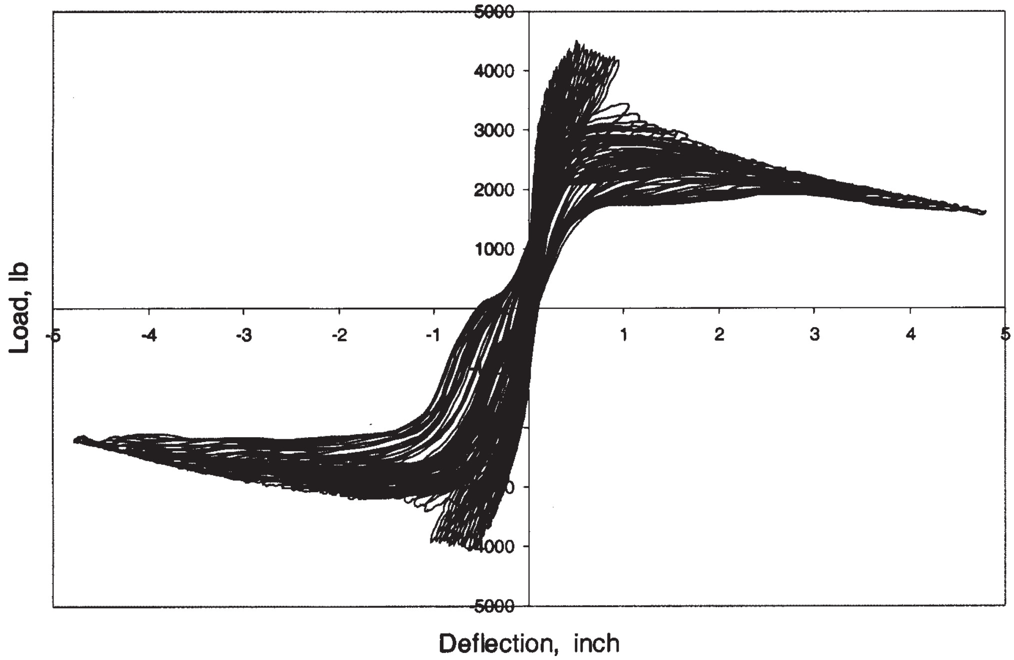

Figure 8—Load-Deflection Curve of the Out-of-Plane RetrofittedWall (1 in. = 25.4 mm, 1 lb = 4.448 N)

curve in Figure 6 is showing that up to five inches of deflection, the actuator had to push/pull the wall with a force of 2,100 lbs (9.3 kN) to produce a five inch deflection, i.e. the wall still has a resistance of 2,100 lbs (9.3 kN) at 5 inches (127 mm) of deflection. If the applied actuator force of 2,100 lbs (9.3 kN) is removed, then the wall will return to a position close to the at rest position. This magnitude of deflection is very ample to prove a very ductile behavior of the originally very brittle brick wall keeping in mind that the maximum deflection allowed by the actuator used was plus or minus 5 inches (127 mm), i.e. the test was stopped at 5 inches (127 mm) because of the limitations of the testing equipment not because of the wall reaching its ultimate capacity. It was not possible to see such ductile plastic hinges in the wall without the expansive epoxy. A catastrophic failure would have taken place because the portion of the wall above any of the two horizontal cracks may slide out of the plane of the wall causing the wall to suddenly loose the ability of carrying vertical loads.

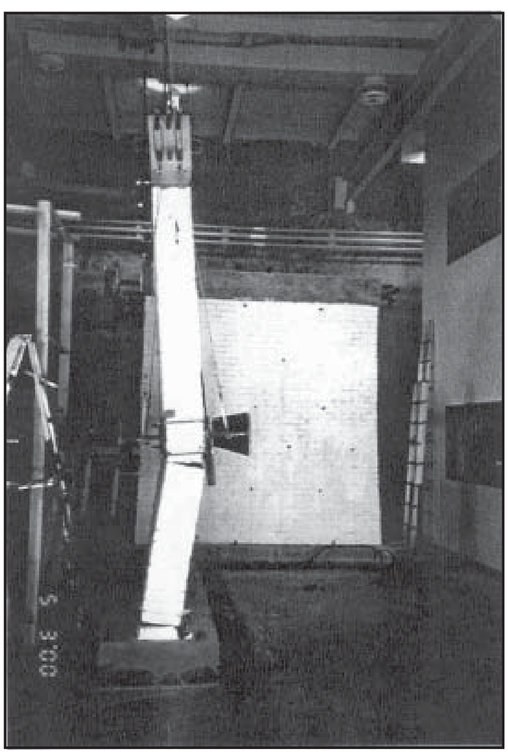

Figure 9—Failure of the Out-of-Plane Retrofitted Wall

Comparing the load-deflection curve of the retrofitted wall to the repaired wall shows that the load required to form the plastic hinge increases by 20%. Another observation in the retrofitted wall is the sudden drop of load after the formation of the plastic hinge. This sudden drop of load is attributed to the cracking of the brick mortar in brittle mode. In the repaired wall, this crack has already taken place when the wall was initially cracked before the injection of the expansive epoxy. This explains why we see gradual drop of load with the increase of deflection beyond the formation of the plastic hinges in the repaired wall, while a sudden drop of load is observed in the retrofitted wall that has not been cracked prior to be tested.

RESULTS OF TESTED WALLS IN THE IN-PLANE SHEAR LOADING CONDITION

Test of the Third Wall without Expansive Epoxy

The test was a cyclic displacement control test. The period of one cycle was 10 seconds. The amplitude of the

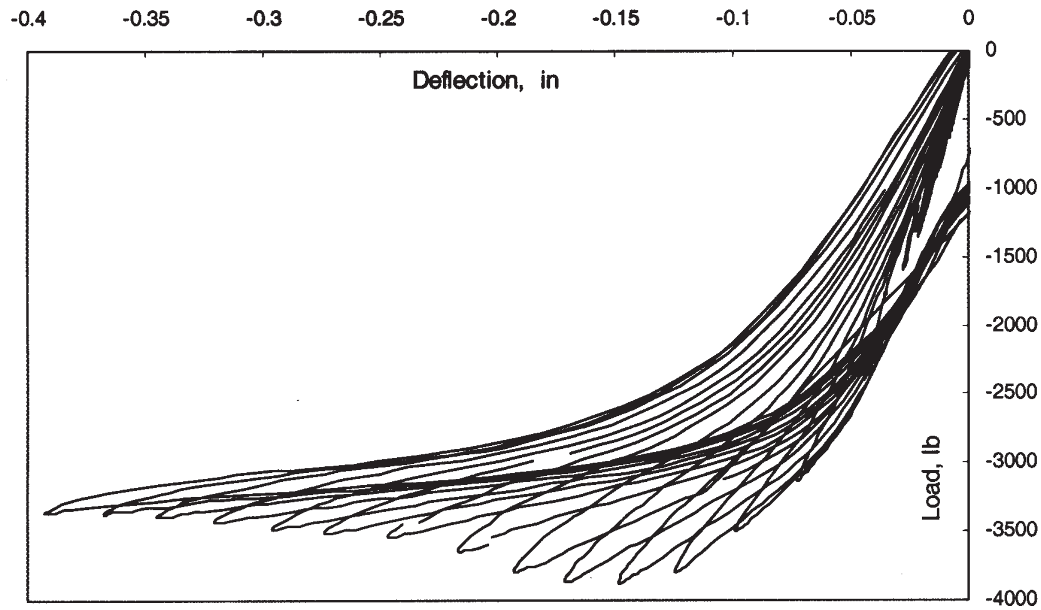

Figure 10—Load-Deflection Curve of the In-Plane Un-Injected Brick Wall (1 in. = 25.4 mm, 1 lb = 4.448 N)

first cycle was 0.005 inches (0.127 mm) and the increment was 0.005 inch (0.127 mm) per cycle. The vertical load applied on the top of the wall was not symmetric around the middle of the wall because of the weight of the actuator is applied on one side but not the other. Another reason is the uplift of the actuator when the wall is pushed versus no uplift when the wall is pulled. The resistance of the actuator to uplifting is high when the wall is pushed because the actuator did not have a hinge to allow for free rotations. This mechanism yielded a non-symmetrical hysteresis loops. It was decided to consider only the pulling side of the hysteresis loops because the actuator does not uplift in this case. Figure 10 shows only the pulling side of the hysteresis loops. The pushing side is omitted because it does not represent the pure strength of the wall. The wall failed in tension at the horizontal mortar joints near the bottom of the wall as shown in Figure 11. Horizontal mortar joints near the bottom of the wall cracked and the portion of the wall above these joints started to uplift and rock in a rigid body motion. The ultimate capacity of the wall was 3,860 lb (17.2 kN). There were no signs of diagonal shear failure.

Test of the Third Wall After Being Repaired with Expansive Epoxy

The wall broken in the previous test without expansive epoxy was then repaired by injecting the expansive epoxy to fill the two-inch gap of the entire wall as described in Section 3. The epoxy was allowed to cure for several weeks. After

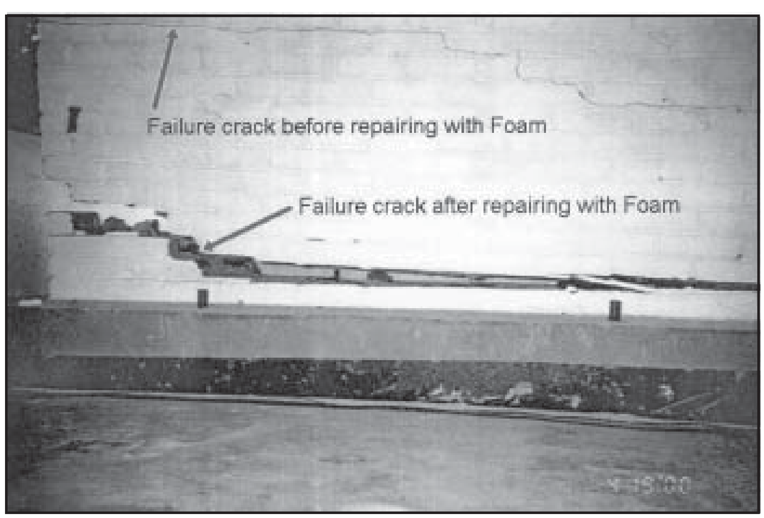

Figure 11—Failure Cracks of the In-Plane Wall Before and After Repairing with Expanisve Epoxy

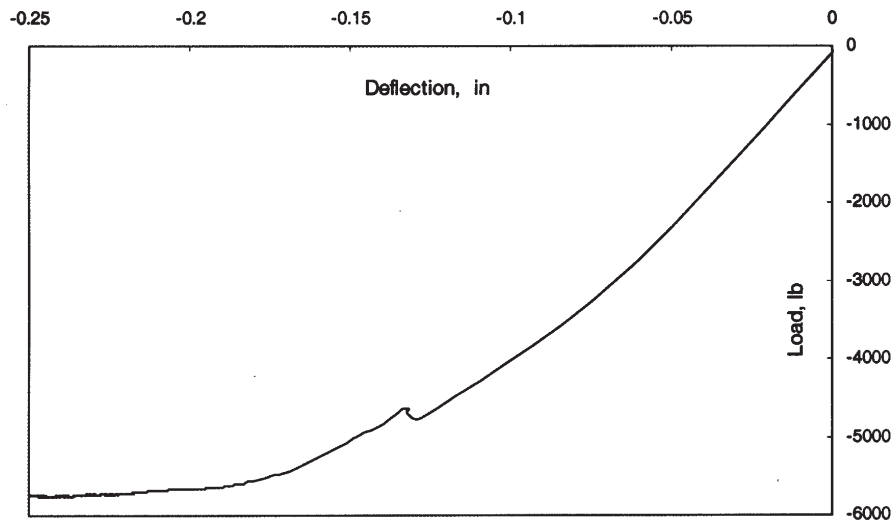

Figure 12—Load-Deflection Curve of the In-Plane Repaired Wall – Phase I: Monotonic (1 in. = 25.4 mm, 1 lb = 4.448 N)

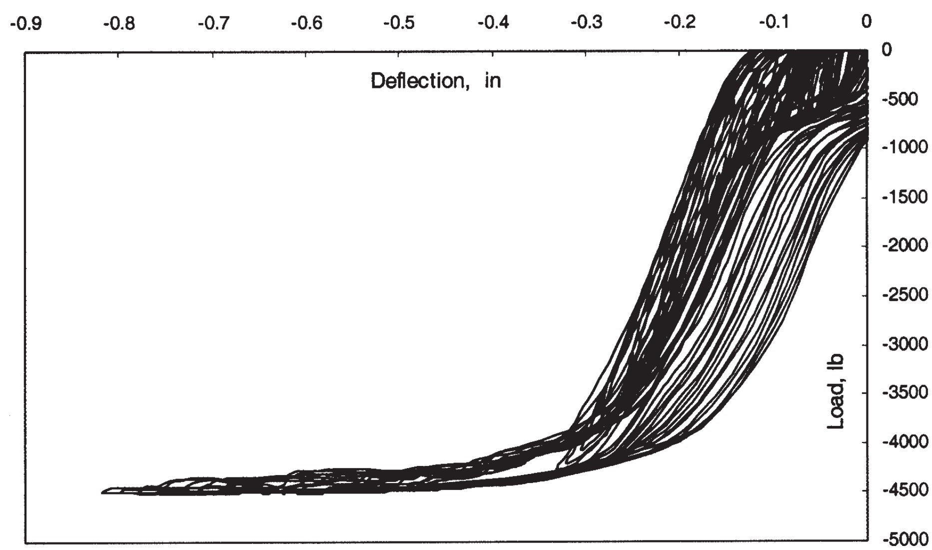

Figure 13—Load-Deflection Curve of the In-Plane Repaired Wall – Phase II: Cyclic (1 in. = 25.4 mm, 1 lb = 4.448 N)

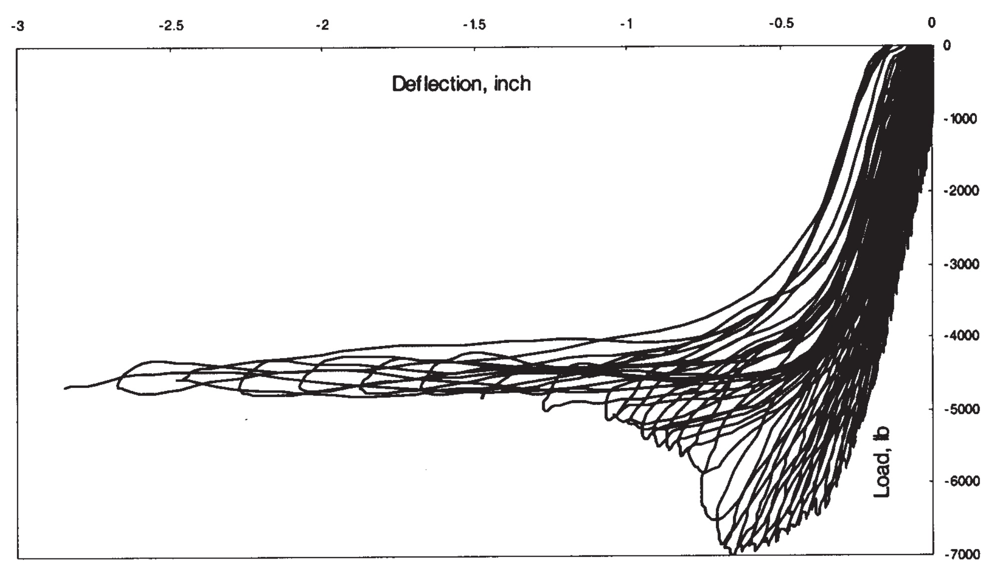

Figure 14—Load-Deflection Curve of the In-Plane Repaired Wall and Anchored to Foundation with Fiberglass(1 in. = 25.4 mm, 1 lb = 4.448 N)

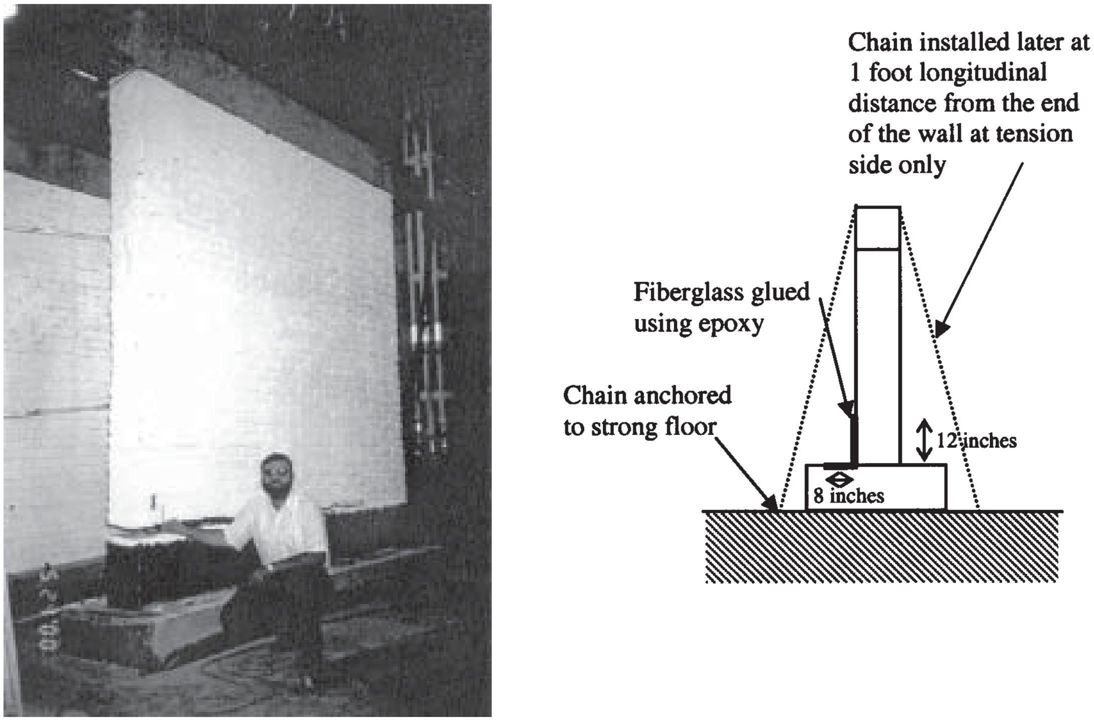

Figure 15—Failure of In-Plane Repaired Wall Anchored to Foundation with Fiberglass

that, the wall was tested in two phases. The first phase was a monotonic test where the wall was pulled to a deflection of 0.25 inch (6.4 mm). As shown in Figure 12, the capacity of the wall has increased from 3,860 (17.2 kN) (plain) to 5,750 lb (25.6 kN), i.e. 49%, as a result of the expansive epoxy. This relatively large increase in capacity is attributed to the fact that the failure section after injecting the expansive epoxy shifted 22 inches (558.8 mm) towards the bottom of the wall as shown in Figure 11.

The second phase was a cyclic displacement control test. The period was 10 seconds with initial amplitude of 0.02 inches (0.508 mm) and increments of 0.02 inch (0.508 mm) per cycle. This test was done after the wall has already developed a failure crack because of the monotonic test. Due to non-symmetrical loading conditions, only the pulling side of the hysteresis loops is shown in Figure 13.

Figure 11 shows the wall at failure. It was observed that the cracks that opened during the testing of the un-injected wall remained closed in this test as a result of the expansive epoxy injection. In addition, the expansive epoxy helped in preserving the integrity of the wall by helping the mortar joints in transferring the loads between bricks. Due to the brittle nature of the mortar material, mortar fails first. The expansive epoxy material is more flexible than mortar and allows much more deformation before it fails. After the wall failed in tension by cracking at the horizontal mortar joints near the bottom, the part of the wall above cracked mortar joint started to rock in a rigid body motion. There were no signs of diagonal shear failure.

Test of the Third Wall After Being Repaired with Expansive Epoxy and Anchored with Fiberglass

Figure 11 show the failure cracks before and after repair. The expansive epoxy sealed the original failure cracks and new cracks developed at a section near the foundation where there is little amount of or no expansive epoxy. As a result, it was decided to repair the wall again for the second time using fiberglass and epoxy. The fiberglass was glued to both wall and foundation to provide anchorage between the wall and its foundation, and to cover the area at the bottom of the wall where there is little amount or no expansive epoxy. As shown in Figure 15, the fiberglass anchorage was installed on one side of the wall only to simulate the real life conditions where only one side of the wall is accessible. The fiberglass also covered the second failure crack produced due to the previous testing of the repaired wall.

The wall was then subjected to a cyclic displacement control test with amplitudes from zero to maximum value. During one cycle, the wall was pulled from the neutral position to the full amplitude and then returned back to the neutral position. The wall was not pushed due to the unsymmetrical loading conditions explained before. The period of one cycle was 10 seconds. The amplitude of the first cycle was 0.02 inches (0.508 mm) and the increment was 0.02 inch (0.508 mm) per cycle up to 1 inch (25.4 mm) of total displacement. After that, the increment was

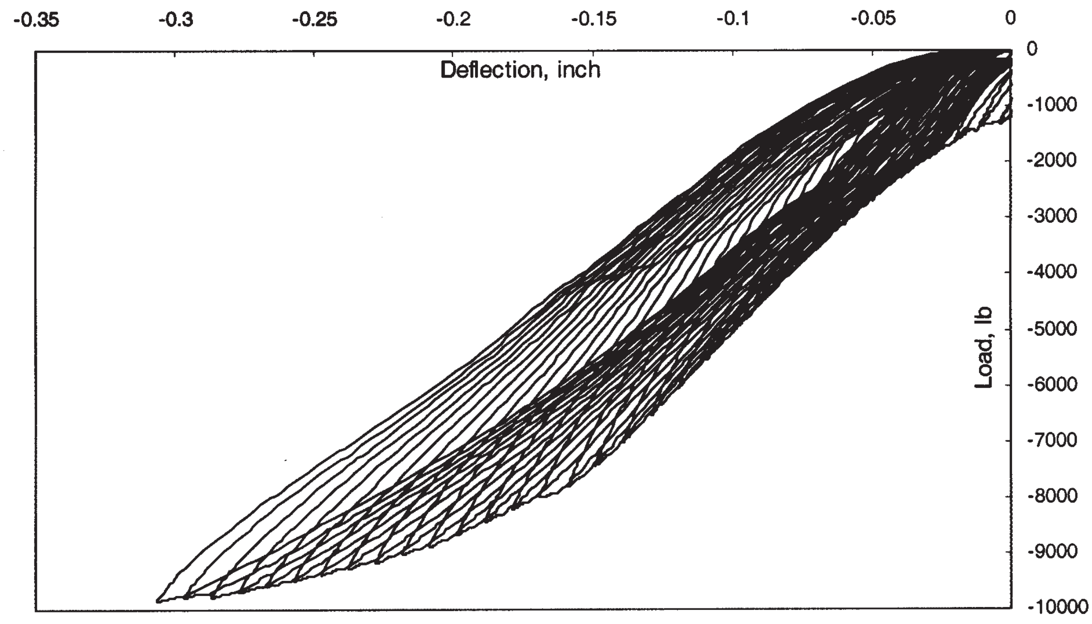

Figure 16—Load-Deflection Curve of the In-Plane Retrofitted Wall with Extra Axial Load and Anchored to Foundation with Fiberglass (1 in. = 25.4 mm, 1 lb = 4.448 N)

0.1 inch per cycle. Figure 14 shows the hysteresis loops of the wall when subjected to such cyclic excitations. It was observed that the wall was cracked at a horizontal mortar joint section right above the fiberglass as shown in Figure 15, and the resistance of the wall increased considerably from 5,800 lb to 7,000 lb (25.8 kN to 31.1 kN), i.e. 21%. This increase is attributed to the fact that the fiberglass prevented failure at the bottom of the wall where is little or no expansive epoxy and forced the failure to take place in an area of the wall rich with expansive epoxy material.

Test of the Fourth Wall After Being Retrofitted with Expansive epoxy and Fiber Glass Anchorage along with Increase in Axial Loading

The axial load in the test of the third wall consisted of the weight of the concrete header beam and the own weight of the actuator, which corresponds to an axial stress of 190 plf (2,772.1 N/m) or 2 psi (0.014 MPa). Such axial load represents the worst-case scenario where a brick wall is supporting one light roof. In the test of the fourth wall, it was desired to experiment with the effect of various axial loading conditions. The fourth wall was a new wall that was not broken before and has been injected with expansive epoxy. The axial load was increased by adding two concrete blocks carried by steel beam from the bottom, as shown in Figure 17. The axial stress in this case adds up to 1,100 plf (16.05 kN/m) or 11.5 psi (0.079 MPa). The objective of this was to explore the change in the wall's mechanical properties for the case of the wall supporting heavier roofs or multiple floors.

Wall is Anchored with Fiberglass Only

The test was a cyclic displacement control test with amplitude from zero to the maximum value allowed by the actuator. During one cycle, the wall is pulled from the neutral position to predetermined amplitude and then returned back to the neutral position. The period of one cycle was 20 seconds. The amplitude of the first cycle was 0.01 inches (0.254 mm) and was increased by 0.01 (0.254 mm) inch per cycle. The period was increased to 20 seconds instead of 10 seconds to prevent the oscillations of weights hanged from the top of the wall. The test stopped as soon as the tension crack shown in Figure 17 was observed. The load deflection curve shown in Figure 16 indicates that the test was stopped at a deflection of 0.31 inch (7.87 mm). It was possible to continue the test beyond this point; however, it was decided to stop the test to install a chain that anchors the wall to the foundation to prevent the tension crack shown in Figure 17 from further progressing. Figure 16 shows that the wall is resisting a lateral load of up to 9,900 lb (44.04 kN), and it could resist more if the test was continued. That shows that increasing the axial load will increase the capacity of the wall from 7,000 lb (31.1 kN) to at least 9,900 lb (44.04 kN), if not more if the test is continued and the horizontal crack near the bottom of the wall shown in Figure 17 continues to develop. However, the test was stopped because it was desired to further explore increasing the axial load by installing a chain to anchor the top of the wall to the strong floor as shown in Figure 15.

Wall is Anchored with Fiberglass and Steel Chain

The wall was tested under cyclic loading by pulling from the equilibrium position to full amplitude and then

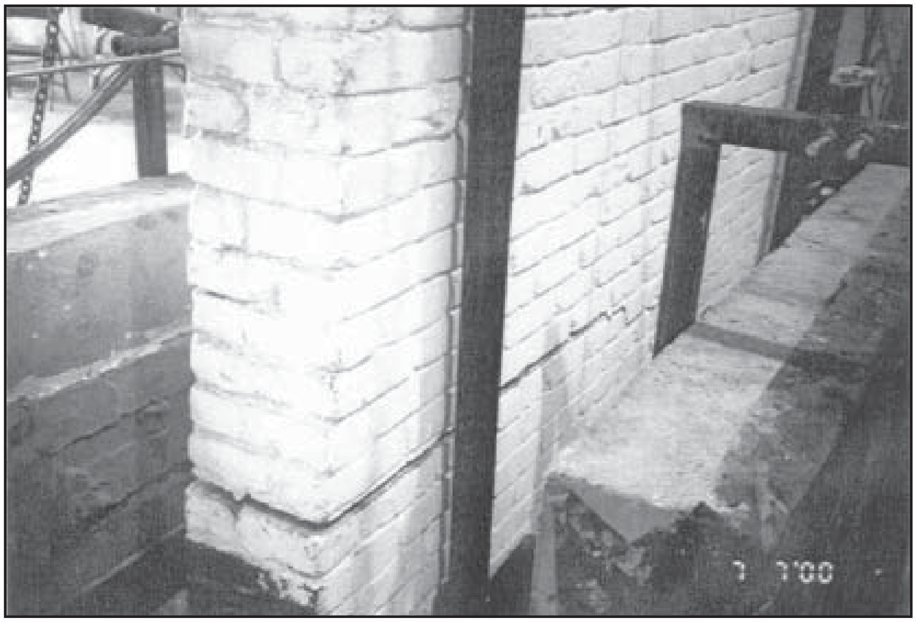

Figure 17—Initial Tension Crack of the In-Plane Retrofitted Wall with Extra Axial Load and Anchored to Foundation with Fiberglass

back to zero load. The period of one cycle was 10 seconds. The period was decreased back to 10 seconds because it was found that 10 seconds period is long enough to prevent oscillation of the concrete blocks hanging from the wall. The amplitude of the first cycle was 0.05 inches (1.27 mm) and the increment was 0.05 inch (1.27 mm) per cycle. Chain was installed to prevent the tension crack developed from progressing and to further add axial load on the top of the wall. The extra axial load produced by the stretching of the chain made the formation of horizontal tension cracks not possible due to the heavy axial compressive load. The chain did not totally prevent the wall from uplifting because the chain was not pre-stressed. The wall had to uplift some distance to stretch the chain and produce the desired axial load. Figure 18 shows the hysteresis loops until failure of the connection between the wall and foundation. The entire wall slid for a distance of 2 inches (50.8 mm) on its foundation and the foundation itself cracked as shown in Figure 19. The

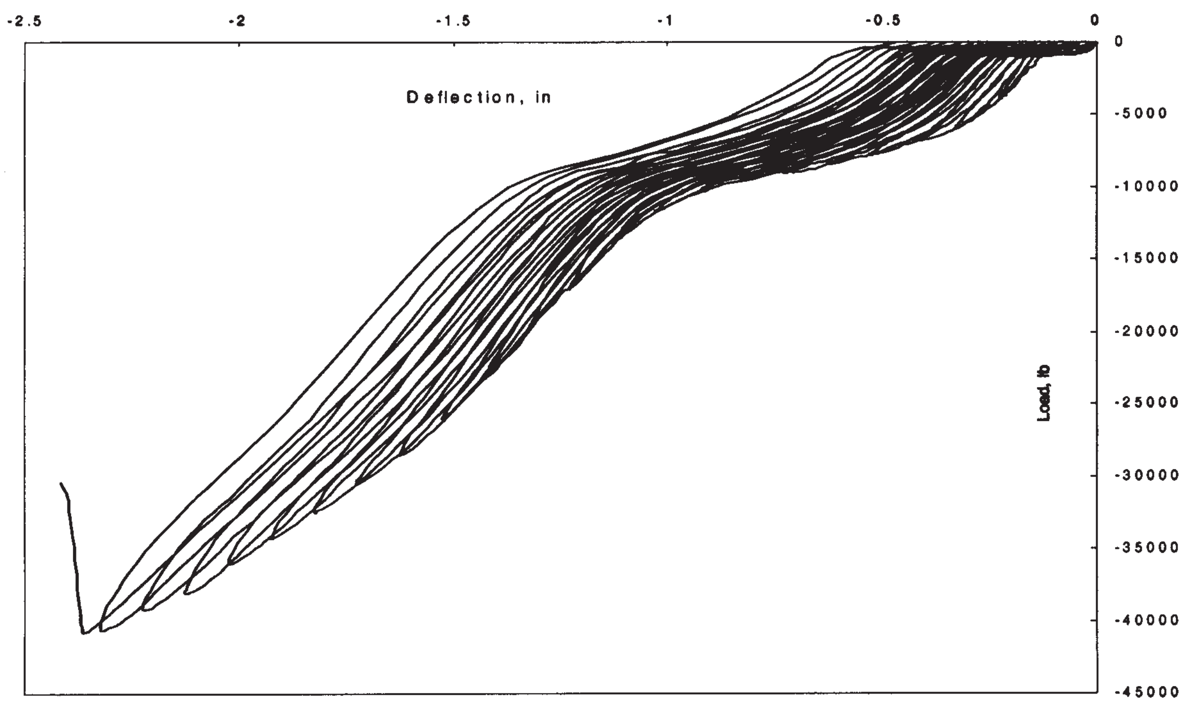

Figure 18—Load-Deflection Curve of the In-Plane Retrofitted Wall with Extra Axial Load and Anchored to Foundation with Fiberglass and Steel Chain

Figure 19—Sliding, Fiberglass and Foundation Failure of the In-Plane Retrofitted Wall with Extra Axial Load and Anchored to Foundation with Fiberglass and Steel Chain

wall itself showed no signs of any additional failure than the tension crack produced in the previous test. Before the wall slid, the fiberglass pulled out from the foundation due to the uplift of the wall. The wall was able to resist a load up to 41,000 lb (182.4 kN) before the sliding failure. Sliding failure took place in the connection between the wall and foundation but the wall itself did not fail yet. The sliding failure is not expected in real life applications because the dead and live loads will apply heavy compression stress on the wall that may reach up to 3,850 plf (57.2 kN/m) or 40 psi (0.276 MPa). Such heavy axial load will make uplifting or sliding of the shear wall not possible. The real life failure mechanism of brick walls under heavy axial loads is expected to be stair-steps diagonal crack in mortar joints due to the effect of diagonal tension.

Figure 19 also shows a piece of fiberglass pulled out of the wall. It is clear from the picture that the bonding strength between the fiberglass and brick wall due to gluing epoxy exceeded the strength of the brick itself. This resulted in a thin layer of brick pulling out of the wall and remaining with the fiberglass. This leads to the conclusion that using such an epoxy, not exposed to moisture or weathering, in adhering the fiberglass to the brick wall is adequate because it provides bonding resistance, which is more than the shear resistance of the brick itself.

Wall Laterally Supported by Steel Strut and Anchored with Fiberglass and Steel Chain

The same wall was repaired again and tested for the third time as shown in Figure 21. This time, a lateral horizontal steel strut was installed at mid height of the wall to provide lateral support and to prevent the wall from going into further sliding when pulled. The objective was to force the wall to develop the expected diagonal tension failure, since sliding failure is not expected for such walls under heavy axial loadings, and to measure the corresponding strength of the wall. The effective loaded portion of the wall is the top half of the wall, which simulates a wall of aspect ratio of 2:1. That portion of the

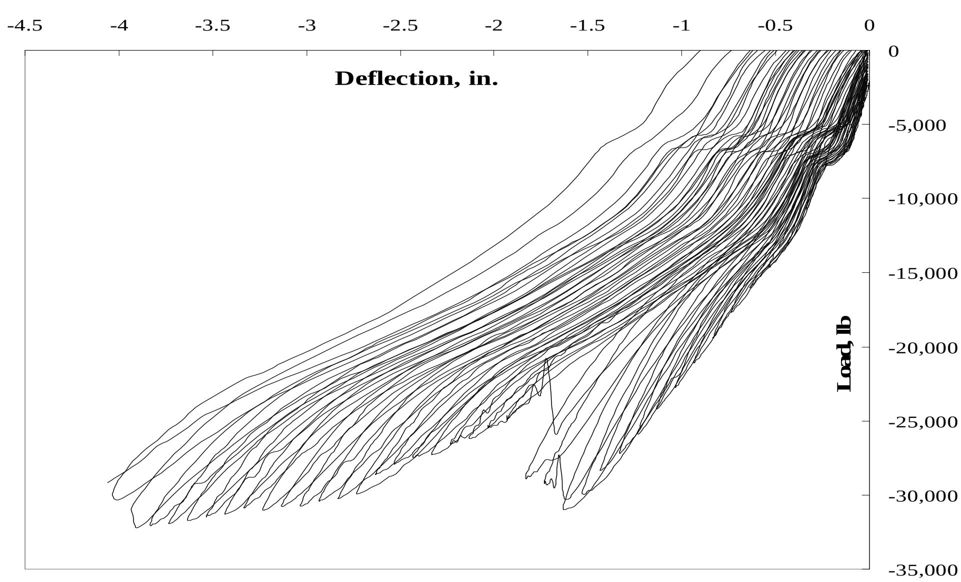

Figure 20—Load-Deflection Curve of the In-Plane Laterally Supported Wall with Extra Axial Load and Anchored to Foundation with Fiberglass

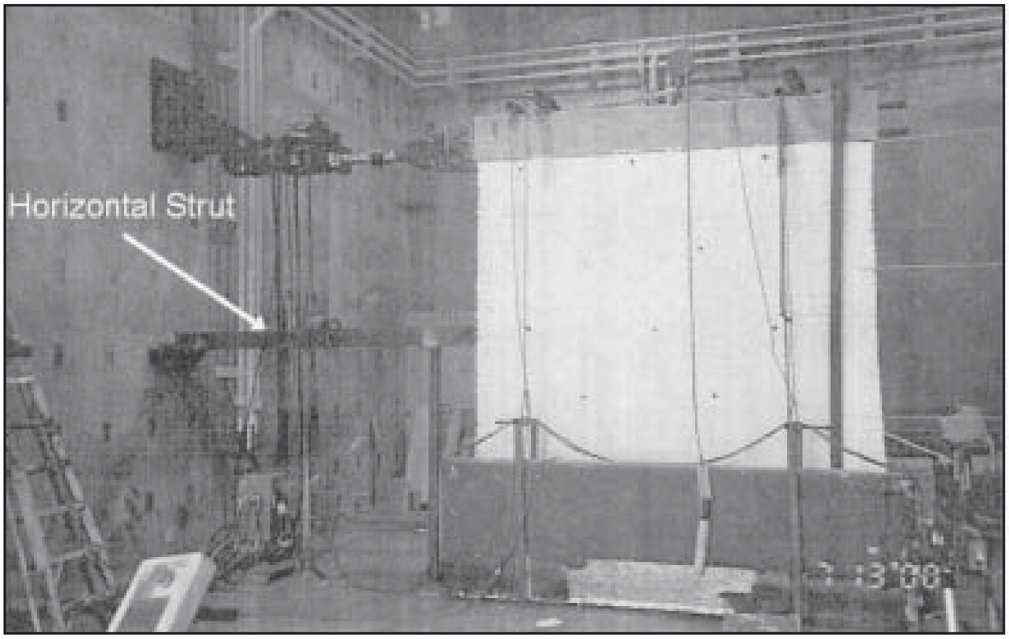

Figure 21—Test Setup of the In-Plane Laterally Supported Wall with Horizontal Strut Along with Extra Suspended Axial Load and Anchored to Foundation with Fiberglass and Steel Chain

wall was free of any cracks or signs of failure from the previous two tests. The wall was then subjected to a cyclic displacement control test that range from zero to the maximum value allowed by the actuator. During one cycle, the wall is pulled from the neutral position to a maximum value and then returned back to the neutral position. The period of one cycle was 10 seconds. The amplitude of the first cycle was 0.05 inches (1.27 mm) and the increment was 0.05 inch (1.27 mm) per cycle. The chain was kept in place to prevent the wall from uplifting and to provide extra axial loading when stretched. First, a curved tension crack was formed as shown in Figure 22 to allow the wall to uplift a little bit to stretch the chain. Such uplifting was necessary for the chain to develop enough axial loading to produce the desired failure mechanism. Then the stair-steps diagonal-tension crack was developed as expected. This

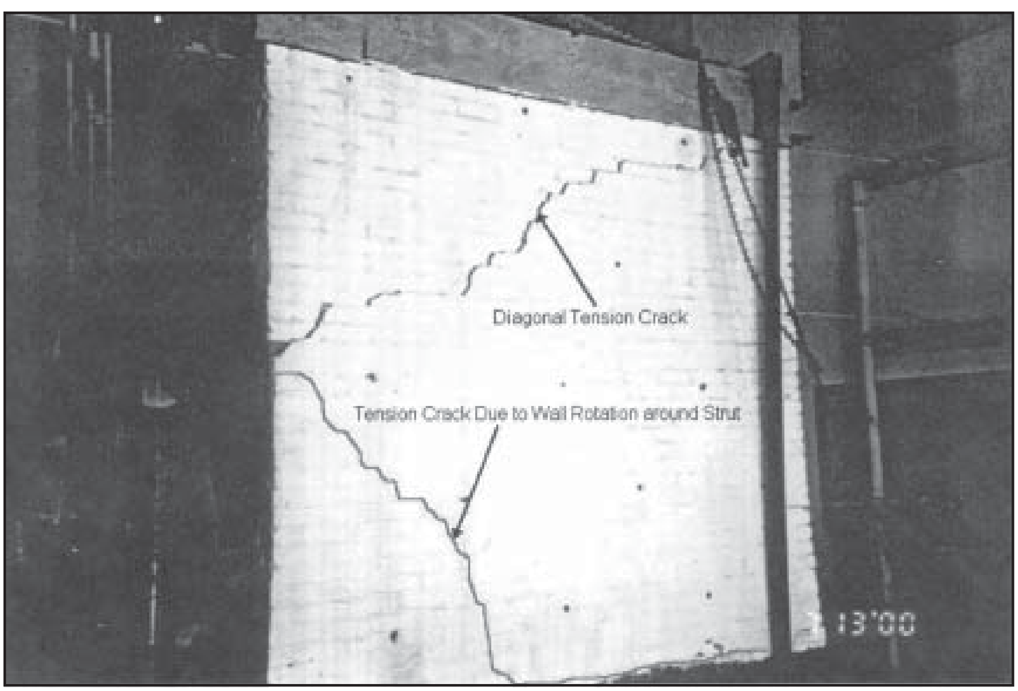

Figure 22—Failure of the In-Plane Laterally Supported Retrofitted Wall with Extra Axial Load and Anchored to Foundation with Fiberglass and Steel Chain

failure mechanism is expected in case of brick load-bearing wall supporting heavy axial loads. Figure 20 shows the hysteresis loops until the formation of the stair-steps diagonal crack. It shows that the strength of the wall against a stair-step diagonal tension failure is 32,000 lb (142.3 kN) and the deformation at failure is 4.1 inches (104.1 mm).

CONCLUSION

This test introduces the technology of injecting expansive epoxy into brick walls as an effective method to repair and retrofit brick walls used as structural elements in historical buildings. In such brick walls, the mortar may have deteriorated to such a level that it can be easily removed by a pocketknife. The bond between the expansive epoxy and brick substitutes for the deteriorated mortar joints without the need to remove them. It makes the loose brick wall monolithic and increases its integrity. In addition, the ductile expansive epoxy substitutes the function of the brittle mortar making the wall able to produce more ductile response in case of seismic ground motions. If the mortar joints are not deteriorated, then they will break at very small deflections due to its brittle nature and inability to carry large tension loads. The expansive epoxy herein works as the second line of defense that will pick up the lost function of the mortar but in a much more ductile fashion allowing a better distribution and transfer of stresses in the wall. Without the expansive epoxy, a complete catastrophic failure at relatively small deflections may be the case.

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