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TECHNIQUE FOR STRENGTHENING OF MASONRY WALL PANELS USING STEEL STRIPS

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ABSTRACT

An experimental research program was undertaken to ascertain the compressive and shear strength enhancement of masonry wall panels using steel strips. The study includes eight wall panels, four each for compressive and shear strength evaluation. In each group of four walls, one wall was un-strengthened, the second was single sided coarse steel mesh, the third was double sided coarse steel mesh and the fourth one was single sided fine steel mesh with closely spaced horizontal strips. Separate testing arrangements were made for compressive and shear strength determination. During compression testing only vertical load was applied and for shear strength determination, lateral load with vertical pre-compression was applied. During the test observations were recorded covering all important parameters like stress-strain, vertical load-deflection, lateral load-deflection and behavior of steel strips under vertical and lateral loading. Load carrying mechanisms were observed, varying from the initial, un-cracked state, to the final, fully cracked state. The results demonstrate that a significant increase in compressive and shear strength can be achieved by anchoring steel strips to the surface of masonry walls. It is concluded on the basis of experimental work that the technique / approach is viable for rehabilitation of old deteriorating buildings and strengthening of un-reinforced masonry structures in seismic zones.

Keywords: Masonry walls, strengthening technique, ductility, masonry confinement, steel strips mesh

1. INTRODUCTION

In Pakistan, masonry structures are very common and all the monumental buildings including old ones are made of brick masonry. Masonry strengthening specially in shear is of particular interest in Pakistan, which is now considered as prone to seismic activities. It is also beneficial for existing masonry structures requiring repair. The old parts of cities have multistory un-reinforced masonry (URM) buildings out of which some are centuries old.

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These buildings are in very poor and dangerous conditions due to lack of maintenance which has caused rapid wearing out of material and deteriorated the buildings adversely. For example only in Lahore, Pakistan, due to aging and lack of maintenance large number of buildings has been declared dangerous. As per official record 540 buildings have been declared dangerous out of which 70 buildings require immediate demolition [1]. Old residential buildings in Lahore and also buildings in seismic zone may require strengthening to enhance their life and to reduce their vulnerability against lateral and compressive load failure. In these buildings, preservation of existing architecture does not govern and the strengthening can be applied to a larger area of the structure. Moreover, during 8^{th} October earthquake, which struck Northern Areas of Pakistan, a large number of masonry structures were damaged and a strong need was felt to develop a simplified and cost effective technique for their strengthening. To fulfill the need, a technique to strengthen the un-reinforced masonry wall panel using steel strips was experimentally investigated.

The masonry wall panel test specimens were prepared in the laboratory for carrying out compressive and shear tests. The size of the panel was kept as 4×4 feet square. Eight masonry wall panels were constructed for carrying out compressive and shear tests with different steel mesh arrangements. The first class bricks procured from local market were used having 1610psi average compressive strength and 13.45% water absorption rate. These bricks were laid in 1:4 cement/sand mortar with 0.6 w/c ratio. The wall panels were strengthened with galvanized mild steel strips having dimension of 45×1.3 mm and with yield strength (f_y) of 33 Ksi and ultimate strength (f_u) of 44 Ksi. 45mm long bolts having 6mm diameter along with plastic rivets were used to ensure proper anchorage of strips to the wall. In the present study steel strips are externally applied to the wall surface. The main advantage of this approach is its simplicity, elimination of visible alteration and cost effectiveness as the steel strips used for strengthening are cheap and locally available in the market. Masonry panels with end as well as intermediate anchorages were tested for vertical loads to determine the compressive strength with and without steel strips and to compare the effectiveness of steel strips. The various stages of failure are observed ranging from initial, un-cracked state to the final, fully cracked state.

2. LITERATURE REVIEW

A variety of approaches have previously been tried for strengthening masonry using FRP and steel. One approach of strengthening is to embed FRP rods into the horizontal joints of masonry walls [12,13]. Among the advantages of this method is the lack of visible alteration to the structure and the minimum use of binding resins, however, inserting the FRP rods and re-pointing the masonry is labor intensive. An alternative approach is to apply the FRP over the surface of the masonry. Strips of FRP, containing unidirectional fibers, are bonded to the surface of a wall and arranged to give an external truss system, tailored according to the applied load [14]. In addition to this, there are number of conventional retrofitting techniques which use steel as strengthening material for example shotcrete in which closely spaced multiple layers of hardware mesh of fine rods with reinforcement ratio of 3-8% completely embedded in a high strength cement mortar layer [2,4,5,6,7]. The center core method was. The center core system, introduced by Plecnik [9], consists of a reinforced, grouted core placed in the center of an existing URM wall. A continuous vertical hole is drilled from top to the bottom of wall. Post tensioning technique involves a compressive force applied to masonry wall. This force counteracts the tensile stresses resulting from lateral loads. Post tensioning technique was researched by Lissel and Shrive [11], Rosenboom, Kowalsky [8], and Schultz [10]. There are many other retrofitting techniques, which utilize external application of steel for strengthening the masonry structures. All these techniques are expensive, difficult to apply and require special skills, where as the present technique is simple, cost effective and can be applied to any existing masonry structures.

3. NOMENCLATURE AND TESTING ARRANGEMENTS

Four masonry wall panels each with same strengthening arrangements were prepared in the laboratory for compressive and shear testing. The size and dimension of the wall was kept constant as shown in Figure 1.

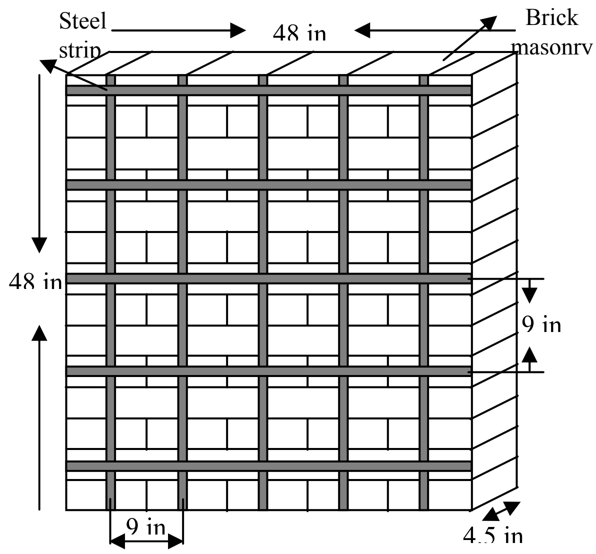

Figure 1. Layout of masonry wall panel

3.1 First panel was prepared without any reinforcement / strengthening. The size of the panel was kept as four feet square and was designated as US panel. It was kept as reference wall to determine the effectiveness of steel mesh application in compressive and shear strength enhancement. The pictorial view of US panel under lateral testing is shown in Figure 2.

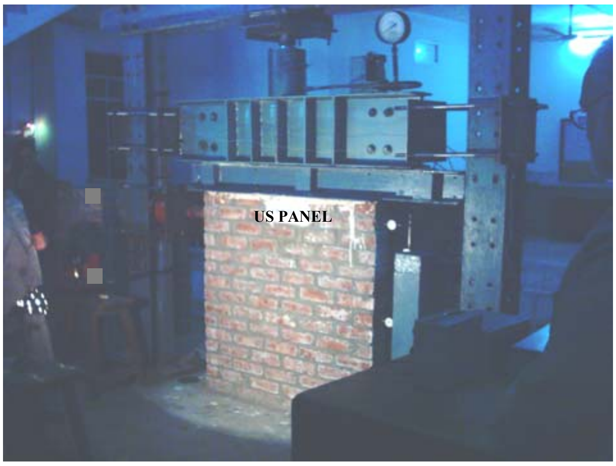

Figure 2. Un-strengthened masonry wall Panel

3.2 The second masonry wall panel was constructed and strengthened with steel strips in vertical and horizontal directions on one side of the wall. Vertical strips were anchored with bolts at a spacing of 9 inches center-to-center and horizontal strips 6 inches center-to-center making fine steel strips mesh. The wall specimen is designated as FSM panel (Figure 3).

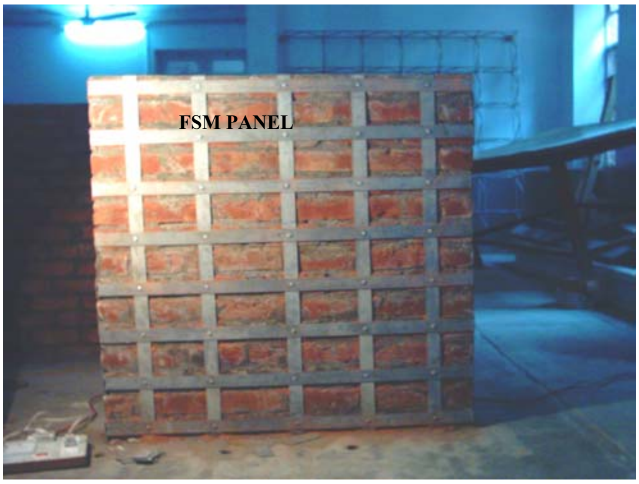

Figure 3. Fine steel mesh masonry panel

3.3 The third masonry wall panel was strengthened with steel strips in vertical and horizontal directions with increased spacing of horizontal strips as compared to FSM panel and was designated as SCM panel. Again the steel mesh was applied to only one side of the wall. Vertical strips and horizontal strips were anchored at a spacing of 9 inches center to center as shown in Figure 4.

Figure 4. Single coarse mesh masonry panel

3.4 The fourth masonry wall panel was strengthened with steel strips in vertical and horizontal directions on both sides of the wall. The spacing of vertical strips and horizontal strips were kept same as for SCM panel. It was designated as DCM Panel and Figure 5 shows the DCM panel during shear testing.

Figure 5. Double coarse mesh masonry panel

3.5 Compressive testing arrangement

A vertical in-plane compressive load was applied to all the four wall specimens. The vertical load was applied through connected hydraulic jack. This load was distributed over the top of the specimen by a rigid steel beam resting on the leveling plate. The vertical load was applied to the wall in small increments till failure to assess the failure pattern. One deflection gauge was attached at vertical center of the masonry wall panel to calculate the buckling of the wall under vertical load. In order to calculate the vertical and horizontal strains produced in the masonry wall under compressive load, DIMMIC points were attached to the wall panel with the help of adhesive. Two DIMMIC points each in vertical and horizontal direction are attached to brick masonry at a distance of 8 inches apart(gauge length). Strain values were calculated from the readings taken from DIMMIC gauges. Similar arrangements are made for steel strips to measure strains produced under compressive load.

3.6 Shear testing arrangement

A combination of vertical load (simulating load from the building above) and in-plane shear lateral load was applied to all the four specimens. The vertical pre-set load of 18 ton was applied through hydraulic jack. The jack was placed on the top of the stiff steel horizontal reaction beam, which was restrained horizontally by steel bars and resting on the rigid steel beam. A flat polytetrafluoroethylene (PTFE) bearing was placed between the stiff horizontal reaction beam and rigid steel beam. The vertical concentrated load was distributed all along the wall top through rigid steel beam. The testing arrangement adopted for the shear test is shown in Figure 6.

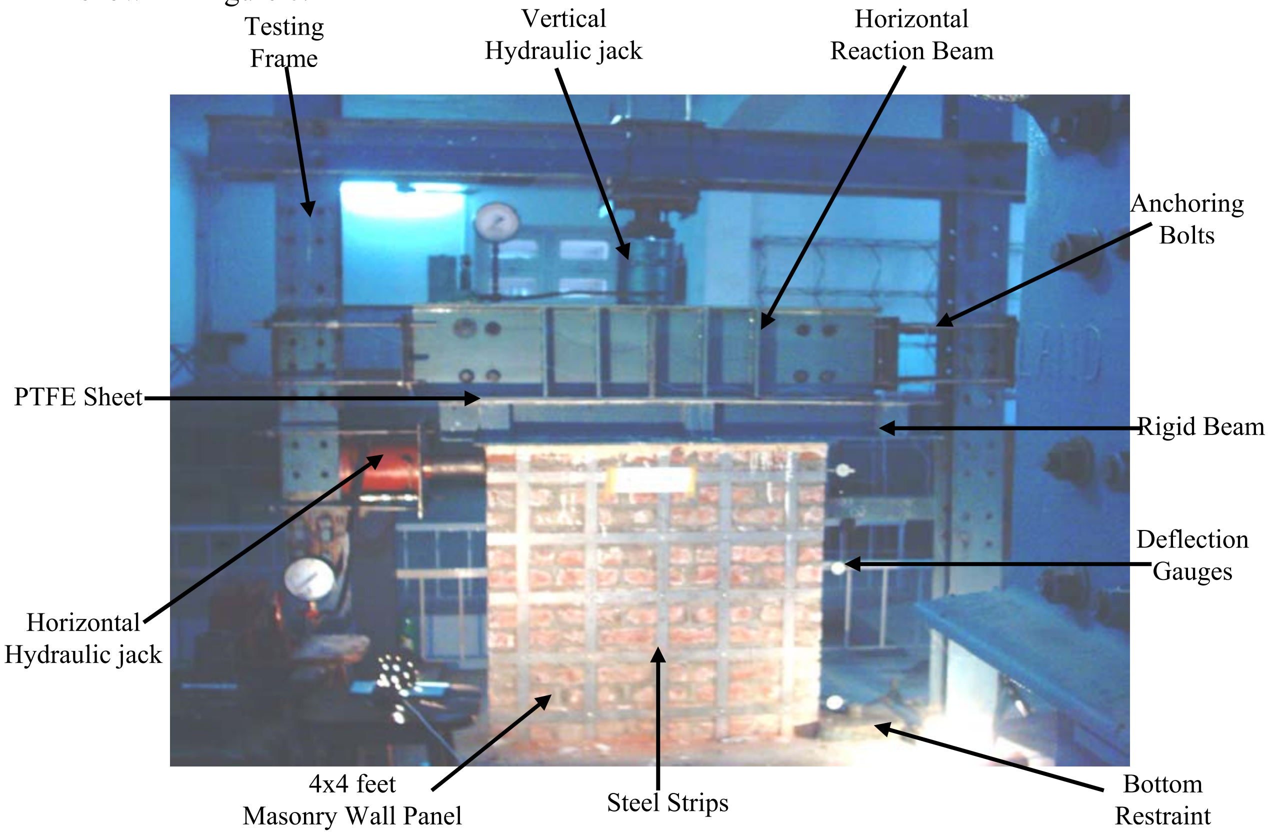

Figure 6. A typical masonry wall panel under shear test arrangement

The PTFE bearing allowed the rigid steel beam to slide horizontally relative to the horizontal reaction beam. The shear load was applied to the wall by a horizontal hydraulic jack. To assess the proportion of this load carried across the PTFE bearing by friction, strain gauges were attached to the anchoring bolts, giving the horizontal reaction force. The horizontal deflection was measured using a deflection gauge at the same level as the lateral load application point. The deflection gauges were also attached at middle and bottom of the wall to measure the horizontal deflection under lateral load. Moreover, DIMMIC points were attached with steel strips and un-reinforced masonry wall in horizontal direction in the center of the wall to determine the horizontal strain produced under lateral load. In order to avoid the sliding, the bottom of the wall was horizontally restrained. The load was applied in small increments to assess the failure pattern and crack initiation.

4. TEST RESULTS OF SPECIMEN WALL PANELS UNDER COMPRESSIVE LOAD

Testing of un-strengthened and strengthened wall panels under vertical load had generated the following results.

4.1 The compressive strength of US panel was recorded as 653.08 psi and collapse load of 65 tons. The failure load for SCM panel was 72.8 tons with an increase of 12% in compressive strength in comparison to US panel. An increase of 13.2% and 26.6% in compressive strength was recorded for FSM and DCM panels respectively. The failure load for FSM and DCM panels was 73.56 tons and 82.06 tons.

4.2 Highest strains in vertical and horizontal directions were recorded for DCM panel and least values were recorded for SCM panel as shown in Figures 7 and 8. The strain values recorded in vertical direction were much higher than the strain values in horizontal direction. The higher compressive stress-strain values for DCM panel were primarily due to confinement of masonry on both sides of the wall. The compressive stresses in FSM and SCM panels were almost same but slightly higher values of strain were recorded for FSM panel due to more reinforcement ratio. However, much higher values of compressive stress-strain were recorded in strengthened panels as compared to US panel. The vertical strips contributed more in strength enhancement as compared to horizontal strips.

4.3 For steel strips, maximum values of strain in vertical and horizontal directions were recorded for DCM panel and least values were observed for SCM panel (same as recorded earlier for brick masonry) as shown in Figures 9 and 10. The strain values in steel strips in both the direction varied in a similar manner as earlier recorded for masonry. However, after the appearance of micro cracks in masonry, buckling in vertical steel strips was observed.

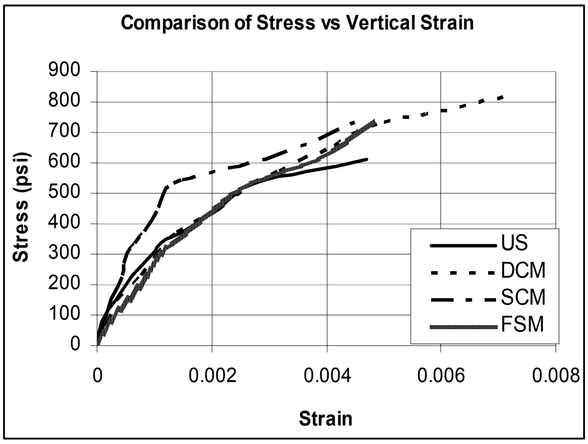

Figure 7. Stress vs vertical strain comparison

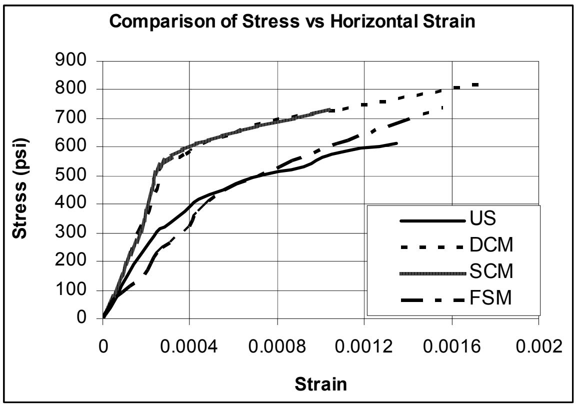

Figure 8. Stress vs horizontal strain comparison

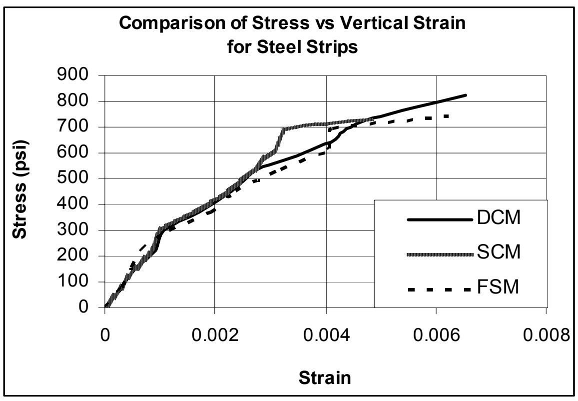

Figure 9. Stress vs vertical strain in steel strips

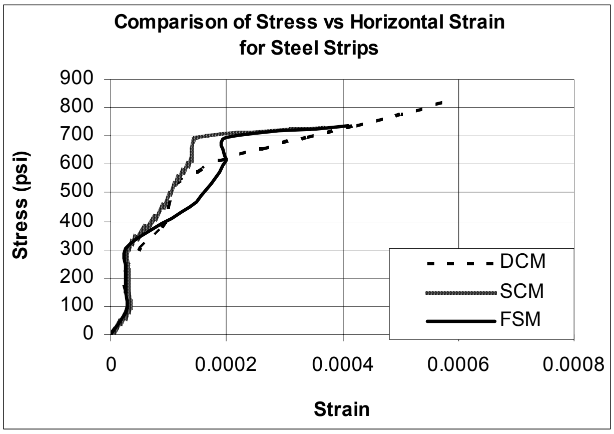

Figure 10. Stress vs horizontal strain in steel strips

5. FAILURE PATTERN OF SPECIMEN MASONRY WALL PANELS

All the four panels were tested under compressive load. The load was applied in small increments till failure to study the crack pattern of the panels. The failure patterns observed in different panels are as under.

5.1 In US panel minor cracks appeared at vertical load of 30 tons corresponding to a compressive stress of 301.42 psi. These cracks were widened as the load was increased. Initially the cracks appeared in the direction of loading and spread all along the width of the wall. This propagation of cracks caused the crushing of bricks along fourth wythe and the wall completely collapsed at a vertical load of 65 tons. More values of vertical strains were observed as compared to horizontal strain under same compressive stresses.

5.2 In the DCM panel minor cracks appeared at vertical load of 53 tons corresponding to a compressive stress of 532.51 psi. The cracks appeared in direction of load application and were widened on increasing the load causing buckling of vertical steel strips. The failure occurred at a compressive load of 82.06 tons corresponding to a stress of 824.49psi. The plane of failure was along the third / fourth wythe extending from center to right as shown in Figure 11. The failure was not sudden and good composite behavior was observed due to presence of steel strips. The vertical strips contributed more than the horizontal strips and considerable increase in compressive strength was achieved due to confinement of masonry on both sides of the wall panel.

5.3 In SCM panel minor cracks appeared at vertical load of 45 tons corresponding to a stress of 452.1 psi with buckling of vertical strips. The failure occurred at a vertical load of 72.8 tons corresponding to a stress of 731.45psi. The failure plane was observed along second / third wythe extending from left to right in a straight line as shown in Figure 12. The location of failure zone was almost same as for DCM panel and the residual strength recorded after failure was 30 tons. The wall showed good composite behavior along with increase in compressive strength in comparison to US panel.

Figure 11. DCM wall panel failure

Figure 12. SCM wall panel at failure

5.4 In the FSM panel minor cracks appeared at vertical load of 53 tons same as for the DCM panel. The failure occurred at a vertical load of 73.56 tons corresponding to a compressive stress of 739.09psi. The plane of failure was along a straight line at the center of the panel as shown in Figure 13. The panel showed good composite behavior due to presence of steel strips. At initiation of cracks the buckling of vertical steel strips started and it was maximum at failure.

Figure 13. FSM wall panel at failure

6. DISCUSSION ON COMPRESSIVE TEST RESULTS

After carrying out compressive testing it was revealed that maximum compressive strength and strain values in both the directions were achieved in case of DCM panel as shown in table 1. The strain values in steel strips were also recorded in a similar pattern as for the masonry wall panel. More values of strain in vertical direction were recorded as compared to strains in horizontal direction. Significant increase in compressive strength was achieved for walls strengthened on both the faces. However, increase in compressive strength was primarily due to vertical strips and horizontal strips contributed less in strength enhancement. The higher elastic limits were recorded for double side application of steel strips. In case of coarse and fine steel mesh, the elastic limits were almost same. For US panel, the initiation of cracks started at much lesser vertical load and resulted in sudden collapse. Overall, much better performance of strengthened masonry wall panels was observed as compared to US panels. The summary of results obtained during compressive testing is given in Table 1.

Table 1. Comparison of compressive test results of masonry wall panels

Test Results	US	DCM	SCM	FSM
Compressive strength (tons)	65	82.06	72.8	73.56
% age increase	-	26.26	12	13.2
Compressive stress (psi)	653.08	824.49	731.45	739.09
Masonry strain in vertical direction	0.0047	0.0073	0.0045	0.00485
Masonry strain in horizontal direction	0.0014	0.0073	0.0010	0.00156
Steel strain in vertical direction	-	0.00654	0.0049	0.0062
Steel strain in horizontal direction	-	0.000586	0.00037	0.000411

6. TEST RESULTS OF WALL PANELS UNDER LATERAL LOAD

All the four panels were tested under lateral load with a pre-compressive load of 18 tons applied on each panel. Results are as under.

6.1 The shear strength of US masonry wall panel was recorded as 9.243 tons, where as that of DCM panel were 17.3 tons showing an increase of 87 percent. An increase of 40.76 % and 29.6 % was recorded for FSM and SCM panels respectively.

6.2 More values of lateral displacement at top were recorded for DCM panel and least for FSM panel. The graphical representation of deflection at top for all the masonry wall panels is shown in figure 14. Maximum value of lateral displacement at mid-height was recorded in case of SCM panel as shown in figure 15. However, much higher elastic limit was achieved in case of DCM panel

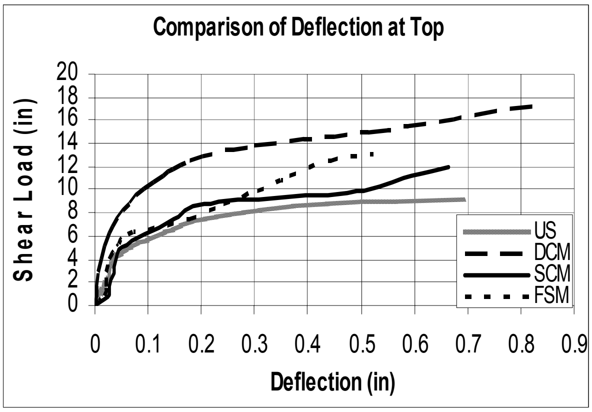

Figure 14. Lateral load vs deflection at top

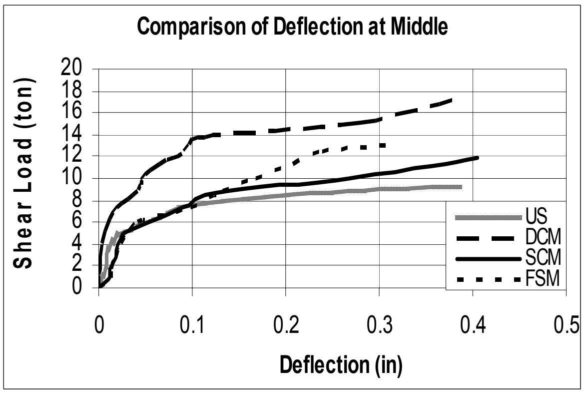

Figure 15. Lateral load vs middle deflection

6.3 Maximum strain in horizontal direction was recorded for DCM panel and least strain was recorded for FSM panel as shown in Figure 16.

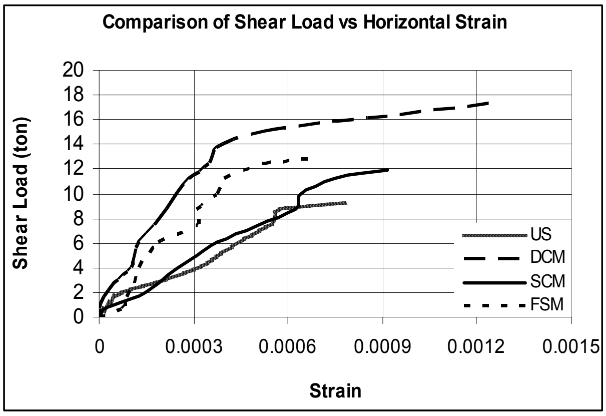

Figure. 16 Lateral load vs horizontal strain

6.4 Discussion on shear test results

Strengthening of masonry wall panels using steel strips results in considerable increase in shear strength. The elastic limit also increased reasonably due to steel mesh confinement. Maximum values of lateral displacement and strains were recorded in case of DCM panel. The details of shear test results obtained are summarized in Table 2. Similar failure pattern, i.e. diagonal cracking was observed in all the strengthened masonry wall panels. However, sliding shear failure was observed in US panel.

The comparison of compressive and shear strength enhancement due to steel strips are summarized in the Table 3. It is evident that DCM panel gave maximum compressive and shear strength enhancement. In case of SCM and FSM panels the increase in compressive and shear strength is almost same.

Table 2. Details of shear test results

Test Result	**US**	**DCM**	**SCM**	**FSM**
Shear strength	9.243	17.3	11.979	13.01
% Age increase	-	87.2	29.6	40.76
Lateral displacement at top	0.696	0.845	0.665	0.522
Lateral displacement at middle	0.387	0.389	0.405.	0.306
Strain in horizontal direction	0.0008	0.0013	0.00091	0.0007

Table 3. Comparison of shear test results for masonry wall panels

S/N	Panel Type	US Panel	DCM Panel	SCM Panel	FSM Panel
1	Compressive failure stress (psi)	653.1	824.5	731.4	739.1
2	Failure stress in shear (tons)	9.243	17.3	11.98	13.01
3	%Age increase as per US panel				
a	Compression (psi)	-	26.26	12	13.2
b	Shear (tons)	-	87.2	29.6	40.76

7. SHEAR FAILURE OF MASONRY WALL PANELS

The failure pattern observed after testing strengthened and un-strengthened masonry wall panels under lateral loads are as below.

7.1 In US panel, cracks appeared at

Right edge of 14th wythe and sliding along horizontal plane in the bed mortar between 13th and 14th wythes was observed as shown in the Figure 17. Rocking as well as sliding of wall panel was also noticed**.**

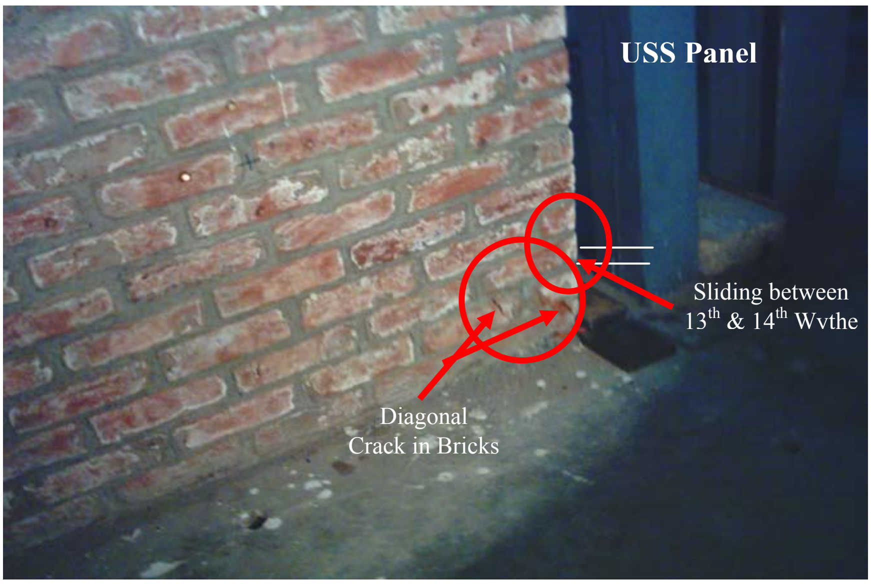

Figure 17. Sliding failure of un-strengthened masonry wall panel

7.2 In DCM panel diagonal cracks appeared which were initiated from load application point and extending towards the right bottom edge. The cracks were produced generally in the vertical joints and mortar bed extending from top to bottom in the direction of lateral load. Cracks also traveled through bricks at right top point of load application and at the bottom causing crushing of bricks as shown in Figure 18. The failure was not sudden and good composite behavior was observed with sufficient residual strength due to presence of steel strips. The strength increase was achieved primarily due to confining effect on masonry provided by steel mesh.

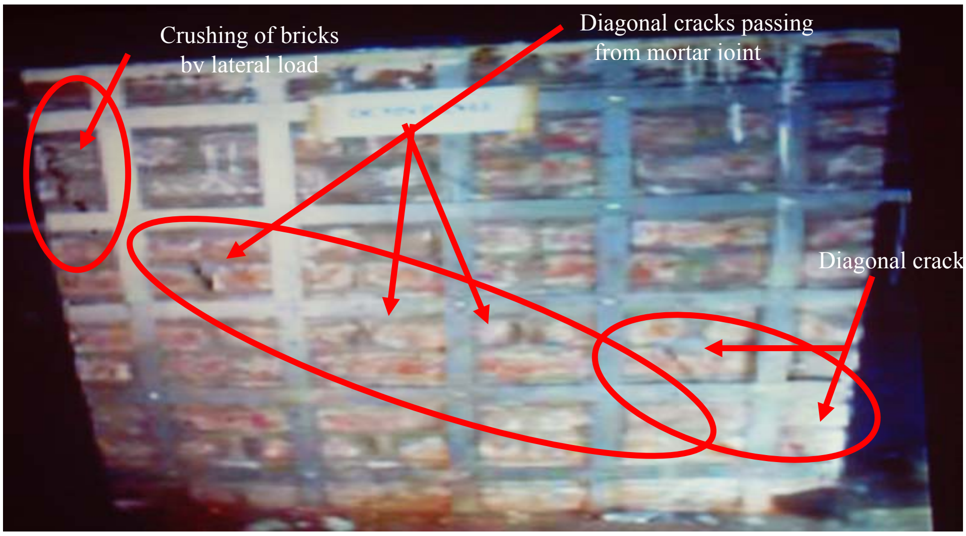

Figure 18. Shear failure of double sided coarse steel mesh masonry wall panel

7.3 In SCM panel diagonal cracks appeared starting from load application point and extending towards the right bottom edge as shown in figure 19. Similar pattern of failure was observed as noticed earlier for DCM panel. Again good composite behavior was observed due to presence of steel strips and strength increase was achieved primarily due to confining effect on masonry.

7.4 In FSM panel, the diagonal cracks were produced generally in the joints and mortar bed extending from top to bottom. Cracks also traveled through bricks at top near load application point and at the bottom where the horizontal restrain were provided as shown in Figure 20. The failure was not sudden and good composite behavior with residual strength ensuring sufficient warning time. The strength increase was achieved primarily due to confining effect on masonry.

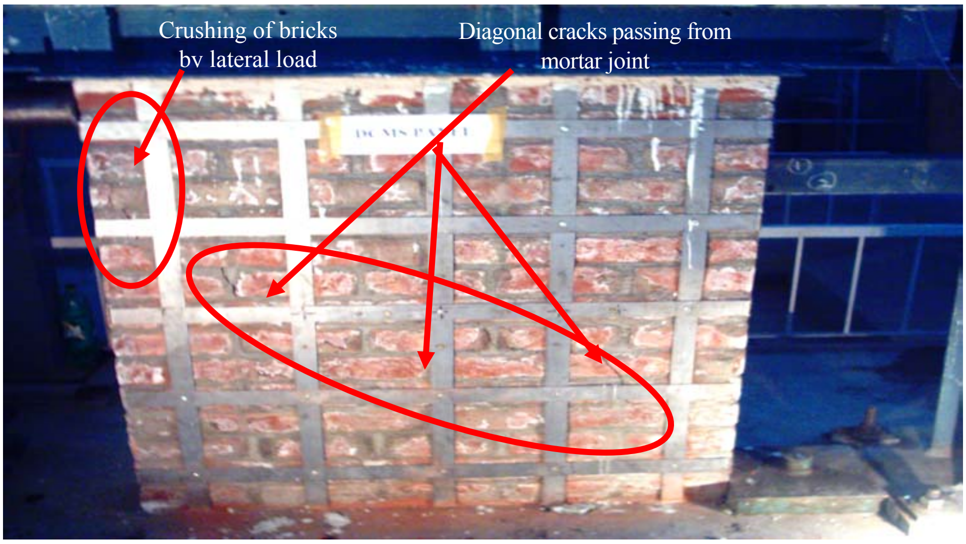

Figure. 19 Shear failure of single sided coarse steel mesh wall panel

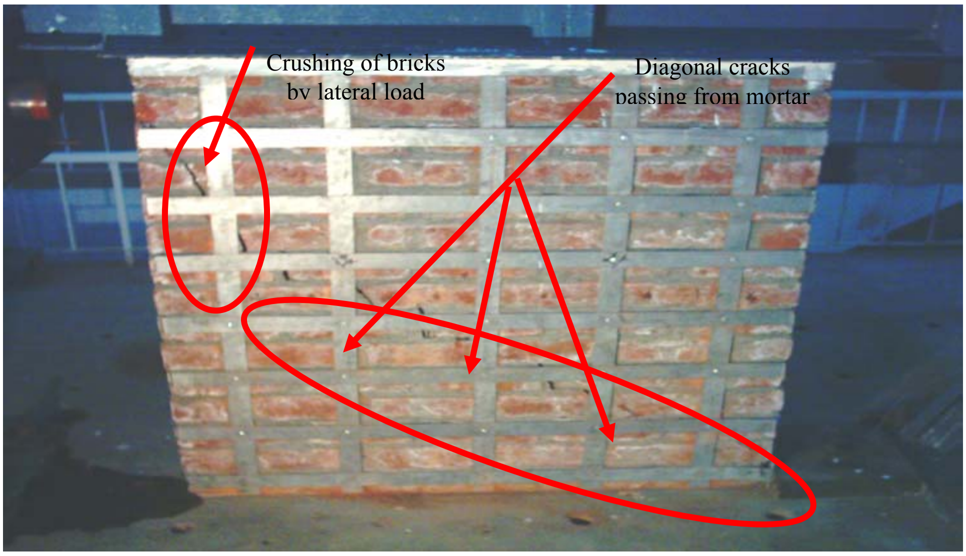

Figure 20. Shear failure of fine steel mesh wall panel

8. CONCLUDING REMARKS

An experimental work was carried out to study the enhancement of compressive and shear strength of masonry wall panels using steel strips. The conclusions are drawn and observations are made as under:-

1. The compressive strength was increased upto 12 to 26 percent due to strengthening

of masonry wall panel with steel strips. The increase was due to confinement of masonry by steel strips and wall showed reasonable composite behavior.

2. It was observed that strengthened masonry wall showed reasonable increase in elastic limit by using steel. The more ductile material, as compared to unstrengthened masonry wall panel. Micro cracking was observed at much higher loads as compared to un-strengthened masonry indicating considerable increase in elastic limit. Whereas, a sudden collapse under vertical loading was observed at failure in case of un-strengthened masonry wall panel.
3. The shear strength was increased upto 30 to 87 percent due to strengthening of masonry wall panel with steel strips, possessing more ductility. In shear testing the horizontal and vertical steel strips contributed equally in confining the masonry wall against the lateral displacement. The composite behavior and confinement of masonry improved warning time and safety of life.
4. It was observed during shear testing that initially vertical compressive strains were recorded in the steel strips under pre-compression but with increase in lateral load the tensile strains were observed.
5. The easy external application, effectiveness against lateral / gravity loads and less skill is the added advantage of the technique.
6. The technique is found effective for old buildings requiring strengthening and can be used in seismic zones after establishing the performance of strengthened masonry wall panel under dynamic and earthquake loading.

9. FUTURE RECOMMENDATIONS

The recommendations are made, based on the experimental work related to masonry wall strength enhancement are as under:-

1. It is found necessary to use computer and numerical modeling for practical application of this technique and evaluation of behavior of walls before execution of strengthening and rehabilitating with steel strips.
2. It is found important to study behavior of strengthened wall panel with addition of diagonal member of steel strips and effect of wall opening on strength.

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