OUT-OF-PLANE PERFORMANCE OF FULL-SIZE UN-REINFORCED BRICK WALLS RETROFITTED WITH EXPANSIVE EPOXY

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ABSTRACT

A pioneer technique to repair un-reinforced brick walls cracked during past seismic events, or to retrofit existing brick walls to meet the current code requirements is subjected to experimental investigation. Such walls are very common in historical buildings. The walls are injected by expansive epoxy, known as Bisfoam-3. After the material is shot into walls, it expands, bonds and hardens. This injection technique does not affect the appearance of these historical walls and consequently it preserves their historical value. The investigation consists of testing the seismic performance and ductility of the plain brick walls first. Then, those broken walls are repaired using the foam and tested. In addition, another set of walls that has not been broken first are strengthened with foam and tested. Performance of all walls is studied and compared to prove the effectiveness of the foam material in the retrofitting and repairing of brick walls.

Keywords: Expansive, Epoxy, Un-Reinforced, Brick Walls, Retrofit, Out-of-Plane.

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INTRODUCTION

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 produced by Delta Plastics Company, called Bisfoam-3, was tested to determine its potential for structural retrofitting and strengthening of existing brick masonry buildings.

The Delta Plastics Co. Bisfoam-3 is a monolithic complex composite. This composite material, when injected into a void area within the walls of buildings increases the ductility, damping and strength of these walls. Without this material inside the wall, catastrophic failure is the norm in case of major seismic events.

This paper presents the results from the laboratory testing of two brick wall in the structural lab of California State University, Fresno. The size of walls is 10 ft by 10 ft by 10 inches thickness with 2 inches void in between and they are fabricated using aged brick and masonry mortar to simulate the conditions existing in old brick buildings. One wall was loaded directly as plain, un-reinforced brick wall and results were obtained. The other wall, identical to the first one, was first injected with the foam material, allowed to cure for seven days and then tested under similar support and loading conditions. After the plain wall was loaded beyond its full cracked state, it was also repaired with the foam 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. In this paper, the emphasis is on the behavior of un-reinforced brick walls under out-of-plane bending, while in another paper presented in this conference by the same authors, the emphasis is on the behavior under in-plane shear.

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 dependant to their good luck. Various strengthening and retrofitting techniques have been used through the years, including more recently the used 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).

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 desired to provide also structural enhancing with the epoxy.

In 1971, the technology of FR-4 was developed specifically for the rehabilitation of the Los Angeles City Hall building, which was severely damaged in the 1971 San Fernando earthquake. The FR-4 product would be chemically irreproducible after 1976 due to the use of Freon as the foaming agent. This technology is now back into chemical production and renamed to Bisfoam-3. The Delta Plastics Co. Bisfoam-3 is now foamed $_2$ instead of Freon, which is a non-regulated method of chemical expansion.

Bisfoam-3 is a functional equivalent to the time tested, in-place exposures of Whittier, Northridge, and all other ground movements as reported by Cal Tech. After better than 30 years of on the job service, the epoxy foam is still in pristine condition and is ever vigilant for the next ground movement. The Delta FR-4 application at the Los Angeles City Hall was accomplished by VTN of Orange County with the assistance of the Army Corps of Engineers, the Office of Emergency Preparedness, better known as FEMA, and the approval of the Los Angeles building department. The Los Angeles City Hall report (Galletti, 1972) outlines extensively the application, building condition, and other methods considered. The 19th method tested was the Delta foam developed by Delta Plastics. The technologies obtained from the restoration of the Los Angeles City Hall along with their engineering and architectural skills made VTN of Orange County a natural choice for the State Capitol building restoration project. The Delta Bisfoam-3, when compared to other types of restoration methods including base isolation technology, is both cost effective and time tested. The Bisfoam-3 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. During three of these projects, the application of the Bisfoam-3 was straightforward. The Mayflower Presbyterian Church application was unique. The church is a single load-bearing wall structure. The approximately 1-2 inch of void area 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. The application was accepted and now church services have resumed. Void areas will 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.

CONSTRUCTION PROCEDURE

One type of construction of brick walls of historical buildings consists of two layers of brick with 2 inches 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 gap to pump the expansive epoxy in a liquid form. The holes are drilled in a diamond shape distribution as shown in Fig. 1 with 2 feet spacing on center. Expansive epoxy is pumped at about 70°F 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 Fig. 2. Then after few minutes, the foam starts to expand and hardens. The expansion ratio 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 foam to cure is seven days. The method can also be implemented for brick walls with single layer of brick. The approximately 2 inch 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. It should be noted that the mortar used to build the walls for this test was according to ASTM standards. In the 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 historical buildings, the variability of the strength of both the brick and the mortar is high. The main goal in this procedure is to test the plain walls without any foam and establish this as a reference line against which repaired and retrofitted walls are compared. This will clearly point out the improved mechanical properties due to the use of foam. Another immediate advantage of using the foam is that it substitutes for the deteriorated mortar joints. It makes the loose brick wall more monolithic and increases its integrity. In addition, the ductile foam substitutes for the brittle mortar making the wall able to produce much more ductile response in case of seismic ground motions.

TEST SET-UP

Two walls were built in the structural testing lab at California State University, Fresno. The walls were subjected to out-of-plane loading, as shown in Fig.3. The axial loading is limited to the own 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 own weight of the actuator. This adds 3500 lb of additional weight to the wall. This represents the worst-case scenario because increasing the axial 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.

RESULTS

Plain Wall without Foam

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 inch displacement followed by increments of ±0.01 inch each cycle and at a frequency of 0.1 cycles per second.

The load deflection curve (Fig. 4) shows typical hysteresis loops with expected stiffness degradation. The ultimate capacity of the plain brick wall was 3000 lbs. The wall started to crack at about 2000 lbs and 0.1-inch deflection. The wall became fully cracked at 0.15-inch deflection. Increasing the displacement more than 0.15 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, 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. Two horizontal cracked sections 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.

Wall Repaired with Foam

The repaired wall 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 and then was increased by 0.02 inch 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). Fig. 5 and Fig. 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 Fig.7. Two horizontal cracked sections 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 horizontally cracked section, 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 foam. In addition, the maximum load observed in the foam-retrofitted wall was approximately 25% higher than the maximum load observed in the plain wall. This indicates that the injection of the foam not only restored the strength of the cracked wall by sealing all previous cracks, but also increased the strength by 24%. Add to that the added ductility and damping due to the formation of the plastic hinges.

Out of Plane Wall Retrofitted with Foam

This test consisted of applying a cyclic out-of-plane load in a new brick wall that was treated with the expansive epoxy injection prior to the test. The load was tested by applying a similar cyclic load as the previous tests, but with initial amplitude of 0.01 inch. The amplitude increased gradually at a rate of 0.01 inch per cycle to reach to total of 1.0 inch after 100 cycles. Then the amplitude was increased 0.05 inch per cycle from there on. The period was maintained at 10 seconds as in the previous tests. Fig.8 shows typical hysteresis loops with expected stiffness degradation. The ultimate capacity of the retrofitted wall is 4200 lbs. 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 close. This rocking mechanism was similar to the mechanism developed in the repaired walls.

Comparison of Results from Foamed Walls with Results from Plain Brick Wall

Fig. 5 shows the ultimate strength of the repaired wall at a value of 4500 lbs, which is 1500 lbs more than the plain brick wall. Fig. 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 curve in Fig. 6 is showing that up to five inches of deflection, the actuator had to push/pull the wall with a force of 2100 lbs to produce a five inch deflection, i.e. the wall still has a resistance of 2100 lbs at five inches of deflection. If the applied actuator force of 2100 lbs 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 five inches, i.e. the test was stopped at 5 inches 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 foam. 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.

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 foam. 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.

CONCLUSION

The technology of Bisfoam-3 has proved its effectiveness in the repair and retrofit of brick walls used as structural elements in historical buildings. In such brick walls, the mortar has deteriorated to such a level that it can be easily removed by a pocketknife. The foam substitutes the deteriorated mortar joints. It makes the loose brick wall monolithic and increases its integrity. In addition, the ductile foam substitutes the function of the brittle mortar making the wall able to produce much 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 foam 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 foam, a complete catastrophic failure is expected at relatively small deflections.

The foam also has another important function. It provides a passive control of the vibration of the wall by adding additional damping to the system. The increased damping is resulting from the foam material itself in addition to the energy dissipated in the friction between adjacent blocks of brick. The foam allows more ductile response where various blocks of brick will have large relative motion between them and as a result dissipating much more energy.

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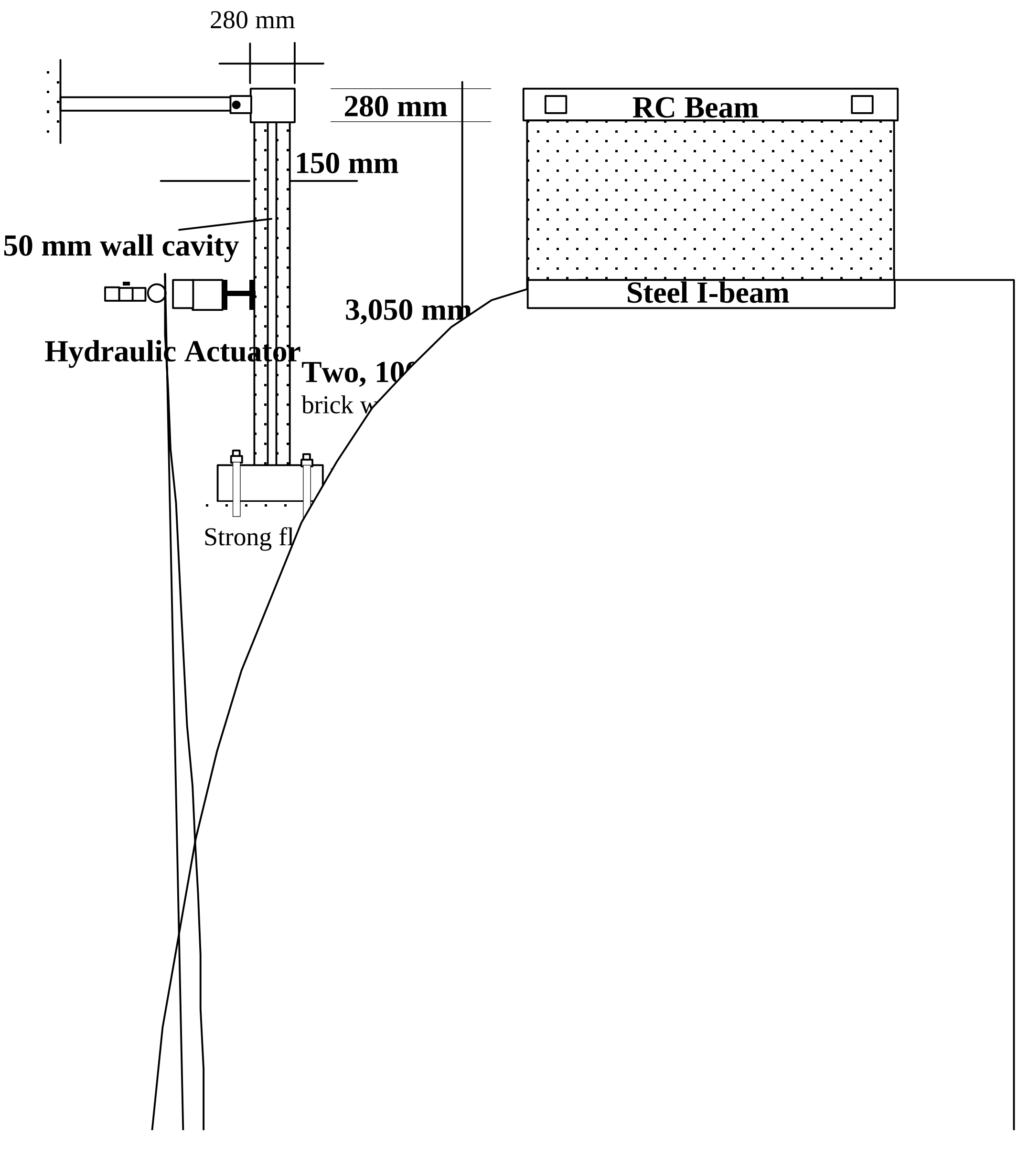
Figure 1: Distribution of Holes on the Wall

Figure 2: Pumping of Expansive Epoxy in the Wall



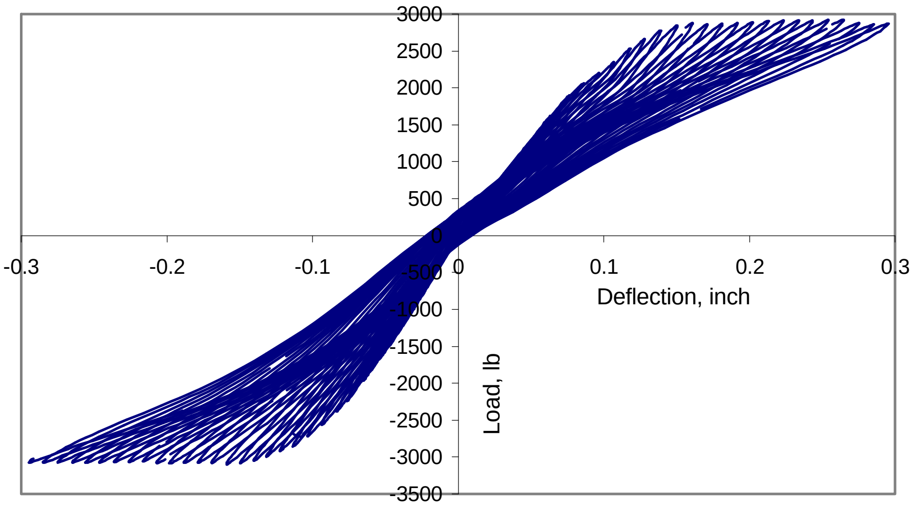


Figure 4: Load-Deflection Curve of the Un-Injected Wall

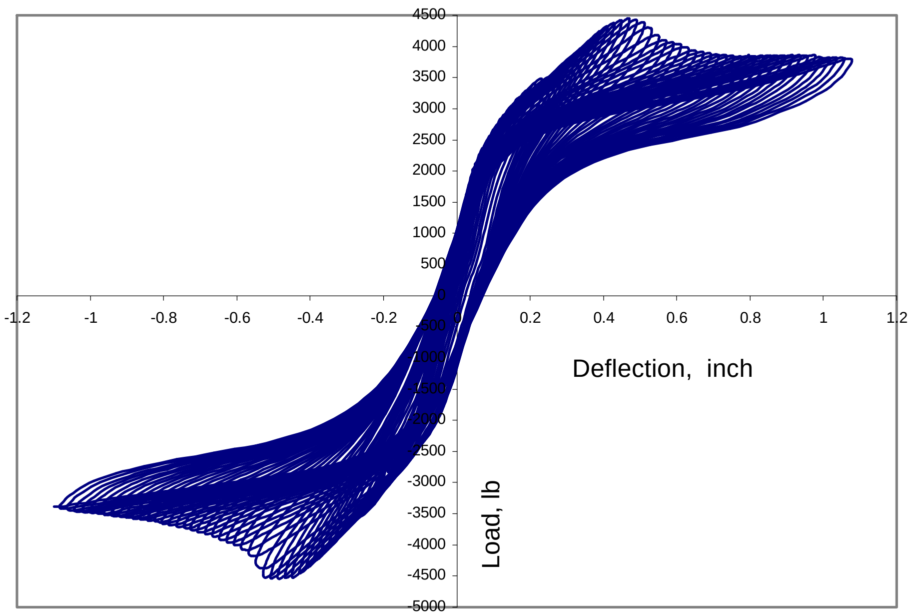


Figure 5: Load Deflection Curve of the Repaired Wall (Phase I: Up to 1 inch Deflection)

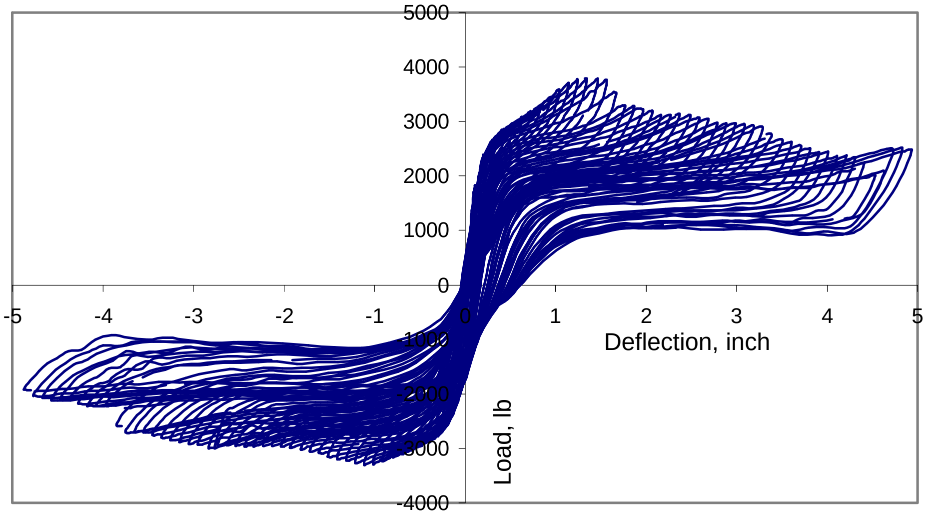


Figure 6: Load-Deflection Curve of the Repaired Wall, (Phase II: Full Deflection Range)

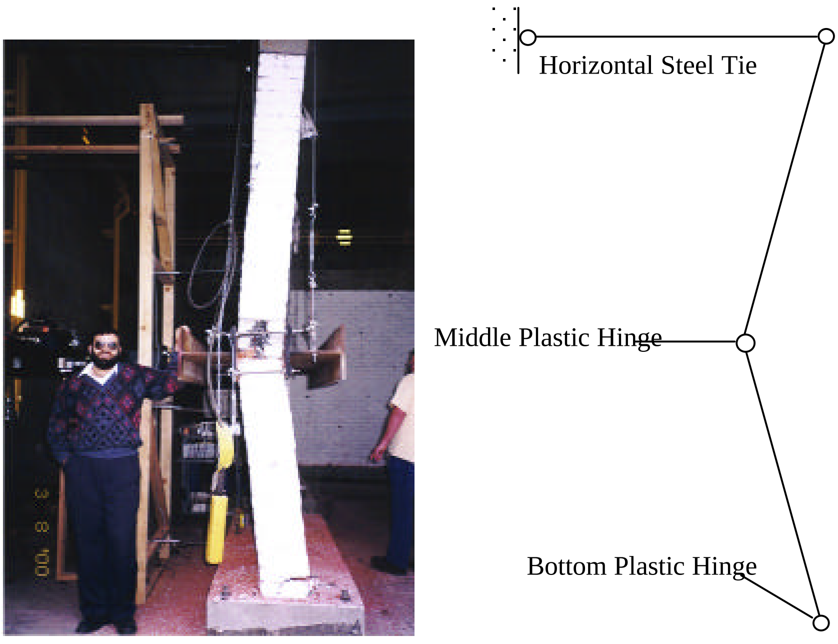


Figure 7: Failure Mechanism of the Repaired Wall

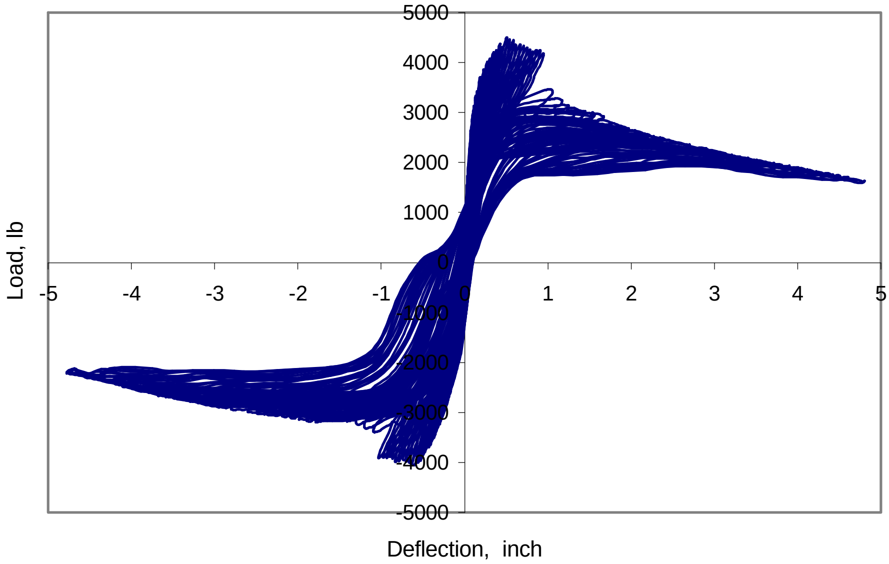


Figure 8: Load-Deflection Curve of the Retrofitted Wall