CYCLIC LOADING ON EXTERNALLY REINFORCED MASONRY WALLS

by

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SUMMARY

Experimental results on three categories of externally reinforced masonry walls subjected to cyclic loading are presented. The categories correspond to walls with external reinforcing on both faces, walls with reinforcing on one face only, and walls which have been previously damaged, using the external reinforcement as a means of repair. The load deflection curves, stiffness degradation characteristics, energy absorption capacities and observed damage patterns are discussed. It is concluded that externally reinforced masonry construction behaves at least as well, if not better than internally reinforced masonry under cyclic loading; and provides a technically attractive solution to reinforce existing buildings or to repair damaged buildings of unreinforced masonry construction.

INTRODUCTION

The past performance of unreinforced masonry buildings subjected to earthquakes has been generally poor. As a result, reinforced masonry is recommended for construction in active seismic regions. For new reinforced masonry construction, reinforcement can be placed within the masonry joints and cavities in the masonry blocks. However, in the case of strengthening existing buildings of unreinforced masonry construction, or repairing damaged buildings of this type after an earthquake, internally reinforced masonry construction becomes impractical. A variety of solutions have been offered by engineers, both for strengthening existing buildings and repairing damaged buildings [1, 2]. It is the purpose of this paper to explore the feasibility of another alternative solution, namely, externally reinforced masonry construction. Subjecting externally reinforced wall panels to cyclic loading, the suitability of this type of construction for strengthening or repairing buildings in seismic zones is judged based on the criteria of ductility capacity, stiffness degradation characteristics, energy absorption capacity and the overall damage patterns as compared to those found in internally reinforced masonry walls [3, 4].

TEST ARRANGEMENT

Each test specimen was an approximately half-scale representation of a single storey wall. The dimensions were 6'8" in length and 4'8" in height. It was constructed using standard 6'x 8" x 16" hollow concrete blocks. The concrete blocks had an average strength of 1200 p.s.i. based

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on gross area. The mortar for the wall construction had a cement to sand ratio of 1:3 and reached an average cube strength of 1,000 p.s.i. The wall was encased in a steel frame. Slits were cut along the web of the frame columns to make the frame more flexible. The infilled frame was anchored to a steel beam which in turn was rigidly attached to the test floor. Such an arrangement minimizes the uplifting of the test wall under lateral loading. The load was applied by means of a hydraulic jack acting on one upper corner of the frame. The jack was actuated by means of a M.T.S. servo-controlled hydraulic system and was capable of push and pull action to provide the cyclic loading function. Stroke displacement was the controlling parameter in all tests. Loads were measured by means of a load cell between the frame and the jack. Mechanical dial gauges were used to measure the displacements at the corners of the panel.

The external reinforcement consisted of expanded metal sheets bonded to the sides of the block wall by means of a one inch thick layer of mortar. Standard 1 1/2 inch #16 expanded metal sheets weighing 0.38 lb/sq.ft. were used. The expanded metal sheet had an overall thickness of 0.05 inches with an 83% open area. The mortar for the reinforcing layer had an average strength of 2800 p.s.i. In addition, seven 1/4 inch diameter bolts with 2" x 2" x 1/8" plates welded at the ends were driven through the joints of the blocks to further improve the bonding. The location of the steel bolts and the general test set up is shown in Fig. (1).

In each test, the specimen was subjected to a number of cycles of reverse loading. The load-displacement curve for each cycle was measured. In addition, the damage patterns were observed. Based on the load-deflection curve, the energy absorption per cycle and the secant stiffness of the specimen were deduced. Although some mortar paste was used to fill in the space between the frame and the wall, the bond broke down in general during the first cycle of loading. Therefore, the stiffness of the specimen in subsequent cycles can be considered as the algebraic sum of the wall and the frame stiffnesses. The stiffness of the frame alone is given in Fig. (2).

EXPERIMENTAL RESULTS

Typical test results are presented under three categories: (i) walls reinforced on both sides; (ii) walls reinforced on one side only and (iii) damaged walls reinforced on both sides. The first two categories correspond to an investigation of strengthening existing unreinforced walls. The third category relates to the repair problem of damaged unreinforced masonry walls.

(i) Wall Reinforced on Both Sides (Wall No. 2)

The specimen consisted of plane masonry block walls with external reinforcement on both faces of the walls. In one wall, fifteen cycles of loading were executed. The load deflection curves for the first eight cycles are shown in Fig. (3). A maximum lateral load of 100 kips was reached in the second cycle. As the maximum displacement of subsequent cycles increased, a substantial loss of stiffness was observed. This can best be seen in Fig. (4) in which the secant stiffness for increasing loading and decreasing loading for each cycle are shown. Stiffness degradation for the first few cycles is particularly noticeable. Also, there was slight stiffness degradation for repeated cycles in which the maximum displacement was the same as the previous cycle. The stiffness curves tend to approach a limiting value after the ninth cycle.

The energy absorption capacity is shown in Fig. (5). There is an increase of energy absorption per cycle as the cycle displacement increases. However, subsequent cycles of the same maximum cycle displacement tend to give a lower value of energy absorption capacity. The final cycle (cycle 15) had a maximum displacement of 1.5 inches in each direction. The specimen had an energy absorption capacity of 115 kip-inch per cycle. It resisted a load of 75 kips and there was no indication that the load resisting capacity of the specimen had been exhausted. The load deflection curves for the final few cycles are shown in Fig. (6).

The observed damage of the specimen is mainly confined to the bottom third of the panel. Some damage was observed at the bottom corner of the specimen during the third and fourth cycles. Also, some separation was observed between the masonry wall and the reinforcing layers at the bottom part of the panel. Such damage increased gradually with the subsequent cycles of loading. After 15 cycles of loading the damage to the panel was limited to the local separation of the reinforcing layers from the masonry blocks at the bottom corners. No cracking was observed across the reinforcing layers. When the reinforcing layers were removed after the test, severe cracking of some masonry blocks adjacent to the frame near the bottom part of the wall was observed (Fig. 7). The two bottom metal bolt anchors also suffered some damage. The upper five anchors were undamaged and were effective in their role to keep the layers attached to the upper part of the masonry wall to form a monolitic structure. As a result, there was little damage to the blocks at the centre and upper part of the wall.

(ii) Wall with Reinforcement on One Side (Wall No. 4)

The specimen in this category consisted of a plane masonry block with the externally reinforcing layer on one face of the wall only. Seven anchor bolts were also used to increase the bonding of the reinforcing layer to the masonry wall. The load deflection curves and the stiffness degradation characteristics were similar to walls that were reinforced on both sides. One specimen was subjected to 14 cycles of loading. The maximum load reached 100 kips at a deflection of 0.35 inches. Fig.(8) shows the stiffness degradation characteristics of the wall.

The main difference between walls of this category as compared to walls that were reinforced on both sides were the energy absorption capacity, the lateral load the wall can resist after a number of cycles and and the damage pattern. Fig. (9) shows the energy absorption capacity of the specimen. In contrast to Fig. (5), the energy absorption capacity tends to level off to a plateau when the maximum excursion exceeds 0.5 inches. Comparing Figs.(10) and (6) shows that in the final cycle the load capacity of the wall with reinforcement on one face reached approximately 45 kips while the load capacity for the wall with both faces reinforced reached a value of 75 kips.

However, the most dramatic difference is the damage pattern of the panel. Some cracking along the mortar joints between the masonry blocks was observed in the first four loading cycles. Extensive cracking developed in the masonry after the sixth cycle. At this stage, there was very little cracking in the reinforcing layer. Diagonal cracking of the reinforcing layer started in the seventh cycle when the maximum displacement reached 0.5 inches and progressively propagated along the diagonals in subsequent cycles of loading. The mortar joints between the masonry blocks had essentially failed completely by the eighth cycle and some cracking of the blocks occurred. The load appeared to be resisted solely by the reinforcing layer. Due to the cyclic action of the horizontal load and the failing of the mortar joints, out of plane movements as much as half an inch was observed among the masonry blocks. At the final cycle (cycle 14), two rows of masonry blocks blew out of the panel during loading.

This is in marked contrast to the wall reinforced on both sides which retained its integrity after 15 cycles of loading.

(iii) Damaged Wall with Reinforcement on Both Sides (Wall No. 3)

The specimen consisted of an unreinforced masonry wall. It was initially loaded cyclicly until cracks were observed along the joints and at the blocks. Then, two reinforcing layers were applied to the damaged wall. The repaired wall was subsequently subjected to further cyclic loading. In one specimen, the unreinforced wall was subjected to 11 cycles of loading up to a maximum displacement of 1.0 inches. It was then repaired and the repaired wall was subjected to a further 17 cycles of loading.

The load deflection curves for the first four cycles of unreinforced wall is shown in Fig. (11). A drastic stiffness degradation occurred in the first two cycles. The maximum load in all cycles remained below 33 kips. After the fifth cycle, the force deflection curve for the panel became very similar to that of the metallic frame, indicating that the contribution of the masonry to the overall stiffness of the panel was minimal.

Cracks along the masonry joints and in some corners blocks were observed when the maximum displacement was below 0.25 inches. After 11 cycles, cracking of some blocks close to the columns of the frame was observed. Shear failure and crumbling of mortar joints with relative slip of the blocks along these joints was evident.

The load deflection curves for the first four cycles of the repaired wall are shown in Fig.(12). It can be seen that the stiffness of the repaired wall was much larger than the undamaged unreinforced wall. With small displacements of up to 0.12 inches, there was no noticeable stiffness degradation. Initial damage was observed at the corners when the cycle displacement reached 0.16 inches. However, the stiffness remained high and the stiffness degradation relatively small. A load of over 100 kips was reached in cycle 7 with a displacement of 0.3 inches. It is interesting to compare this maximum load with that attained by the reinforced undamaged wall of category (i).

The stiffness degradation characteristic and the energy absorption capacity for the unreinforced wall and the repaired wall are shown in Fig. (13) and Fig. (14) respectively. The superiority of the repaired wall over the unreinforced wall is obvious. It is interesting to note that the energy absorption capacity appears to reach a plateau. This is in contrast to the corresponding curve for the reinforced wall as given in Fig. (5).

Other than some minor crushing of the mortar layer at the corners, the main observed damage consisted of some diagonal cracks in the reinforcing layers. These cracks closed to become very fine cracks after the load was removed.

Since the observed damage was minimal after 17 cycles of loading, it was decided to test the strength of this panel subjected to loading normal to the plane of the panel. Angles were welded to the upper and bottom beams to keep the panel attached to the frame during the test. The test was performed with the wall plane in horizontal position, and supported at the four corners. The applied load was distributed over a square foot area at the centre of the panel. Deflections were recorded at the centre of the panel and at the centre of the upper and lower beams. The load deflection diagram for the centre of the panel is shown in Fig. (15). The behaviour was elastic up to a load of 8 kips. At the load of 10 kips large plastic deformations were observed, and a net deflection of more than 1" was reached. Some cracks appeared on the reinforcement shells on both sides. The crack pattern followed closely what is predicted by yield line theory in the bending of the slabs. After the test, in spite of the large deflections and cracks, the panel kept its integrity.

CONCLUSIONS

Based on the load-deflection behaviour and the observed cracking patterns in the test specimens, the following qualitative conclusions can be drawn: (1) Similar to internal reinforcing, externally reinforcing masonry performs much better than unreinforced masonry when subjected to cyclic loading. (2) Walls with reinforcing on both faces perform better than walls with reinforcing on one face only. Provided adequate bonding exists, the two reinforcing layers have a confining effect and act similarly to the stressed skins of a sandwich panel. (3) Damaged walls repaired by means of external reinforcing behave almost as well as undamaged walls similarly reinforced. (4) The damage pattern is different for externally reinforcing walls as compared to internally reinforced walls. Due to the sandwiching effect of the two outer reinforcing layers, the wall remains intact as a unit even after the masonry blocks are cracked. In addition, it possesses substantial strength in a direction normal to its plane after a number of loading cycles. This **is** a distinct advantage of externally reinforced masonry. There is no fall-out of debris after reversible loading such as is commonly associated with other masonry construction.

There are still a number of important questions which remain to be answered. Technically, the effect of vertical loading has not been studied. Economically, the cost of externally reinforcing masonry may be a controlling factor for it to be used in practice. Nevertheless, the present study shows that externally reinforcing masonry does provide a feasible alternative in solving the problems of strengthening and repairing unreinforced masonry construction.

ACKNOWLEDGMENT

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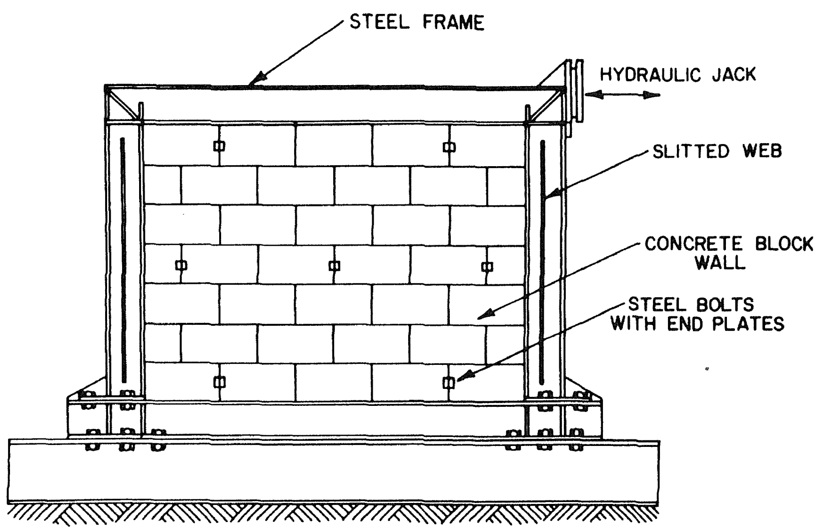

FIG. 1 TEST SET UP

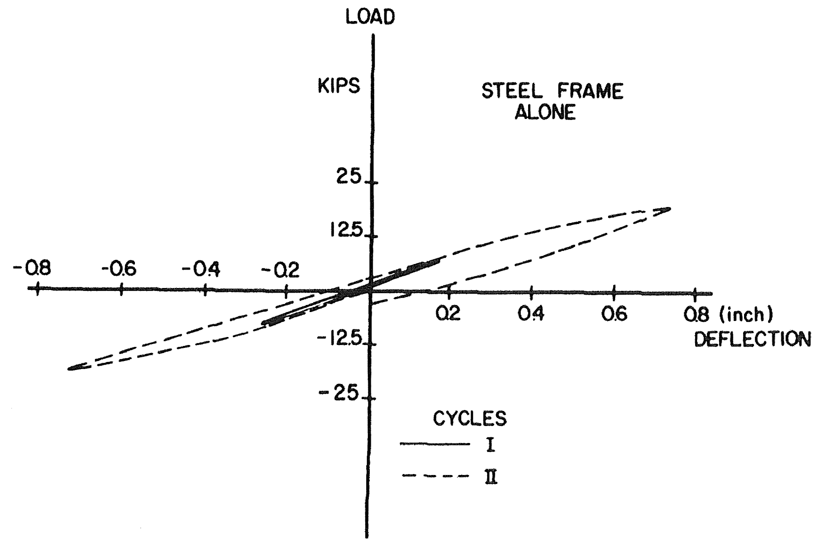

FIG. 2 LOAD DEFLECTION CURVES FOR STEEL FRAME

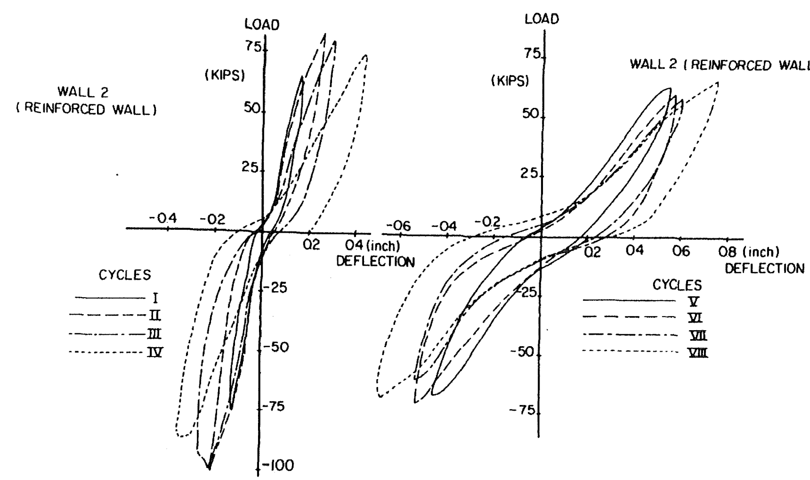

FIG. 3 LOAD DEFLECTION CURVES FOR REINFORCED WALL

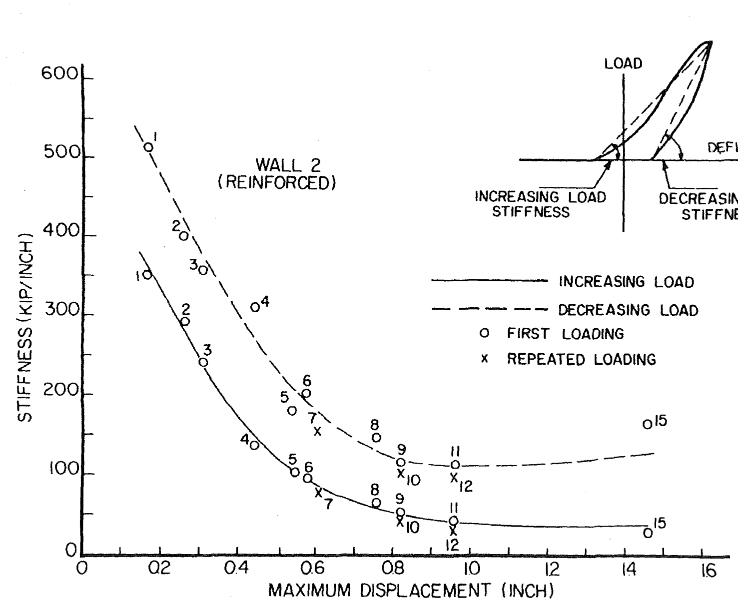

FIG. 4 STIFFNESS DEGRADATION CURVE FOR REINFORCED WALL

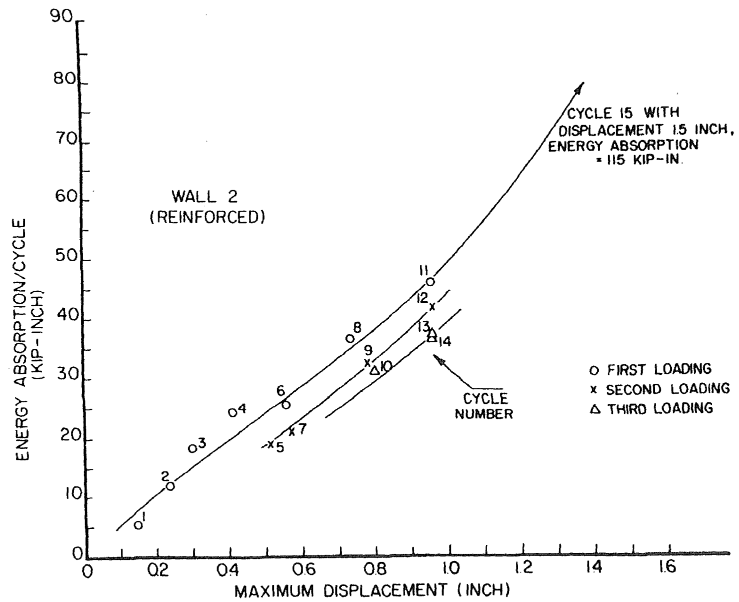

FIG. 5 ENERGY ABSORPTION CURVE FOR REINFORCED WALL

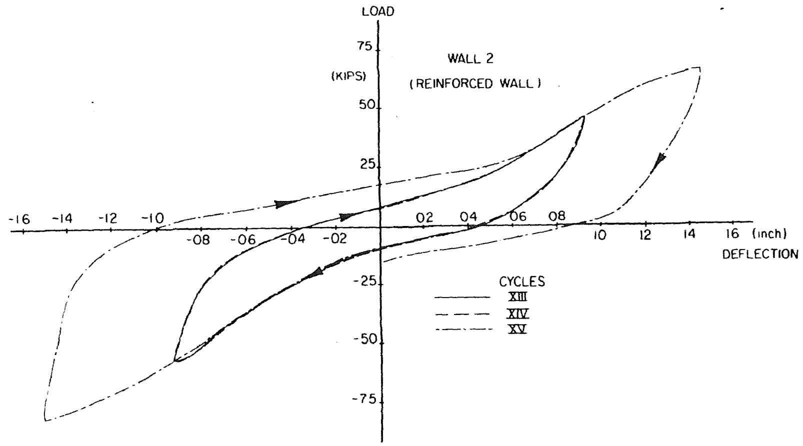

FIG. 6 LOAD DEFLECTION CURVE FOR REINFORCED WALL

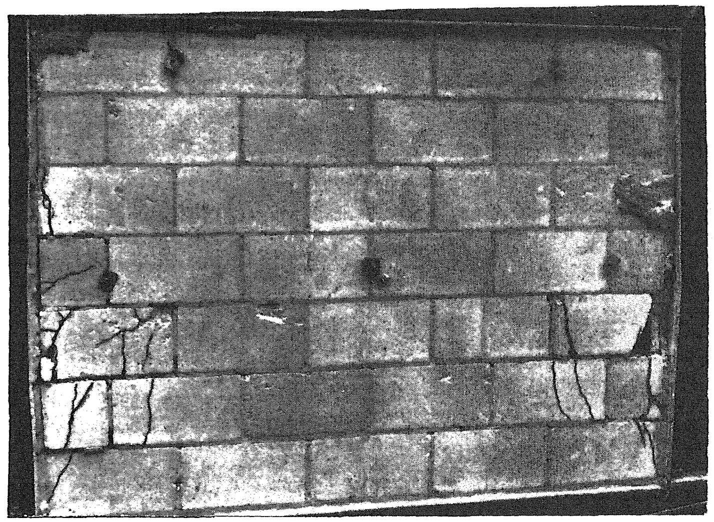

FIG. 7 DAMAGED PATTERN OF REINFORCED WALL AFTER REINFORCEMENT REMOVED

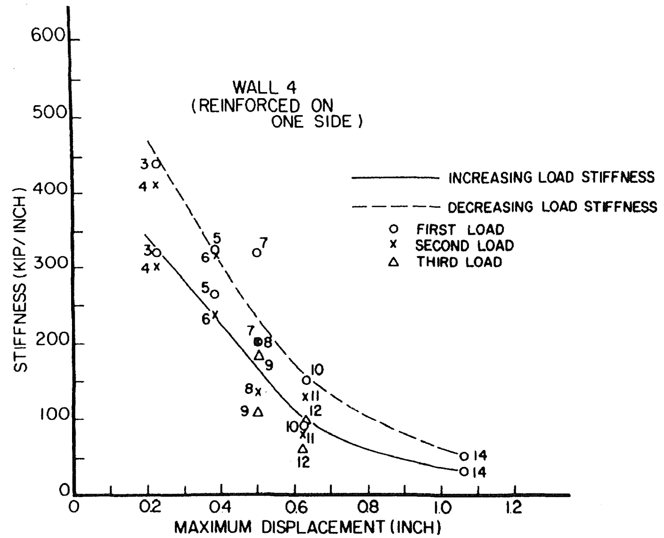

FIG. 8 STIFFNESS DEGRADATION CURVE FOR WALL REINFORCED ON ONE SIDE

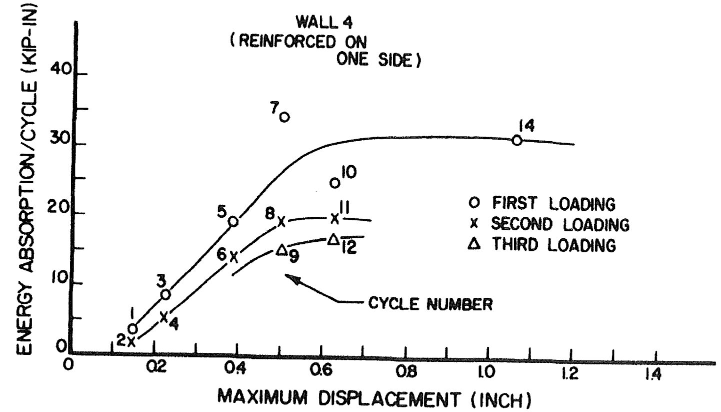

FIG. 9 ENERGY ABSORPTION CURVE FOR WALL REINFORCED

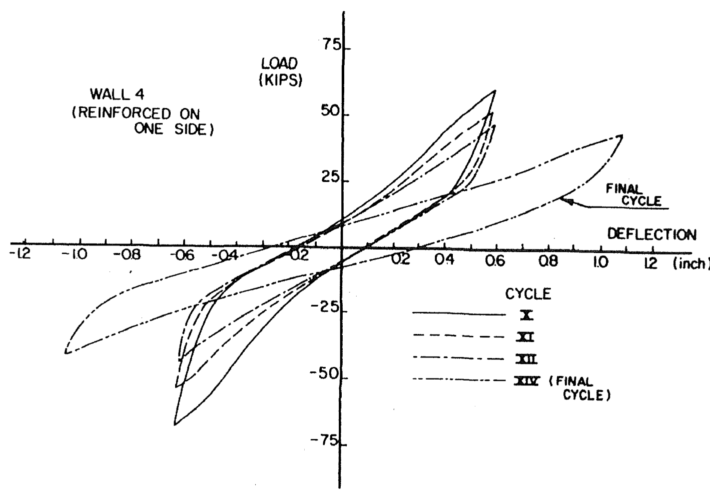

FIG. 10 LOAD DEFLECTION CURVES FOR WALL REINFORCED ON ONE SIDE

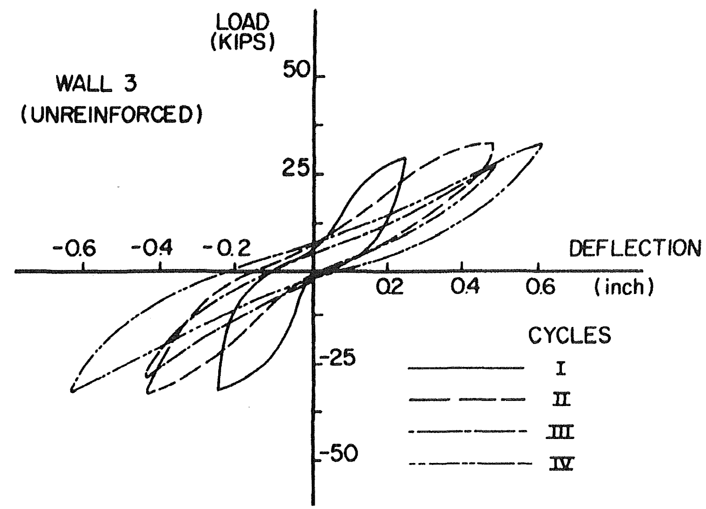

FIG. 11 LOAD DEFLECTION CURVE FOR UNREINFORCED WALL

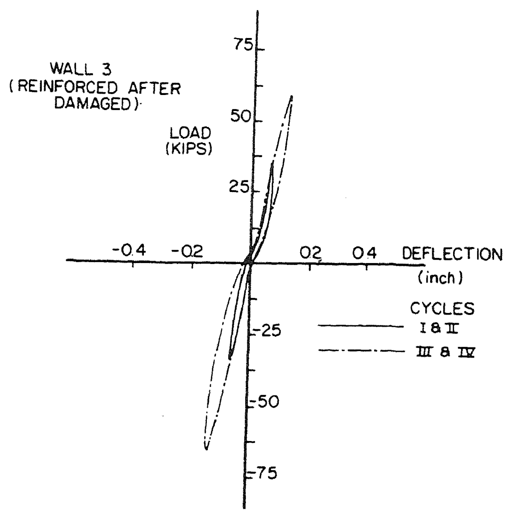

FIG. 12 LOAD DEFLECTION CURVE FOR REPAIRED WALL

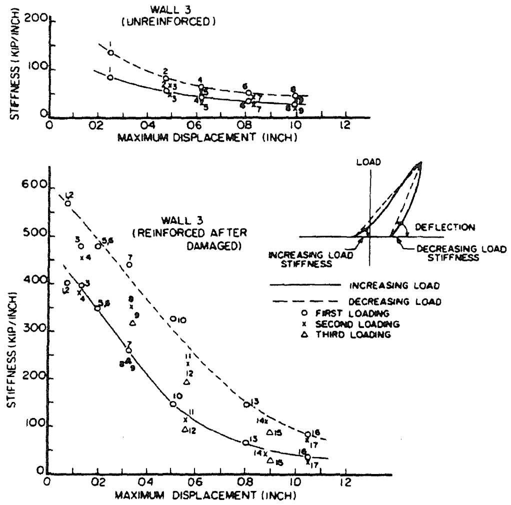

FIG. 13 STIFFNESS DEGRADATION CHARACTERISTICS

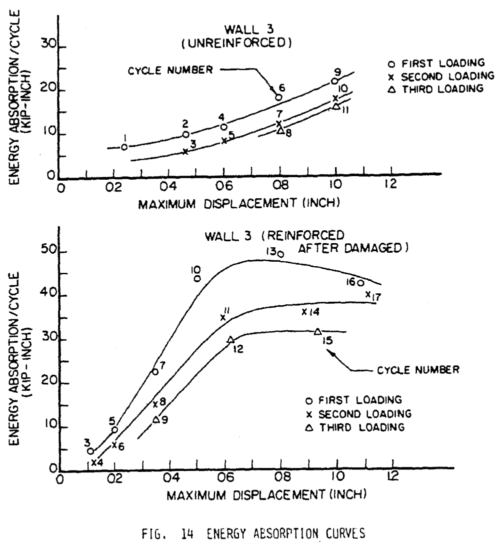

FIG. 14 ENERGY ABSORPTION CURVES

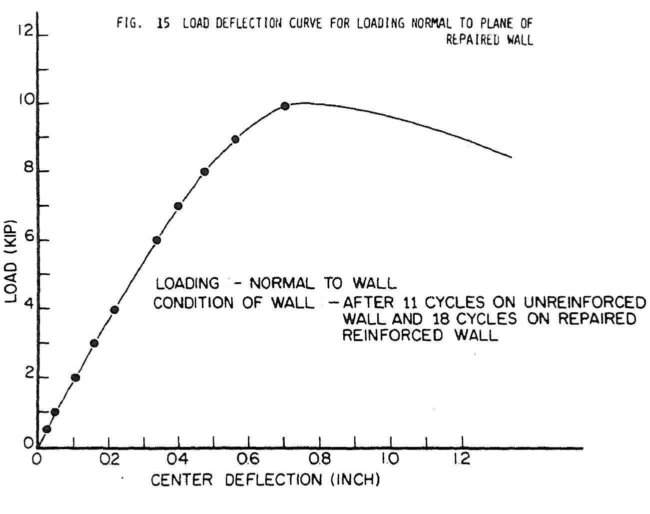

FIG. 15 LOAD DEFLECTION CURVE FOR LOADING NORMAL TO PLANE OF REPAIRED WALL