eJSE International
Electronic Journal of Structural Engineering 15(1) 2015

Damping of unreinforced masonry walls retrofitted with CFRP

M.T. Mansourikia
Student at the National Academy of Science, Republic of Armenia

A. Hoback*
University of Detroit Mercy, US

*hobackas@udmercy.edu

ABSTRACT: Seventeen masonry panels were tested with in-plane loading. Three panels were unreinforced. Fourteen panels were reinforced with either CFRP laminate strips or with CFRP fabric sheets. Retrofits were placed either horizontally or diagonally, and on different sets of panels the loading was either monotonic or cyclic. Strength and damping were found. All types of retrofit with all arrangements of reinforcement produced net increases in strength under all loading. The tests showed that the strength was increased more by laminate strips than fabric sheets. However, conflicting previous studies, horizontally reinforced panels had slightly higher damping.

Keywords: earthquake rehabilitation, strengthening, infill masonry wall, CFRP

1 INTRODUCTION

Unreinforced masonry (URM) walls are a very common structural element around the world. They are more common in rural and suburban areas of the developing countries for several reasons. First, much of the development in the outer rings is from migration of low income people that can't afford the high price of steel reinforcement. However, the suburbs have some pockets of development with wealthier individuals. Second, in areas where housing is constructed without government oversight, building codes are not followed. Third, rural areas often have older building when compared to growing cities. Therefore, economical means of retrofitting URM are important, such as using low cost geotextile as a URM retrofit material. (Mansourikia & Hoback 2014)

Another issue for efficient use of retrofit materials is to understand how each material behaves under stress reversals. That allows materials to be used where it is best. Two versions of carbon fiber reinforced polymer (CFRP), laminate strips versus fabric wrap, are compared in the current tests with various orientations.

A lot of researches have shown that CFRP can be effective in retrofitting masonry walls. (Hamed & Rabinovitch 2008; Rossetti et. al. 2007; Ozcebe et. al. 2004, Ehsani et. al. 1999; Albert et. al. 2001; Mansourikia & Hovhannisyan 2012) When retrofitting URM Walls for increased in-plane strength, the laminate is often placed in two diagonals since those are the direction of maximum tension during stress reversals. Another philosophy is to place the reinforcement on a horizontal line at mid-height. According to the strut and tie method, horizontal reinforcement would be a trigonometric factor less efficient than diagonal reinforcement. This is confirmed by (Santa-Maria et. al. 2004).

Fabric wrap has been mostly used in applications that require versatility. It has been used to enhance confinement of columns. (Seible et. al. 1997) Also, beam-column joints have been wrapped. (Parvin & Blythe 2012) Fabrics have been compared to laminate strips in URM walls. (Santa-Maria et. al. 2004; Mansourikia & Hovhannisyan 2009) Santa Maria et. al. found that laminate has higher damping. Both laminate strips and wrap are relatively the same cost per application in the study area (Iran), but wrap is easier to install since it is more easily fit into place.

Unfortunately, the behavior of the retrofit is often brittle, (Nguyen et. al. 2011) so retrofits are often designed according to elastic force limits. However, damping through absorption of the energy is a primary factor of interest in seismic retrofit.

The objective of these tests will be to simulate the in-plane shear phenomenon to quantify the improvement in shear resistance, stiffness, and energy dissipation of the brittle masonry elements, and to study the effect of the load reversal on the efficiency of the reinforcement and the behavior of the panels.

2 MATERIALS AND METHODS

2.1 *Materials*

The four primary materials in the tests were the masonry, epoxy, CFRP laminate and fabric. Hollow concrete blocks (290 X 147 X 140 mm), with approximately 12-mm-thick mortar joints are used. The premixed mortar is commercially available and had an average prismatic strength of 10 MPa. In the monotonic test, the blocks had cylinder compression strengths of 18 to 22 MPa, and tension of 5 to 6 MPa. In the cyclical tests, the cylinder strength was 9 to 10 MPa, and tension of 3.1 to 3.6 MPa.

CFRP reinforcement with unidirectional laminate (Sika CarboDur S-512) and a woven carbon fabric (SikaWrap) were used in this investigation. See Figures 1 & 2, respectively. Their dimensions and main mechanical characteristics, according to the fabricator, are shown in Table 1.

Figure 1. Laminate (Sika CarboDur)

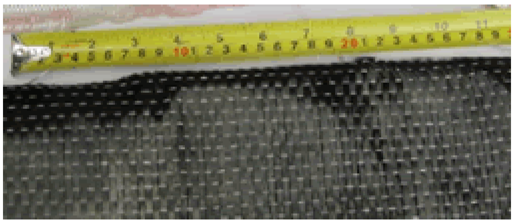

Figure 2. Fabric (Sika Wrap)

Table 1. Nominal Dimensions and Mechanical Properties of Reinforcement

Type of CFRP	Laminate	Fabric
Thickness (mm)	0.9	0.17
Characteristic tensile strength (MPa)	250	370
Tensile modulus of elasticity (GPa)	165	231
Ultimate tensile strain	0.017	0.017

The reinforcement was bonded to the URM with Epoxy: Kimitech EP-TX, ST5-607, ASTM D695-2a. Epoxy was applied along the length of the reinforcing strip. The epoxy (fig. 3) is a two-component, solvent-free thyrotrophic, epoxy resin adhesive. It does not shrink on hardening, which occurs as a result of a chemical reaction in which no volatile substances are released. The epoxy uses for high-resistance structural bonding to common building materials such as concrete, brick, stone, wood , metal. It has a compressive strength of 56 Mpa, flexural strength of 18 Mpa, and an elastic modulus of 1780 Mpa.

Figure 3. Kimitech Epoxy components (EP-TX).

2.2 *Methods*

A series of 17 masonry panels with nominal dimensions of 1060x1100x140 mm were built. Fourteen panels were reinforced with laminate or fabric sheets on each side and 3 panels were not reinforced. Some specimens were tested under monotonic loading so only had diagonal reinforcement along the diagonal opposite of the applied compression load.

Four panels were reinforced with CFRP laminates, two with 100 mm-wide laminates, and two with 200 mm-wide laminates. Ten panels were reinforced with CFRP fabrics, five with 100 mm-wide fabric sheets, and five with a 200 mm-wide fabric sheet.

The specimens are identified as follows: the first character indicates if it is a monotonic (M) or cyclic (C) test; the second shows if it is a panel unreinforced (U), with diagonal reinforcement (D), or with horizontal reinforcement (H); the third character indicates if the reinforcement is CFRP laminate (L) or fabric (F); and the last one is the specimen number. Twelve panels were reinforced diagonally and the two horizontally. The different configurations of the reinforcement are shown in Figure 4 through Figure 8. In figures with cyclic loading, the dashed arrows indicate the alternate sequence of load.

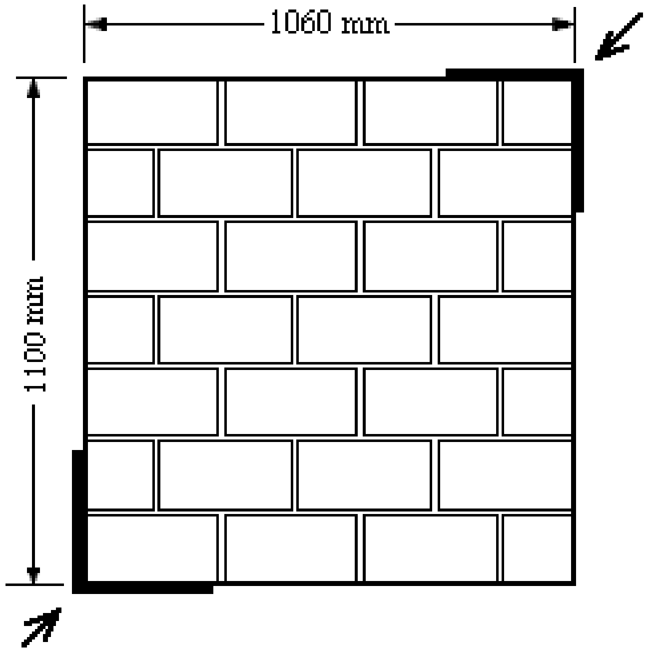

Figure 4. Test arrangement for unreinforced panels under monotonic loading (MU).

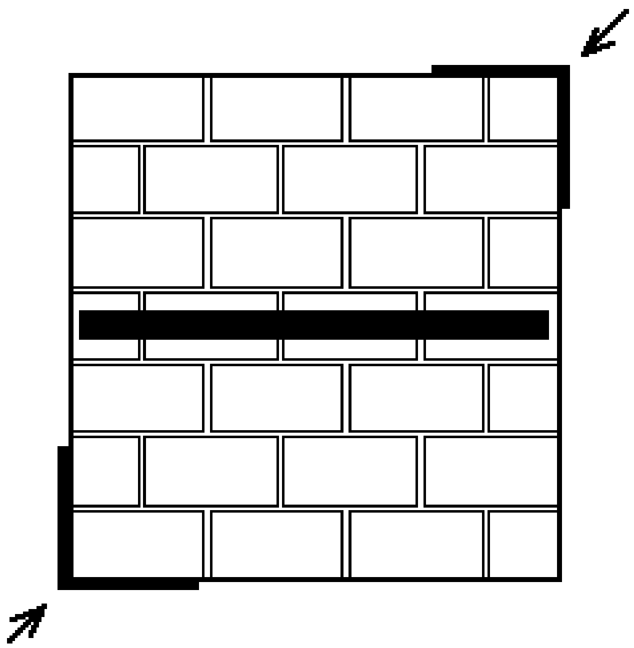

Figure 5. Test arrangement for horizontally reinforced panels under monotonic (MH).

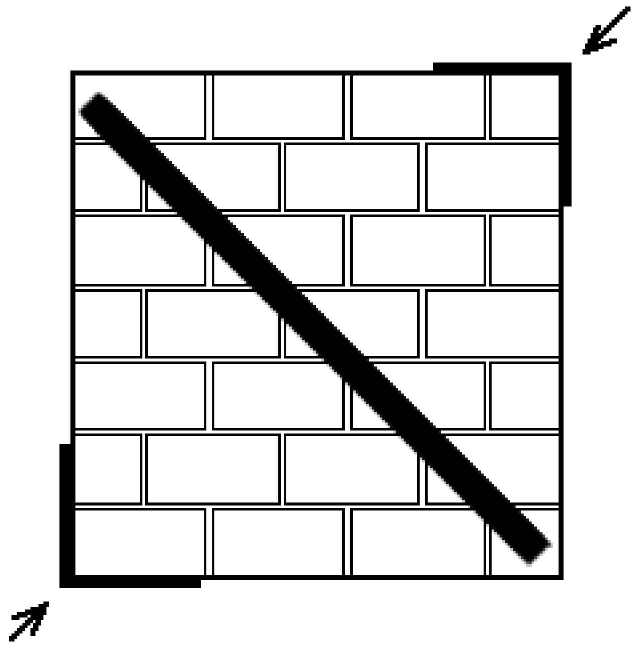

Figure 6. Test arrangement for diagonally reinforced panels under monotonic loading (MD).

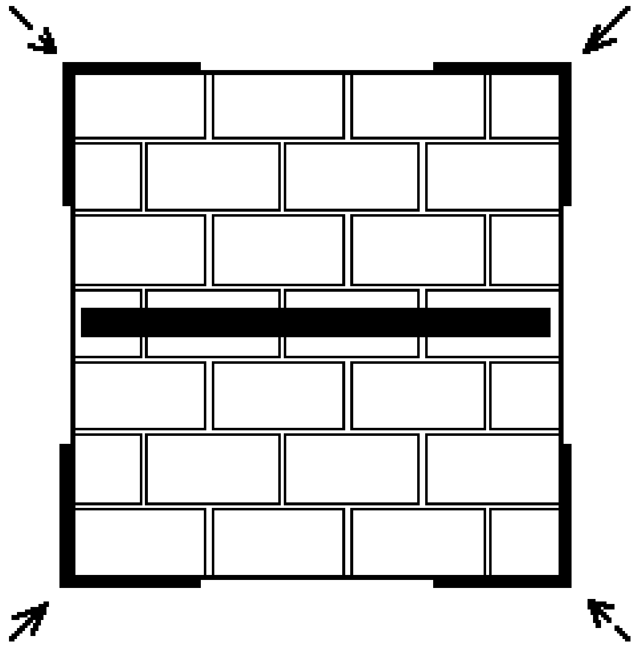

Figure 7. Test arrangement for horizontally reinforced panels under cyclic loading (CH).

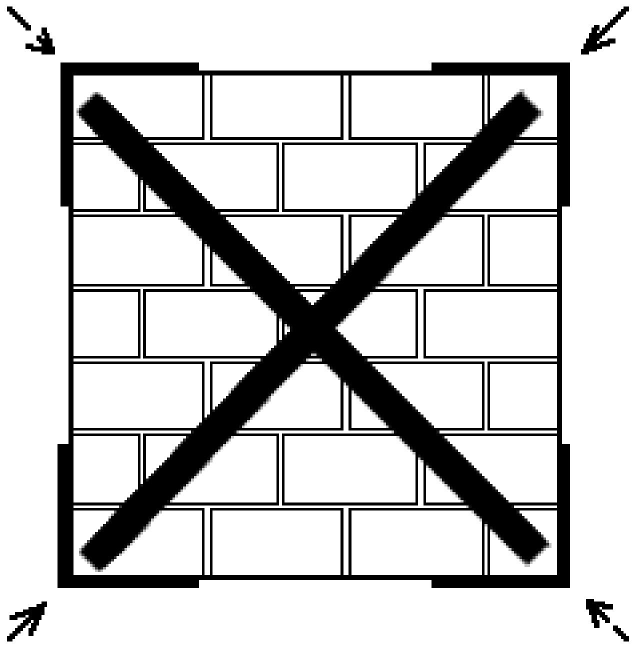

Figure 8. Test arrangement for diagonally reinforced panels under cyclic loading (CD).

The test equipment included hydraulic rams, tension rods as shown in Figure 9. This is a common arrangement among other experimenters. (Mahmood & Ingham 2011) In actual structures, the load is applied through a shear force at the top of the wall, or if the wall is in-fill, then columns also provide force through dowel action. The compression strut analogy for analyzing walls shows that the applied forces have roughly the same effect as if loads were directly applied along the diagonals. However, applying loads along diagonals neglects the effects of confinement provided by the building frame. The seats do not provide significant confinement. A full-scale building frame would be necessary to model the behaviors most accurately, but this is excessive in preliminary investigations.

The panels were tested under displacement control mode with a rate of 0.5 mm/min. With this rate, damage to the wall was able to be observed during the loading process. This load rate was also used by Santa-Maria et. al. (2004)

In the monotonic tests the load is increased up to failure. The cycle testing consisted of the following steps: diagonal compression up to the load level; unloading of the diagonal; compression of the second diagonal; and un-loading of this diagonal. Two cycles were performed at each load level in increments of 24 KN. The force and displacement data were obtained by a data logger (TDS-300). Average deformations were measured along the two diagonals of the panels.

The testing was stopped when failure was reached. This was judged to occur in the monotonic tests when the displacement controlled loading produced lesser applied force in the rams. In the cyclic tests, it was necessary to stop the tests when the reinforcement began to delaminate. It was decided that failure was imminent and that it wasn't worth the risk of sudden shock to the equipment.

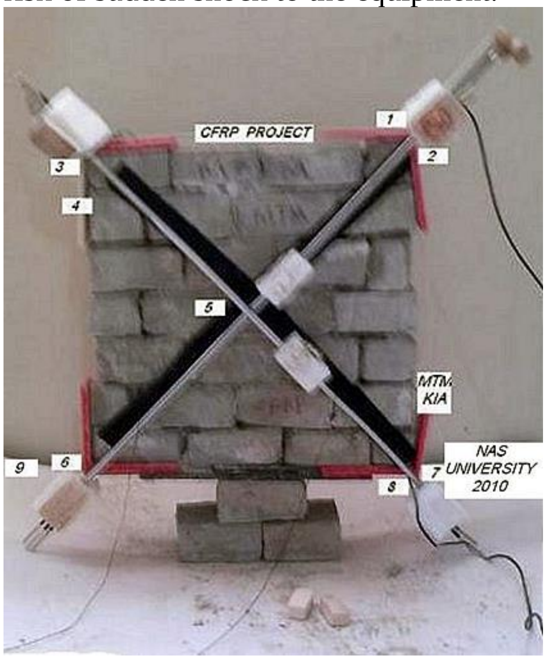

Figure 9. Test Setup for Cyclic Loading Tests. (Key: 1, 3, 7 and 9 are hydraulic rams, 5 is tension rods, 2, 4, 6 and 8 are seats on the edges.)

3 RESULTS

Quantitative results, failure mode, and crack patterns are summarized in Table 2. Reinforcing increased the maximum load that the panels could carry. Some arrangements improved the strength more than other arrangements. Monotonically loading panels with diagonal laminate 200 mm thick were most effective at increasing the strength. The average increased from 141 KN to 270 KN, or by 92%. However, the fabrics increased the strength less. The same arrangement of fabric increased the average strength to 190 KN, or by 35%. The fabric was thinner than the laminate, so that may have influenced the relative benefit of each. Unfortunately, wrap and laminate are produced in only a small selection of shapes, so direct comparison of identical thicknesses was not possible.

The failure modes were primarily cracking in the concrete and delamination of the reinforcement. The CFRP showed no strength failure. Therefore, the reinforcement must have improved the strength of the panels mostly through increasing the stiffness of the wall or by keeping cracks closed.

Cracking in the panels continued to be diagonally oriented after reinforcement. However, the reinforcement changed the pattern of cracking compared to unreinforced panels. Spread diagonal cracks became more common in reinforced specimens.

Table 2. Experimental test results and failure mode

Specimen ID	Maximum Load (KN)	Band width (mm)	Failure Mode	Crack Pattern
MU1	171	0	Splitting crack	Single diagonal
MU2	111	0	Splitting crack	Single diagonal
CU1	138	0	Splitting crack	Single diagonal
MDL1	217	100	Corner failure	Spread diagonal
MDL2	219	100	Corner failure	Spread diagonal
MDL3	270	200	Corner failure	Spread diagonal
MDL4	271	200	Corner failure	Single diagonal
MDF1	170	100	Corner failure	Spread diagonal
MDF2	192	100	Splitting crack & delamination	Single diagonal
MDF3	182	200	Corner failure & delamination	Spread diagonal
MDF4	198	200	Delamination	Spread diagonal
CDF1	180	100	Corner failure	No pattern
CDF2	182	100	Splitting crack & delamination	Spread diagonal
CDF3	215	200	Corner failure, splitting crack & delamination	Single diagonal
CDF4	219	200	Corner failure & delamination	Spread diagonal & single diagonal
MHF1	194	200	Corner failure & delamination	Single diagonal
CHF1	186	200	Corner failure & delamination	Spread & single diagonal

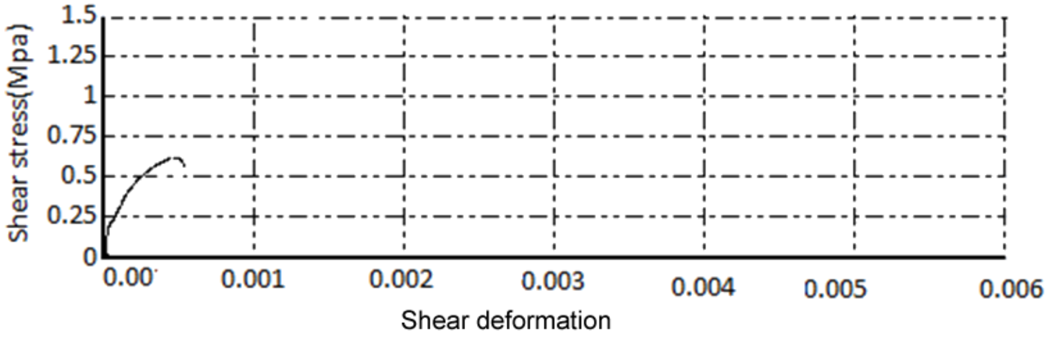

Figure 10. Response of Average of MU1 and MU2.

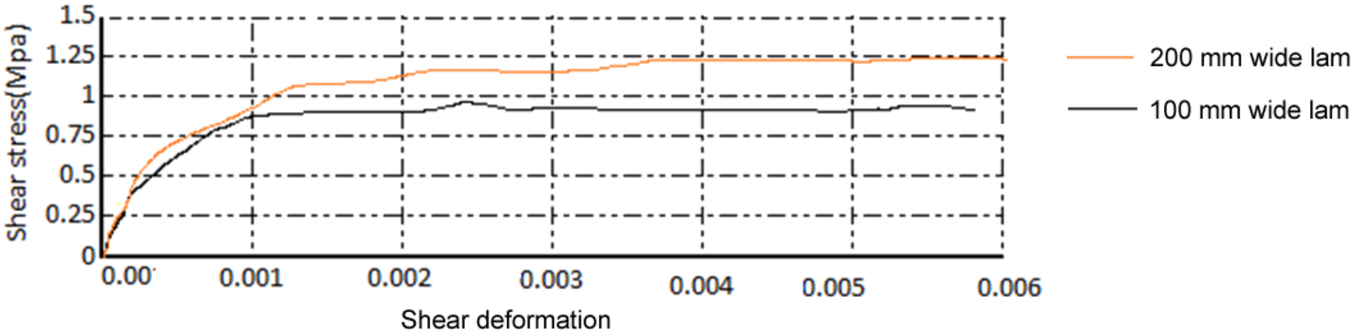

Figure 11. Response of Average of MDL3 and MDL4 in red and MDL1 and MDL2 in black.

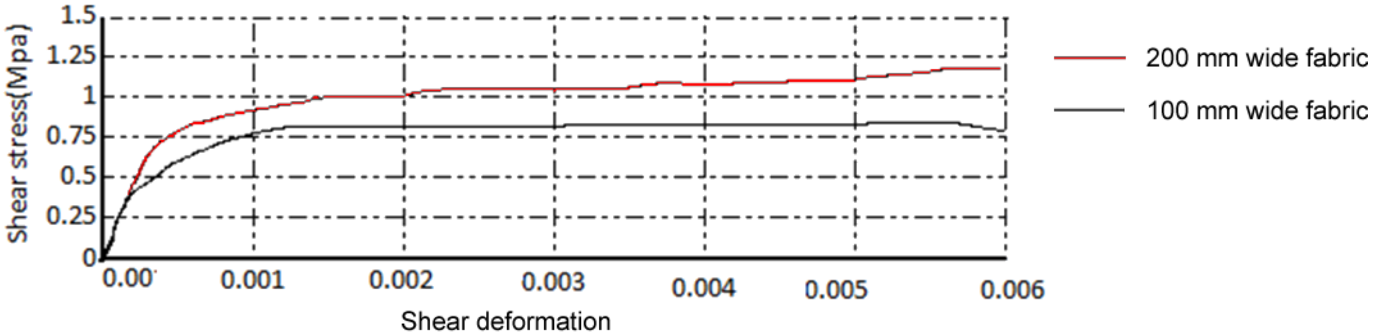

Figure 12. Response of Average of MDF3 and MDF4 in red, and average of MDF1 and MDF2 in black.

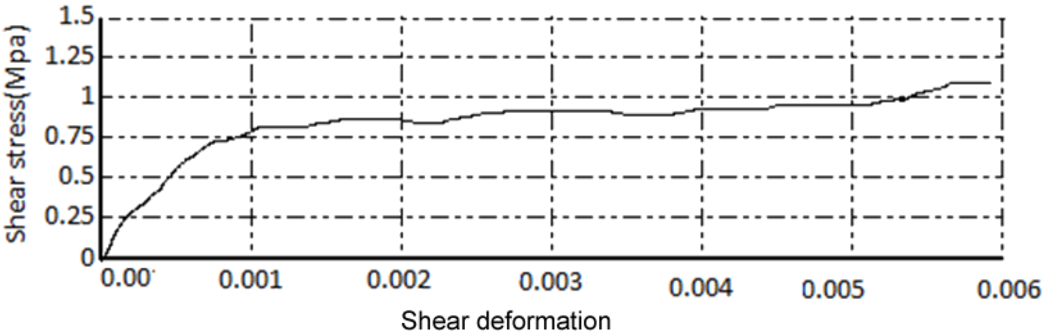

Figure 13. Response of MHF1.

Using wider reinforcement often increased the maximum load of the panels. For example, the monotonically loaded diagonal laminate (MDL) and cyclical diagonal fabric (CDF) tests increased the strengths going from 100 mm to 200 mm width, but increasing the width of diagonal fabric had little apparent effect when monotonically loaded (MDF).

For both cyclic and monotonic loading, horizontally reinforced panels reached nearly the same maximum load as the diagonally reinforced panels. That suggests that angle of reinforcement is not significant, although the number of test results is small in this comparison. From a strength viewpoint, such as with a strut and tie method, it is hard to see how the angle of reinforcement has little effect. However, if the reinforcement's primary role is confining the concrete, then the angle is less important. Considering that double diagonal reinforcement requires about three times the total length of material, horizontal reinforcement seems more efficient.

It is interesting to notice that the coefficient of variation of the strength of the reinforced panels was decreased significantly compared to unreinforced panels. For unreinforced monotonic panels, the coefficient of variation was 30%, but for MDL 100 mm, 200 mm, CDF 100 mm, and 200 mm, the coefficients were all 1% or below, but for MDF 100 and 200 mm, were 9% and 6%, respectively. Unreinforced concrete is inherently unpredictable, but reinforcing it makes it predictable. As a composite of natural materials with great variability, the strength of plain concrete is harder to predict. However, CFRP has tight quality controls on its fabrication. This confirms previous tests. (Santa-Maria et. al. 2004) Therefore, running only a couple tests should have given a reliable estimate of strengths.

Figures 10 to 13 show the equivalent shear stress versus shear deformation for the panels under monotonic loading. Reinforcement with laminate and fabric as shown in Figures 11 to 13 allow the panels to undergo higher deformation than unreinforced panels as shown in Figure 10. Figures 11 and 12 show the effect of adding reinforcement on the response. In both of those situations, widening the reinforcement increased the maximum equivalent shear stress.

3.1 *Cyclic tests*

Cyclic tests were run only on panels reinforced with CFRP fabric or were unreinforced. Figures 14 to 19 show the cracking of wall panels under cyclic loading. The unreinforced panel had one main crack, and a few secondary cracks. The reinforced panels usually had more cracks, but they were smaller. Cracks were observed early in the cyclic loading, and then grew in load increments.

In every cyclic test, the reinforcement began to delaminate at the ends and then propagated towards the middle. Simultaneously, splitting cracks started to grow. The tests were ceased when this started to occur. Corner failures were common in the tests, so incompatibility with the cracking concrete there may have promoted delamination. De-bonding is complex, and many modes of failure occur. For example, micro-cracks in the materials (CFRP, adhesive, and concrete block) were observed.

Table 2 shows the trend in test results for cyclically loaded panels. As mentioned above, all forms of reinforcement increased the strength of the panels for cyclic loading. The horizontally reinforced panel had a slightly lower cyclic strength than diagonally reinforced panels with 200 mm wide fabric, 186 KN vs. 219 KN, respectively. Reinforcing horizontally requires less material than diagonally, and the CFRP has less surface contact area. Even though the loads are lower, the amount of strength gained per unit amount of material is higher for the horizontally reinforced panels. The horizontal reinforcement improved the strength 35% compared to 57% for 200 mm wide diagonally-reinforced panels which required about three times the materials.

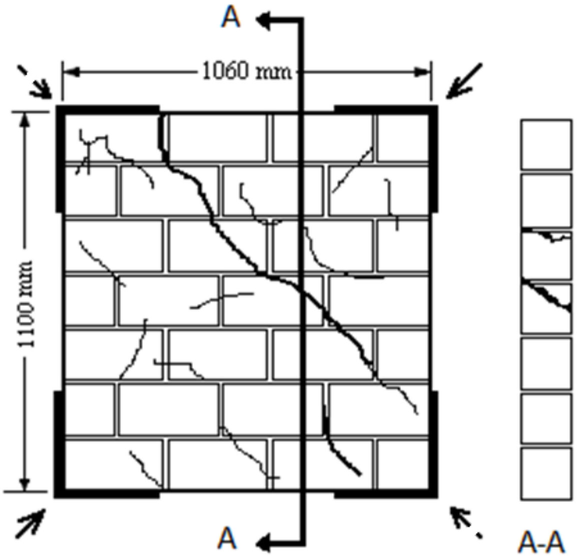

Figure 14. Cracking of CU1.

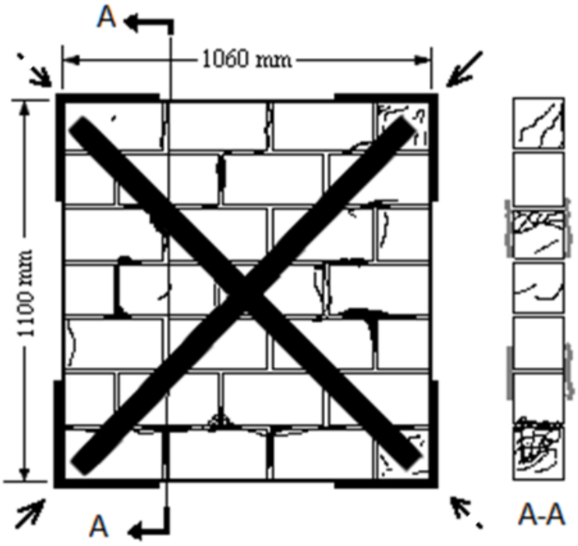

Figure 15. Cracking of CDF3.

Figure 16. Photograph of Cracking of Upper Part of CDF3.

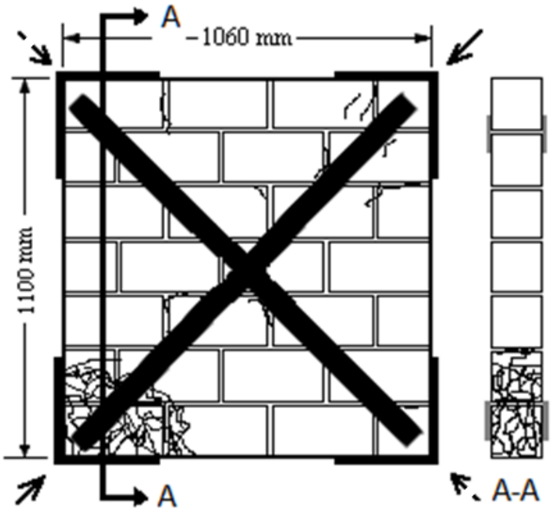

Figure 17. Cracking of CDF1.

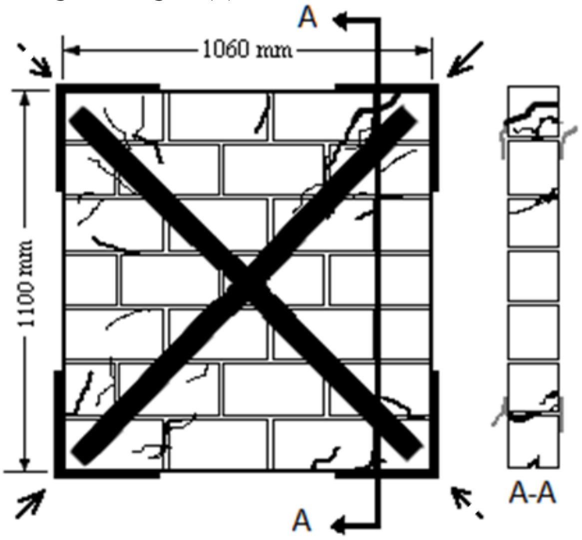

Figure 18. Cracking of CDF4.

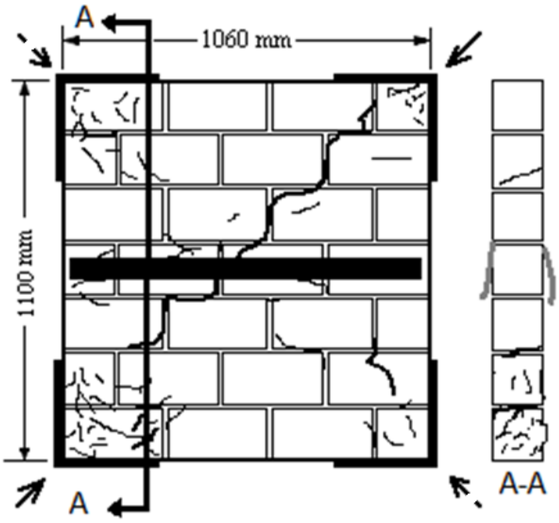

Figure 19. Cracking of CHF1.

Figures 20 to 22 show the show the equivalent shear stress versus shear deformation for the panels under cyclic loading. The reinforced panels show much more hysteresis. This means that they will have more energy absorbed from the applied loading and there will be more damping.

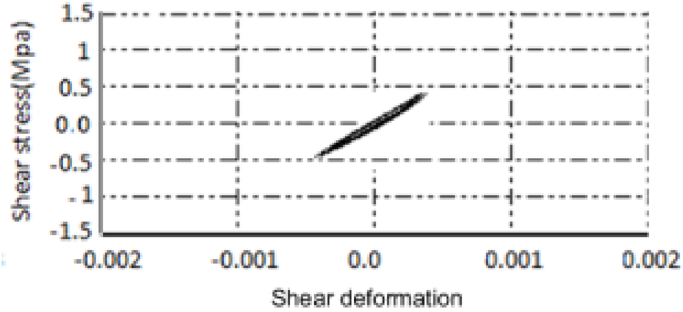

Figure 20. Cyclic Response of CU1.

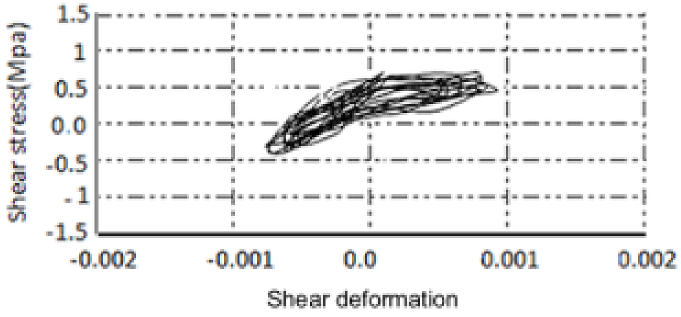

Figure 21. Cyclic Response of CHF1.

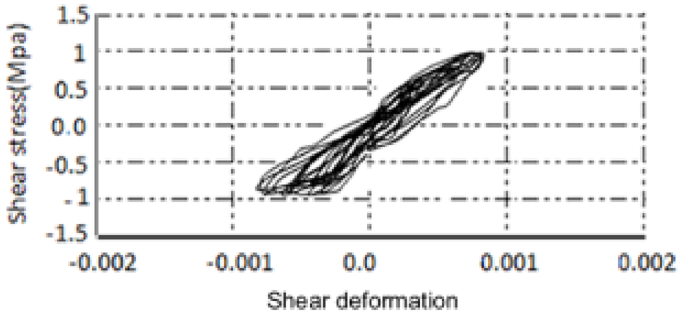

Figure 22. Cyclic Response of CDF1 and CDF2 plotted together.

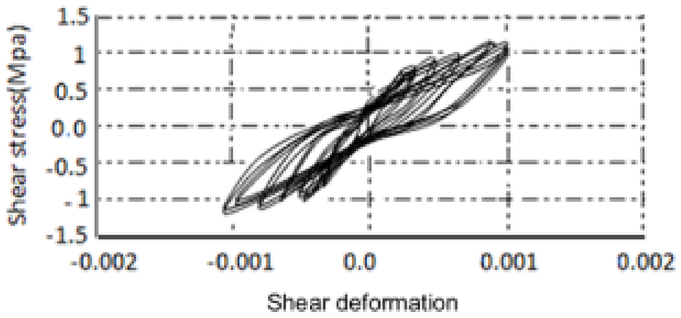

Figure 23. Cyclic Response of CDF3 and CDF4 plotted together.

3.2 *Shear Modulus*

The monotonic and the cyclic shear modulus are calculated as shown in Figures 24 and 25, respectively. For monotonic loading, the estimate of shear modulus is a line drawn to 40% of the maximum shear stress (v). (ASTM 2001) For cyclic, a box is defined around the extent of the data and a line is drawn connecting the corners. Therefore, the cyclic modulus represents an average over cycles of loading. There is large dispersion in the results, but the trends are discussed. It appears that horizontal reinforcement has a small and nearly insignificant increase in shear stiffness of the panels. The only tests with significant effects on the modulus was with monotonically loaded panels with diagonal reinforcement. They had increases up to 52% the average value of the modulus. This is independent of the type of reinforcement and the reinforcement ratio.

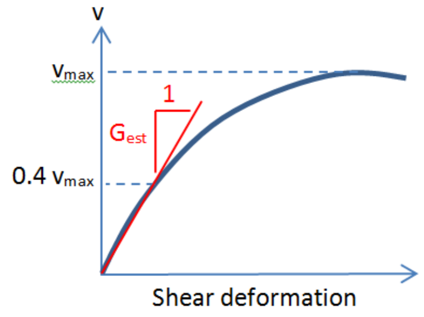

Figure 24. Method of calculation of monotonic shear modulus.

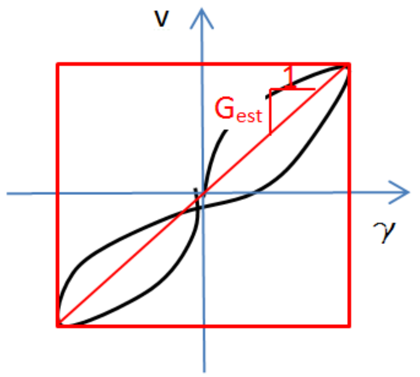

Figure 25. Method of calculation of cyclic shear modulus.

3.3 *Energy Dissipation*

The energy dissipation, expressed as the equivalent viscous damp coefficient, is calculated as:

$$\zeta = \frac{W_D}{4\pi W_S} \tag{1}$$

where W_D and W_S are the work in a hysteretic loop and the static work, respectively. Damping coefficients are calculated for both cycles at each load level. For all of tests, damping coefficient is showed in Figure 26.

The damping coefficient was highest in the first load cycle. This has been observed by Mora. (2003) Then in further cycles it reduced as internal damage occurred in the walls. This suggests a connection between damping and cracking.

The materials and test methods were comparable to Santa-Maria et. al. (2004), so their results were overlaid. As shown in Figure 26, Santa Maria et. al. found damping was higher in diagonally reinforced panels than horizontally reinforced. The dashed lines for CDL are higher than CHL. However, in the current tests, horizontally reinforced panels had higher damping. The solid line for CHF was higher than CDF. Each study used different materials. However, this shows that a blanket statement about diagonal reinforcement being better for damping is not true for all situations. Santa-Maria et. al. used clay bricks, and the current study used concrete blocks, but their properties were similar.

Magenes and Calvi (1997) found that the damping can be taken as 10% for most conditions. The results of the experiments in Figure 26 generally agree with that.

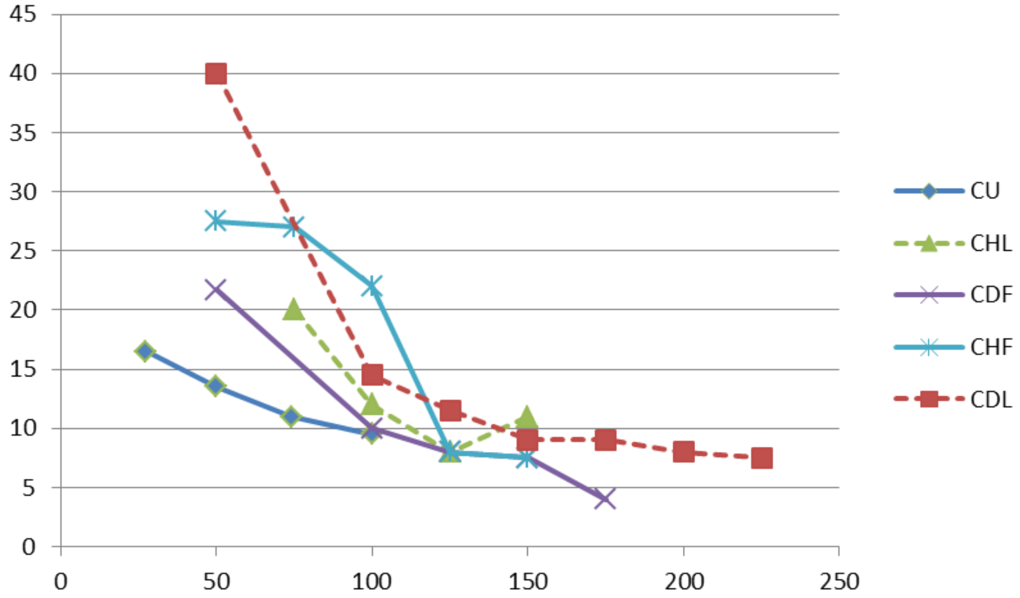

Figure 26. Equivalent Damping Coefficient at Various Load Levels (KN). Dashed are from Santa-Maria et. al. (2004).

4 CONCLUSIONS

Diagonal compression test results show that diagonal laminate strips are slightly better at improving equivalent shear strength. However, horizontal fabric sheets are better for increasing damping.

The test results disagree with the work of Santa-Maria et. al. (2004). Damping was found to be higher for horizontally reinforced panels in the current research versus Santa-Maria et. al. found it to be higher in diagonally reinforced panels. Damping is a function of the wall's material properties and the external reinforcement. For example, more reinforcement keeps the crack surfaces in tight contact and promotes friction. Also, the reinforcement scheme effects the crack direction and width. The material properties were different between the referenced tests and the current ones.

This highlights that test results can't be generalized but apply only to the specific situations of the test. This is especially important for application to real-world walls. Diagonal compression tests are not representative of the behavior of full-scale walls, but only give a general idea of the response of walls reinforced with CFRP. Therefore, it is important to develop modeling procedures that can be used to predict strength and damping. However, in general, a 10% damping coefficient can be used for all load levels among any arrangement of reinforcement. This is confirms Magenes and Calvi (1997).

It was discussed above that reinforced panels usually had more cracks, but smaller cracks at failure. It should be resolved whether keeping the cracks small is related to the improvement in damping.

The failure mode for all reinforced panels involved corner failure, delamination or both. This research leaves open several areas of future work. First, delamination is a complex phenomenon but the first response to this is to investigate if there are better ways to keep the laminations affixed to the walls. Second, corner failure is a load transfer issue. Better understanding of this is necessary to evaluate whether this is a type of failure that would happen in full-scale walls in buildings, or whether it is related to the test conditions. Either scenario would suggest subsequent work. One area is how to prevent corner failure with retrofitted reinforcement.

Future work in modeling should be done to determine how the reinforcement aids strength and damping, such as increasing stiffness, providing alternate load paths, or keeping cracks closed. A better understanding of the failure of retrofitted panels will allow them to be used more effectively, therefore more economically in developing countries.

The tests were run on walls approximately 1 m by 1 m in size, but real walls are more likely in the range of 3 m by 3 m. Since the thickness of the wall would normally be only slightly thicker in a real wall than in the test specimens, a size effect could change the results for real applications. Additionally, cracks sometimes stair-step through mortar joints but the scale of those joints and cracks would be different in larger settings. When applying the results of this work the engineer could either run larger scale tests, or confirm that the controlling theories still apply to a different scale of walls.

5 ACKNOWLEDGEMENTS

The laboratories of the Banian Pey & Mahar Shalodeh companies were used for the tests. The research is partly financed by Khuzestan Water & Power Authority (KWPA), also grant 4072218219 from Banian Pey.

6 REFERENCES

Albert M., Elwi A., & Cheng JJ., "Strengthening of unreinforced masonry walls using FRPs." *Journal of Composites for Construction* Vol. 5, No. 2, 2001, pp 76-84.

ASTM, "469." *Standard test method for static modulus of elasticity and Poisson's ratio of concrete in compression. West Conshohochen: American Society for Testing and Materials* 2001.

Ehsani M., Saadatmanesh. H, & Al-Saidy A., "Behavior of retrofitted URM walls under simulated earthquake loading." *Journal of Composites for Construction* Vol. 3, No. 3, 1999, pp 134-42.

Hamed, E. & Rabinovitch, O., "Masonry Walls Strengthened with Composite Materials - Dynamic Behavior." *European Journal of Mechanics - A/Solids*, Vol. 27, No. 6, 2008, pp 1037-1059.

Magenes, Guido, and Gian Michele Calvi. "In-plane seismic response of brick masonry walls." *Earthquake engineering & structural dynamics* 26.11 (1997): 1091-1112.

Mahmood, Hamid, and Jason M. Ingham. "Diagonal compression testing of FRP-retrofitted unreinforced clay brick masonry wallettes." *Journal of Composites for Construction* 15.5 (2011): 810-820.

Mansourikia, M.T. & Hovhannisyan, S.M., "Rehabilitation of Existing Un-reinforced Masronry (URM) Structures Using CFRP Fabrics", *FRPRCS-9 Sydney, Australia* 2009.

Mansourikia, M.T. & Hovhannisyan, S.M., "Important of CFRP for Rehabilitation of Un-reinforced Masonry (URM) Structures." *Proceedings of the 4th International Conference on Seismic Retrofitting Tabriz, Iran*, 2012.

Mansourikia, M.T. & Hoback , A. S., "Retrofit of Unreinforced Masonry Walls Using Geotextile and CFRP." *Electronic Journal of Structural Engineering* Vol. 14, 2014.

Mora, Mauricio Fernando Sepúlveda. *Influencia del refuerzo horizontal en el comportamiento sísmico de muros de albañilería armada*. Diss. Pontificia Universidad Católica de Chile, 2003.

Nguyen, D.M., Chan, T.K., & Cheong, H.K., "Brittle failure and bond development length of CFRP-concrete beams." *Journal of Composites for Construction* Vol. 5, No. 1, 2001, pp 12-17.

Ozcebe G., Ersoy U., Erduran E., & Akyuz U., "Rehabilitation of existing reinforced concrete structures using CFRP fabrics." *13th World Conference on Earthquake Engineering* 2004. pp. 1-13.

Parvin, A., & Blythe, M.R., "Performance of CFRP-Wrapped Connections." *Electronic Journal of Structural Engineering* Vol. 12, 2012, pp 45-51.

Rossetti A., Kachlakev D.I., & Chadwell, C., "Behavior of Unreinforced Masonry Walls Strengthened with GFRP Composites Subjected to Cyclic Loading." *Tenth North American Masonry Conference (10 NAMC) St. Louis, Missouri*, 2007, pp 6-12.

Santa-Maria H., Duarte G, & Garib A., "Experimental Investigation of Masonry Panels Externally Strengthened with CFRP Laminates and Fabric Subjected to in-Plane Shear Load." *13th World Conference on Earthquake Engineering Vancouver, B.C., Canada* 2004, Paper No. 1627, pp 1-9.

Seible, F., Priestley, M.J.N., Hegemier, G.A., & Innamorato, D., "Seismic Retrofit of RC Columns with Continuous Carbon Fiber Jackets." *Journal of Composites for Construction* Vol 1, No. 2, 1997, pp 52-62.