13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 1627

EXPERIMENTAL INVESTIGATION OF MASONRY PANELS EXTERNALLY STRENGTHENED WITH CFRP LAMINATES AND FABRIC SUBJECTED TO IN-PLANE SHEAR LOAD

Hernan SANTA-MARIA[1], Gonzalo DUARTE[2], Alejandro GARIB[3]

SUMMARY

Recent earthquakes have produced extensive damage in a large number of existing un-reinforced masonry (URM) buildings, showing the need of retrofit techniques for masonry structures. We tested under diagonal compression twenty-four URM panels reinforced with externally bonded carbon fiber reinforced polymer (CFRP) laminates and sheets. Panels with two configurations of the reinforcement were subjected to monotonic and cyclic loading. This paper reports the results of the tests in terms of strength, mechanism of failure, stiffness, and energy dissipation. External CFRP reinforcement decreases the thickness of the cracks and increases the shear strength and stiffness of the panels.

INTRODUCTION

The 1985 earthquake in Chile produced extensive damage in reinforced masonry buildings with more than 3 stories due to in-plane shear actions [1]. In recent earthquakes unreinforced masonry structures, used in historical buildings as well as in current modern construction, have sustained a high degree of damage due to shear action, demonstrating the need for techniques to improve the seismic response of those structures.

A retrofit technique for masonry structures that has been under study in recent years is the use of externally bonded FRP (Fiber Reinforced Polymers) laminates or sheets. FRP is a material made of high strength fibers (glass, aramid, carbon) embedded in a polymeric resin matrix. The fibers resist tension while the resin resists other forces. The most common use of FRP is as external reinforcement for reinforced concrete elements. Typical applications are as tension reinforcement of beams and slabs, shear reinforcement of beams, beam-column joints, and walls, and as confinement reinforcement of columns. Externally bonded FRP elements (laminates or fabric) to be used in retrofit have as advantages low weight-strength ratio, short installation periods, and very low intervention on the structure. A building can be retrofitted with a minimum interruption of its operation.

[1] Assistant professor, Pontificia Universidad Catolica de Chile, Santiago, Chile. Email: hsm@ing.puc.cl
[2] Civil engineer, Pontificia Universidad Catolica de Chile, Santiago, Chile
[3] Civil engineer, Pontificia Universidad Catolica de Chile, Santiago, Chile

Several investigations have shown that FRP reinforcement produces large increases of out-of-plane strength masonry elements. Experimental research by Ehsani et al.[2], Hamoush et al. [3], Albert et al. [4], and others showed that carbon and glass fibers used as laminates or fabric sheets are effective in increasing the out-of-plane strength and ductility of reinforced and unreinforced masonry walls.

Little investigation on the use of externally bonded FRP laminates or fabric as in-plane shear reinforcement of masonry walls has been reported. Experimental results reported by Schwegler [5], Priestley and Sieble [6] and Laursen et al. [7] show that masonry walls externally reinforced with FRP and subjected to in-plane shear have large increase of strength and load deformation capacity. Valluzi et al. [8] reported that 24 externally reinforced masonry panels subjected to diagonal compression had between 15 and 70% increase of strength. In terms of shear strength a diagonal configuration was more efficient than a grid configuration. In all the experiments reported the specimens were tested under monotonic loading.

Five URM panels and nineteen URM panels with externally bonded CFRP were loaded to failure under diagonal compression: 14 panels were subjected to monotonic loading and 10 to cyclic loading. Two reinforcement configurations were used: diagonal and horizontal. The objective of these tests was 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.

This paper reports the results of those tests. They show that the reinforcement decreases the thickness of the cracks and increases the shear strength of the panels. The diagonal configuration produces larger increase of strength and stiffness than the horizontal configuration.

EXPERIMENTAL PROGRAM

Materials

Two types of FRP reinforcement with unidirectional fibers were used in this investigation: factory pultruded carbon laminates (Sika Carbodur S-512) and woven carbon fabric (SikaWrap 230C), laminated and bonded on site. Their dimensions and main mechanical characteristics, according to the fabricator, are shown in Table 1.

Table 1 Nominal dimensions and mechanical properties of the FRP reinforcement

Type of Fiber	Laminate	Fabric
Thickness (mm)	1.2	0.12
Characteristic tensile strength (MPa)	280	350
Tensile modulus of elasticity (GPa)	165	231
Ultimate tensile strain	0.017	0.017

Pull-off tests were performed to both reinforcement types. The average pull-off strength of the laminates was 1.9 MPa, and the rupture occurred at the bricks, while the strength of the fabric was 1.6 MPa and the rupture occurred between the adhesive and the fabric.

The panels were fabricated using hollow clay bricks (140x290x112 mm), with approximately 12-mm-thick mortar joints. The average prismatic strength was 10.3 Mpa, and the bond strength measured using triplets was 0.68 Mpa. Commercially available premixed mortar was used. The monotonically loaded panels had cylinder compressive strength of 20.2 MPa and tensile strength equal to 5.5 Mpa, while in the rest of the panels the cylinder compressive strength and the tensile strength were equal to 9.56 MPa and 3.4 Mpa, respectively.

Test Specimens

A series of 24 masonry panels with nominal dimensions of 1060x1100x140 mm were built. Eighteen panels were reinforced with one strip of laminate or fabric sheet on each side; 1 panel was reinforced with one CFRP laminate on one side; and 5 panels were not reinforced. The specimens with diagonal reinforcement tested under monotonic loading were reinforced only along the diagonal in tension. The different configurations of the reinforcement are shown in Fig. 1.

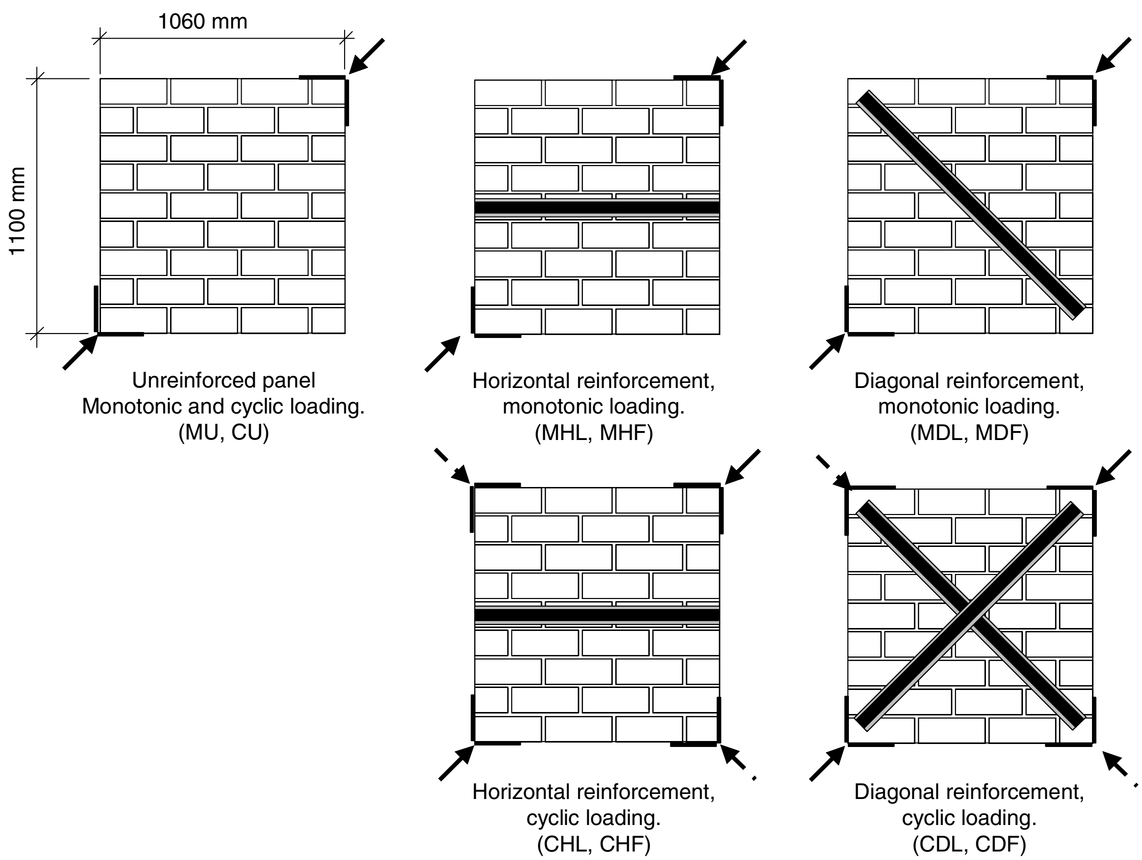

Figure 1 Dimensions of the panels and configurations of the reinforcement

The characters of the alphanumeric code used to identify the specimens indicate the type of reinforcement and load scheme 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 number of the specimen.

Eight panels were reinforced with CFRP laminates, nine with 150 mm-wide fabric sheets, and one with a 300 mm-wide fabric sheet. Nine panels were reinforced diagonally and the rest horizontally. One panel was reinforced on one side. See Table 2 for the list of the panels tested, the failure modes and measured strengths. The average strength of the unreinforced panels was 132 kN, with a coefficient of variation of 15%. It is interesting to notice that the coefficient of variation of the strength of the reinforced panels decreased to less than 10%.

Table 2 Experimental test results and failure mode

Specimen ID	Maximum Load (kN)	Ratio of average reinforced to unreinforced maximum load	Failure Mode	Crack Pattern
MU1	119		Splitting crack	Single diagonal
MU2	134		Splitting crack	Single diagonal
MU3	165		Splitting crack	Single diagonal
CU4	118		Splitting crack	Single diagonal
CU5	122		Splitting crack	Single diagonal
Average	**132**	-		
C.O.V	**0.150**	-		
MDL1	229		Corner failure	Spread diagonal
MDL2	230		Corner failure	Spread diagonal
CDL3	224		No failure	--
CDL4	219		No failure	Single diagonal
Average	**226**	**1.71**		
C.O.V	**0.022**			
MDF1[(1)]	185		Corner failure	No cracks
MDF2	196		Splitting crack and delamination	Spread diagonal
MDF3	196		Corner Failure and delamination	Single diagonal
CDF4	201		Delamination	Spread diagonal
CDF5	203		Corner Failure and delamination	Single diagonal
Average	**196**	**1.48**		
C.O.V	**0.036**			
MHL1	135		Splitting crack	Spread diagonal
MHL2	142		Delamination	Spread diagonal
CHL3	154		Delamination	Spread diagonal
CHL4	146		Delamination	Spread diagonal
Average	**144**	**1.09**		
C.O.V	**0.055**			
MHF1[(1)]	194		Horizontal mortar	Single horizontal
MHF2	186		Horizontal mortar	Single horizontal
MHF3	157		Delamination	Spread diagonal
CHF4	179		Delamination	Spread diagonal
CHF5	194		Corner, Splitting, Delamination	Single diagonal
Average	**182**	**1.38**		
C.O.V	**0.084**			
MDL5[(2)]	121	**0.92**	Splitting crack	Single diagonal

[1] 300 mm wide sheet
[2] Reinforced on one side

Testing Procedure
The panels were subjected to diagonal compression by means of hydraulic rams and tension rods as shown in a photo of the test setup in Fig. 2. In the monotonic tests the load was increased up to failure. The cycle testing consisted of the following steps: diagonal compression up to a certain load level; un-loading 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 25 kN.

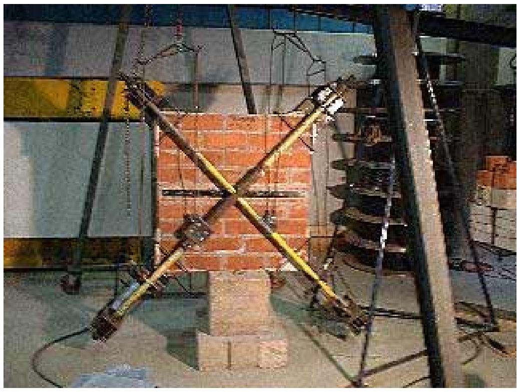

Figure 2 Test setup for cyclic loading tests

Average deformations were measured along the two diagonals of the panels and at 3 points along the reinforcement. Detailed description of each test can be found elsewhere (Duarte [9]).

DISCUSSION OF TEST RESULTS

Quantitative results, failure mode, and crack patterns are summarized in Table 2. The behavior of the panels with different reinforcement layouts is discussed in the following sections.

Unreinforced Panels
The responses of monotonic and cyclic loading of a typical unreinforced panel are plotted in Fig. 3 and 4, and the maximum measured diagonal loads are summarized in Table 2. All the panels had a brittle failure, with a single wide diagonal splitting crack.

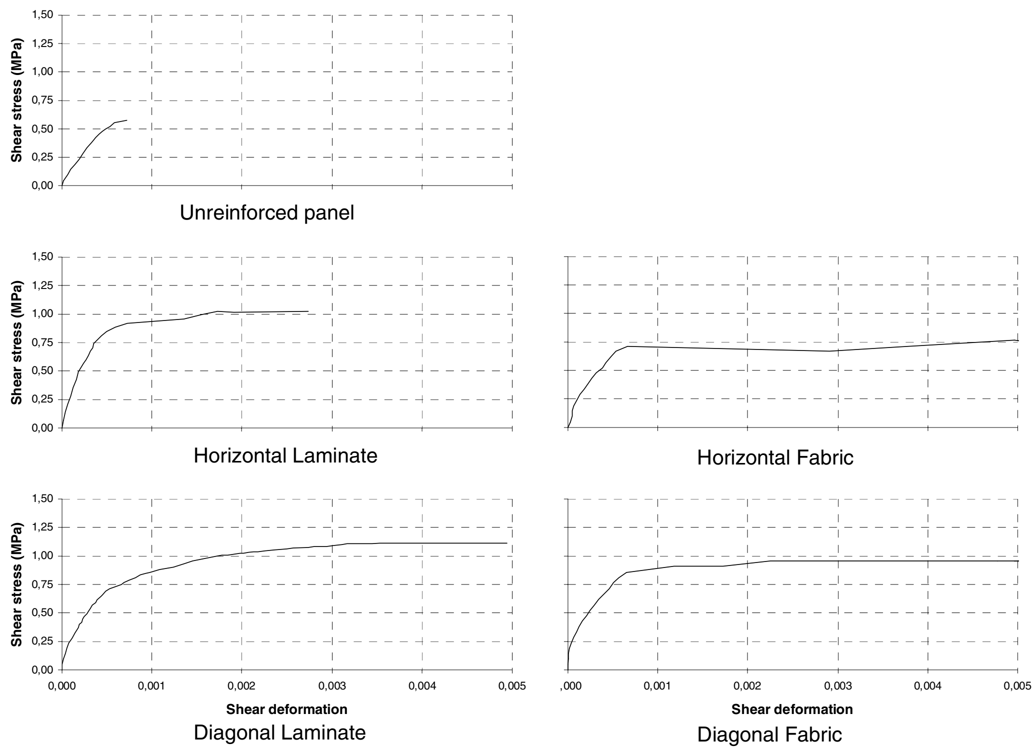

Figure 3 Shear tension-shear deformation responses of masonry panels under monotonic loading

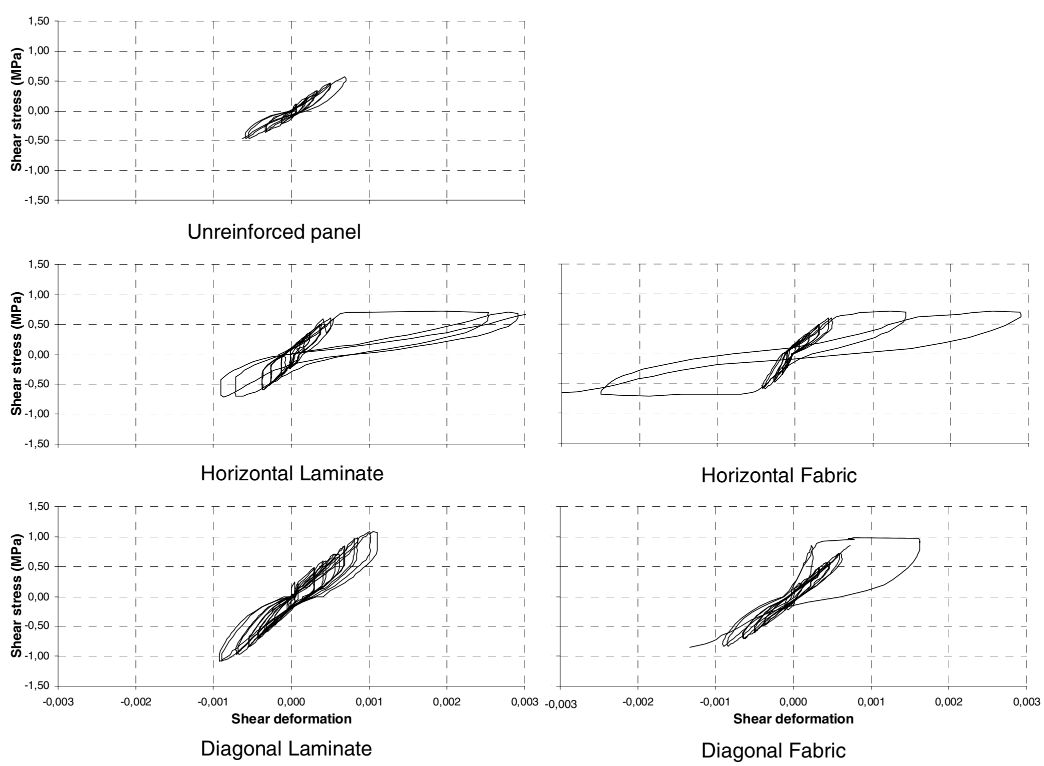

Figure 4 Shear tension-shear deformation responses of masonry panels under cyclic loading

One side reinforcement
The response of the only specimen tested with one side reinforcement was similar to those reported by Valluzi et al. [8]. The specimen showed out-of-plane flexural behavior due to the eccentricity of the reinforcement. As a consequence, the panel failed when one wide crack opened at the unreinforced side, while large deflections perpendicular to the panel occurred. No increment of shear strength was observed.

Two sides diagonal reinforcement
The responses of monotonic and cyclic loading of typical diagonally reinforced panels are shown in Fig. 3 and 4. The diagonal reinforcement produced a 40 to 75 % increase of the maximum measured load over the average strength of the unreinforced panels. The panels reinforced with laminates had slightly larger increase of maximum load than the panels reinforced with fabric sheets. This is explained by the failure mode that occurred with each type of reinforcement: the panels with laminates failed by compression burst of the clay units located at the corner where the load was applied, while the panels with fabric failed with a combination of delamination of the reinforcement in more than 50% percent of its length (see Fig. 5), splitting cracking, and burst of the corner units. Two or three diagonal cracks were observed after failure.

Figure 5 Photo of specimen CDF1 showing the fabric debonded after failure

Two sides horizontal reinforcement
The failure mode of the panels was similar, irrespective of the type of reinforcement: delamination started at one end of the reinforcement and propagated to the center, producing failure of the panels by splitting crack. Delamination of the laminates started at lower loads than in the fabric because the contact surface was smaller in the former. As a consequence, the fabric reinforcement was more efficient in terms of strength than the laminates (see Table 2). Several diagonal cracks were observed prior to failure.

Cyclic loading compared to monotonic loading
The responses of panels with horizontal reinforcement subjected to monotonic and cyclic loading were similar in terms of increase of strength and failure mode. On the other hand, the response of panels with diagonal fabric reinforcement under cyclic loading differs from monotonic loading in the delamination pattern: in the case of cyclic loading delamination started at the corners in compression (see Fig. 5), where compressive stresses were very high, while in the case of monotonic loading delamination started at the center of the panel, where tensile stress were highest.

The panels with diagonal laminates subjected to cyclic loading suffered slight delaminaton at the ends of the laminates, but the panels did not fail. The experiments were stopped before failure due to safety concerns because at that load the hydraulic rams used were very close to their capacity. The large loops shown in Fig. 4 occurred because the panels cracked but did not failed. The panels resisted a complete cycle of loading before delamination of the FRP produced failure.

Shear Modulus

The monotonic and the cyclic shear modulus were calculated as shown in Fig. 6. The monotonic shear modulus is plotted in Fig. 7. The hollow marks represent the result from each experiment, while the dark marks are the average shear modulus for each reinforcement configuration. Even though the results show large dispersion, it can be concluded that the horizontal reinforcement slightly increases the shear stiffness of the panels, while the diagonal reinforcement increases up to 60% the average value of the modulus. This is independent of the type of reinforcement and the reinforcement ratio.

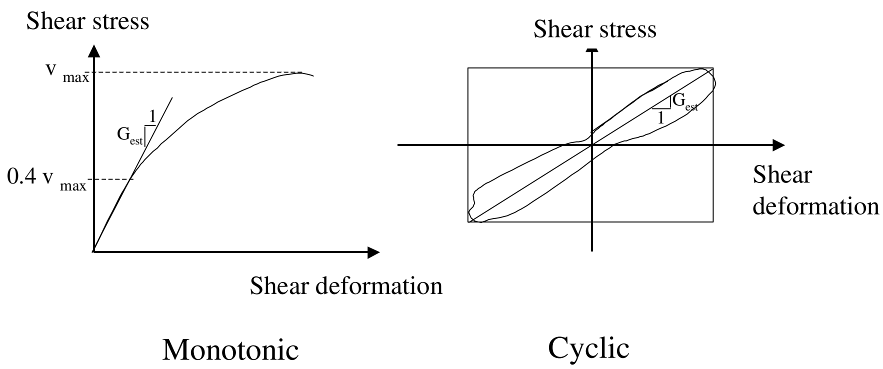

Figure 6 Methods of calculation of the monotonic and cyclic shear modulus

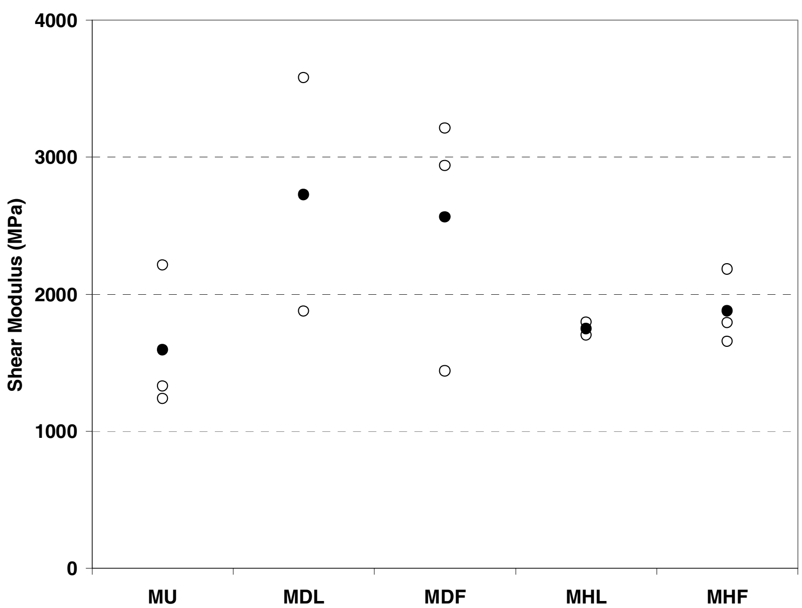

Figure 7 Shear modulus of each specimen and average value for each reinforcement configuration

The cyclic shear modulus is constant at a given load level, and slightly decreases as the load level increases. The monotonic shear load is larger than the cyclic shear load.

Energy Dissipation

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

$$\xi_{eq} = \frac{W_d}{4 \cdot \pi \cdot W_s}$$

W_d and W_s are the work in a hysteretic loop and the static work, respectively. Damping coefficients were calculated for both cycles at each load level.

In the case of unreinforced panels the damping coefficient in the first cycle was approximately 20% larger than in the second cycle due to internal damage of the masonry. The coefficient decreased approximately from 20% to 10% as the load increased. The same was observed in tests of masonry walls subjected to in-plane shear (Sepúlveda [10]).

At a given load level the value of the damping coefficient of the reinforced panels was almost the same in both cycles. The damping coefficient was larger than in unreinforced panels for low load levels, but it decreased from approximately 25% to 10% as the load increased up to failure. The average values of the equivalent damping coefficients for the different configurations are plotted in Fig. 8.

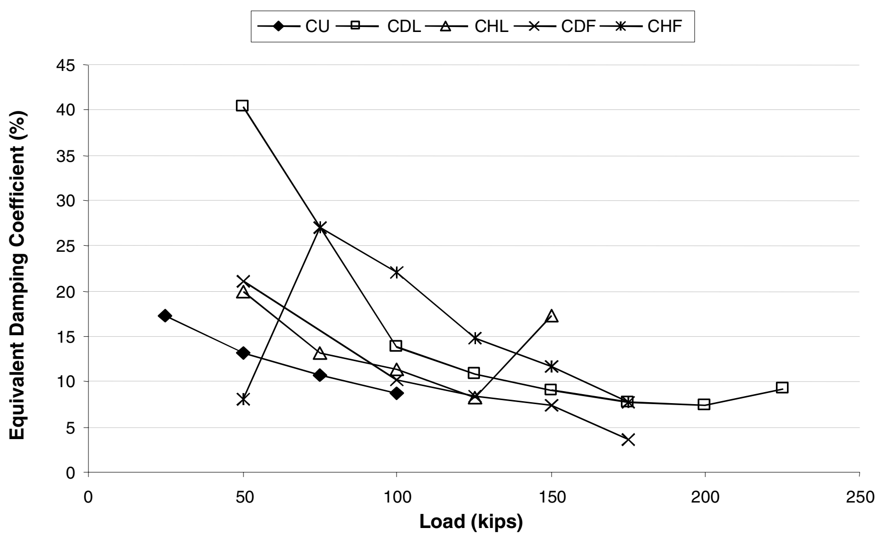

Figure 8 Equivalent damping coefficient at various load levels

The panels reinforced with fabric have slightly larger damping coefficients than those reinforced with laminates. But the equivalent damping coefficient of all the reinforced panels tend to approximately 10%, the same value found for the unreinforced panels.

CONCLUSIONS

The contribution of two configurations of CFRP reinforcement on the shear behavior of hollow clay brick panels has been experimentally investigated. Monotonic and cyclic loadings were considered. The conclusions are summarized as follows:

1. Diagonal reinforcement is more effective in terms of shear strength than horizontal reinforcement. The strength of the unreinforced masonry panels can be increased up to 70%.
2. Diagonal reinforcement increases the stiffness of the panels, while horizontal reinforcement has no effect on the stiffness.

3. The CFRP reinforcement produces a slight increase of the equivalent damping coefficient of clay brick panels. The horizontal reinforcement is more effective in increasing the damping properties of the masonry panels.
4. The panels reinforced showed cracks with small thickness, spread cracks, and a less brittle failure than the unreinforced panels. The horizontal reinforcement was more effective in spreading the cracks.
5. Panels subjected to monotonic and cyclic loading showed similar behavior.
6. High compressive stresses in the masonry produced de-bonding of CFRP fabrics.

The results from diagonal compression tests are not representative of the behavior of full-scale walls, but give a general idea of the response of walls reinforced with CFRP. Experimental work on full-scale walls has to be performed to better study the shear behavior of masonry walls externally reinforced with FRP.

ACKNOWLEDGMENTS

The research reported in this paper was conducted at the Laboratory of Structural Engineering of the Department of Structural and Geotechnical Engineering, Pontificia Universidad Catolica de Chile, with founding from DIPUC, Pontificia Universidad Catolica de Chile, and the collaboration of SIKA Chile.

REFERENCES

1. Cruz E, Hidalgo P, Luders C, Riddell R, Rodríguez F, Troncoso J, Van Sint Jan M, Vasquez J. “Lecciones del sismo del 3 de Marzo de 1985”. Instituto Chileno del Cemento y el Hormigon., Santiago, 1988.
2. Ehsani MR, Saadatmanesh H, Al-Saidy A. “Behavior of retrofitted URM walls under simulated eartquake loading.” Journal of Composites for Construction 1999; 3 (3): 134-42.
3. Hamoush SA, McGinley MW, Mlakar P, Scott D, Murray K. “Out-of-plane strengthening of masonry walls with reinforced composites.” Journal of Composites for Construction 2001; 5 (3); 139-45.
4. Albert ML, Elwi AE, Cheng JJ. “Strengthening of unreinforced masonry walls using FRPs.” Journal of Composites for Construction 2001; 5 (2); 76-84.
5. Schwegler G. “Masonry construction strengthened with fiber composites in seismically endangered zones”. Proceedings of the Tenth European Conference on Earthquake Engineering, Viena, Austria. Rotterdam: A.A. Balkema, 1995, volume I, 467-476.
6. Priestly MJN, Sieble F. “Design of seismic retrofit measures for concrete and masonry structures”. Construction and Building Materials 1995; 9 (6): 365-77.
7. Laursen PT, Seible F, Hegemier GA, Innamorato D. “Seismic retrofit and repair of masonry walls with carbon overlays”. Taerwe L, Editor. Non/Metallic (FRP) Reinforcement for Concrete Structures. RILEM 1995: 616-27.
8. Valluzi MR, Tinazzi D, Modena C. “Shear behavior of masonry panels strengthened by FRP laminates”. Construction and Building Materias 2002; 16(7): 409-16.
9. Duarte G. “Análisis experimental de muretes de albañilería reforzados con CFRP”. Thesis for the Civil Engineering Title. Pontifica Universidad Catolica de Chile, Santiago, Chile: 2003.
10. Sepúlveda MF. “Influencia del refuerzo horizontal en el comportamiento sísmico de muros de albañilería armada”. Thesis for the Civil Engineering Title. Pontifica Universidad Catolica de Chile, Santiago, Chile: 2003.