EXPERIMENTAL INVESTIGATION OF RETROFITTED URM WALLS

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ABSTRACT

An extensive research program for retrofitting of unreinforced masonry (URM) walls has been carried out in Switzerland. The program included in-plane dynamic and static cyclic tests on URM walls retrofitted using composites, post-tensioning, and shotcrete. This paper presents part of the preliminary test results of the static cyclic tests. Five half-scale walls were built using half-scale hollow clay masonry units and weak mortar. The specimens had two effective moment/shear ratios: 0.50 and 0.67. The specimens, before and after retrofitting, were subjected to a series of force and displacement control test runs. For specimens with effective moment/shear ratio of 0.50, the test showed that fiber reinforced polymers improve the lateral resistance as much as 6 times the lateral resistance of the reference specimens. In addition, applying post-tensioning was equivalent to retrofitting the specimens using one layer of glass fiber reinforced polymers. For specimens with effective moment/shear ratio of 0.67, composites improved the lateral resistance as much as 2.5 times the lateral resistance of the reference specimen.

KEYWORDS: retrofitting, strengthening, earthquake, static cyclic, composites, fiber.

INTRODUCTION

Recent earthquakes have shown that many unreinforced masonry (URM) buildings are seismically vulnerable; therefore, the demand for retrofitting strategies of these buildings has become increasingly stronger in the last few years. Numerous conventional techniques have been applied for retrofitting of existing URM masonry buildings. Potential disadvantages of these techniques (e.g. heavy mass, limited efficiency, etc.) have been reported [e.g. 1, 2]. Recently, fiber reinforced polymers (FRP) materials have offered promising retrofitting possibilities for masonry buildings [3, 4]. A literature review of retrofitting URM walls using FRP may be found elsewhere [5].

One of the pioneer dynamic in-plane investigations was carried out by ElGawady et al. [6]. The extensive study includes several test parameters: aspect ratio (slender and squat), fiber type, fiber structure, retrofitting configuration, and mortar compressive strength. The study shows that composites could increase the in-plane ultimate resistance by a factor of three. However, for squat specimens the test was stopped before the ultimate resistance of the specimens was reached because the ultimate resistance of the retrofitted squat specimens was higher than the force capacity of the shaking table hydraulic jack. A second phase of the project includes static cyclic tests on eleven specimens. This paper presents part of these static cyclic tests.

EXPERIMENTAL PROGRAM

The test specimens are representative of an unreinforced masonry wall in the upper floors of a typical Swiss building of the 1950's. Half-scale squat masonry walls were built using half-scale hollow clay masonry. Two wall families were tested: the first one S family with effective moment/shear ratio (α) of 0.67 (Figure 1) and the second one M family with α of 0.50 (Figure 2). The walls were constructed in a single wythe, in a running bond pattern with a mortar joint of 5 mm thickness. The nominal dimensions of the masonry panels were 710 mm height, 1570 mm length, and 75 mm width. Both the head beam and foundation pad were pre-cast reinforced concrete RC. Eleven specimens were tested during the experimental work. This paper reports on the following tests:

S2-REFE-ST:	Reference specimen
S2-WRAP-G-F-ST:	Specimen S2-REFE-ST after retrofitting with fabrics of glass fiber (GFRP)
M2-REFE1-ST:	Reference specimen
M2-POST-ST:	Specimen M2-REFE1-ST after retrofitting by doubling the post-tensioning force
M2-WRAP-G-F-ST:	Specimen M2-POST-ST after taking off the added post-tensioning force (i.e. 30 kN) and retrofitting the specimen with GFRP
M2-REFE2-ST:	Reference specimen
M2-WRAP-A-F-ST:	Specimen M2-REFE2-ST after retrofitting with fabrics of aramid fiber (AFRP)
M2-2WARP-G-F-ST:	Virgin specimen retrofitted directly after construction with 2 layers of GFRP
S2-WIRE-S-F-ST:	Virgin specimen retrofitted directly after construction with one layer of Hardwire

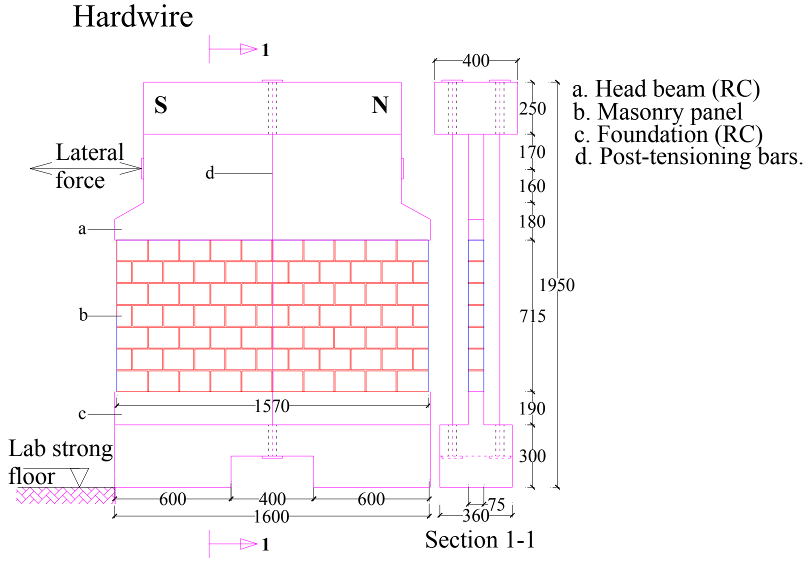

Figure 1 – Typical Dimensions of a S Family Specimen [mm]

Note that, three specimens were tested as reference specimens until a predefined degree of damage was occurred. Then the specimens were retrofitted. Two specimens were retrofitted directly after construction. Also, specimens with names beginning with M had α of 0.50 otherwise the specimens had α of 0.67. Finally, all the specimens that were retrofitted using FRP were retrofitted on the full surface of a single side using different materials. Table 1 shows the properties of the retrofitting materials.

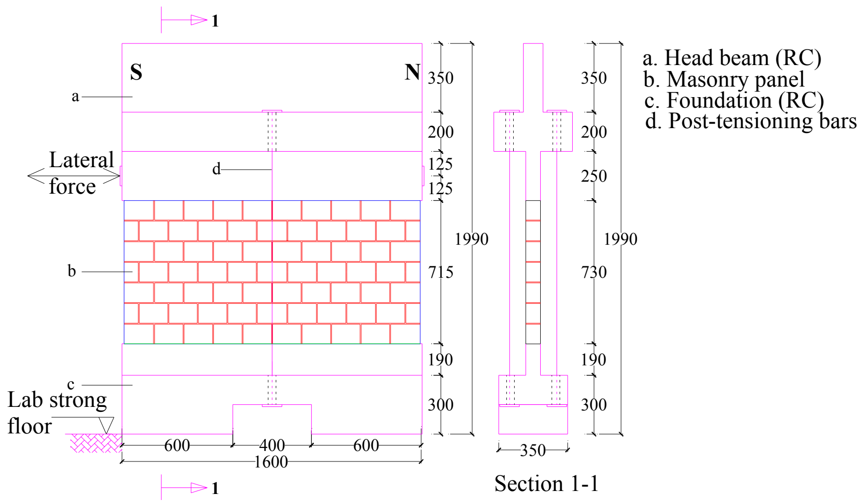

Figure 2 – Typical Dimensions of a M Family Specimen [mm]

Table 1 – Retrofitting Materials Used in the Experimental Program

Commercial name	**F.O. (°)**	**FRP (Type)**	**W_{Warp} (g/m^2)**	**W_{Weft} (g/m^2)**	**f_t (MPa)**	**E (GPa)**	**ε (%)**
SikaWrap-300A	0	Aramid	300	--	2880	100	2.8
SikaWrap-300G	0/90	Glass	145	145	2400	70	3.0
GYZ 12X-4-12	0	Hardwire	524*	--	3150	207	1.5

W_{warp} , W_{weft}: Weight of fiber in the warp and weft directions respectively; f_t: FRP tensile strength; E: Young's modulus; ε: Ultimate strain.

Test set-up and loading system

A test specimen was constructed on a RC footing, which was post-tensioned to the laboratory strong floor (Figure 3). After allowing the specimen to cure, the head beam was fixed to the top of the specimen using strong mortar (M20). A superimposed gravity load of approximately 30 kN was simulated using two external post-tensioning bars. This was in addition to 12 kN of self-weight from steel elements at wall top (due to the test set-up), RC head beam, and masonry panel weight. This normal force corresponded to a stress of 0.35 MPa. Rail springs were used with the post-tensioning bars to avoid increment in the post-tensioning force due to bar elongation. The post-tensioning bars elongate due to the increment in the specimen height due to the widening of flexural cracks.

The horizontal load was applied to the RC head beam; the load was applied manually using two hydraulic jacks and hand pumps. The specimens were subjected to a sequence of test runs (Figure 5): each test run was a half cycle [7]. Before cracking (force control), the applied force was increased gradually with increment of approximately 5 kN. At each applied load, the specimens were subjected to a complete cycle (i.e. two successive test runs). After cracking (displacement control), the first ram (test run in the cracked direction) was controlled by a predefined sequence of displacements, while in the other direction (i.e. next test run or half cycle) the test was controlled in accordance with the measured forces in the previous test run. In this way, equal forces were applied on both sides of a wall specimen.

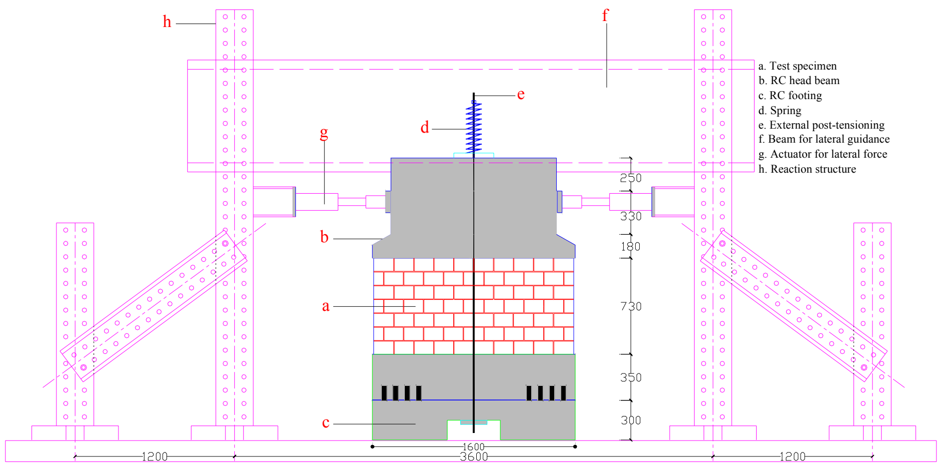

Figure 3 – Test Set-up [mm]

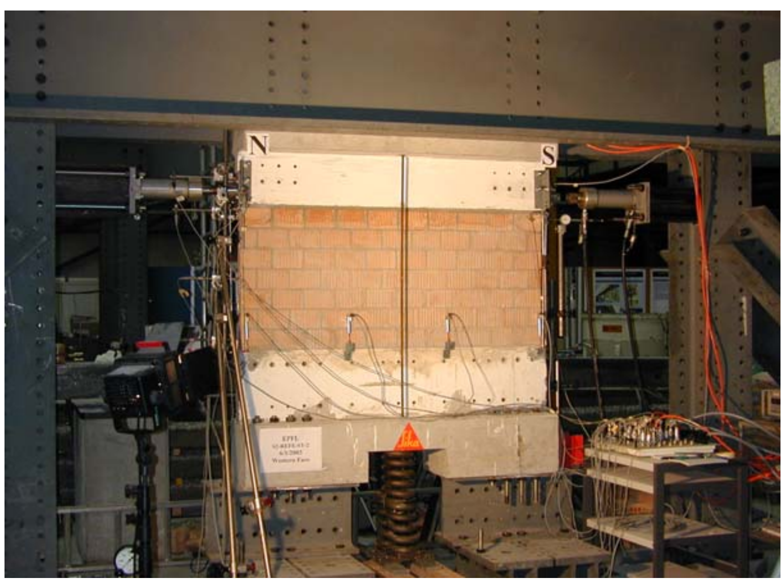

Figure 4 – A M Family Specimen Ready to Test

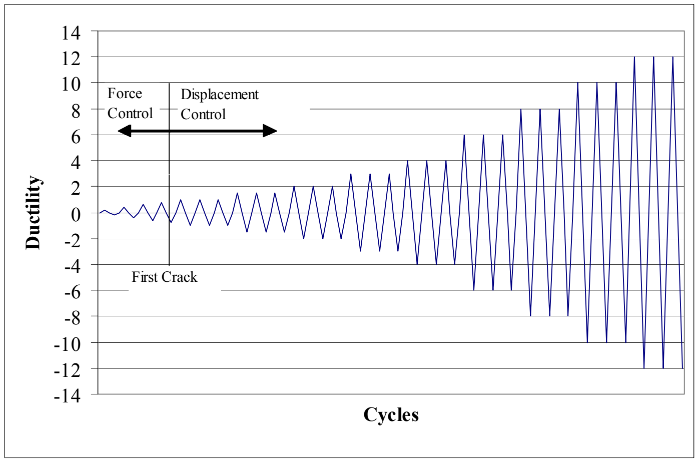

Figure 5 – Loading Sequence

TEST RESULTS

A summary of the test results was collected in Table 2. In the following paragraphs a brief description about the specimens' behaviour during the test is given. For S2-REFE-ST [8], the specimen behavior was dominated by a rocking mode that was initiated by flexural tension crack at bed joints in both sides of the specimen (i.e. north and south sides). These cracks extended through the wall length till it connected together. After the cracks connected, there was no continuity left between the upper part and the lower part of the wall (Figure 6(a)). Finally, the specimen displayed a characteristic rocking behaviour until one toe failed in compression. In addition, before the test ended, the specimen slid on its RC foundation. The coefficient of friction was 0.83. The sliding displacement was approximately 2 mm and the lateral resistance of the specimen was approximately 36 kN.

(a) (b) (c)

Figure 6 – (a) Specimen S2-REFE-ST after Failure, (b) S2-WRAP-G-F-ST (unreinforced face) after Failure, and (c) Typical Vertical Crack

For specimens M2-REFE1-ST and M2-REFE2-ST, both tests were stopped before the specimens reached their ultimate lateral resistance. The stop was necessary to preserve the specimens by preventing heavy damage prior to retrofitting. The test on the first specimen M2-REFE1-ST was stopped after flexural cracks formed at the toes in both directions. The test on the second specimen M2-REFE2-ST was stopped due to strong movement (rocking and sliding) of the head beam which led to stress concentration on a limited length of the wall (i.e. the applied lateral force transferred though limited wall length in spite of the whole wall length) and formation of a diagonal crack passing through head and bed joints. However, both specimens (M2-REFE1-ST and M2-REFE2-ST) had approximately the same lateral resistance (28 kN).

Table 2 – Main test results

Specimen Name	U.M.	N.L.	E.T.	N.	P (kN)		F (kN)	Δ (mm)	F.M.
					Initial	Final			
S2-REFE-ST	--	--	F.C. D.C.	6 69	30	35	36	7	R
S2-WRAP-G-F-ST	GFRP	1	F.C. D.C.	16 43	30	32	51	3	R
S2-WIRE-S-F-ST	HARD WIRE (vertical direction only	1	F.C. D.C.	12 30	30	34	84	11	R
M2-REFE1-ST	--	--	F.C. D.C.	10 12	30	31	28	1	DS*
M2-POST-ST	POST-TENS.	--	F.C. D.C.	4 34	60	63	66	5	R
M2-WRAP-G-F-ST	GFRP	1	F.C. D.C.	24 16	30	34	70	5	RS
M2-2WRAP-G-F-ST	GFRP	2	F.C. D.C.	26 26	29.6	34	95	6	R
M2-REFE2-ST	--	--	F.C. D.C.	8 4	31	32	27	8	DS*
M2-WRAP-A-F-ST	AFRP	1**	F.C.	44	28	31	160	11	R

h: specimen nominal height, specimen nominal dimensions were 75 mm width, and 1600 mm length;
*: diagonal shear due to test set-up problems;
**: one vertical layer and one horizontal layer
U.M.: retrofitting method and material;
N: number of test runs;
P: post-tensioning force;
F, Δ: the maximum of the average of the absolute peak lateral resistances and relative displacement measured in both directions, respectively;
F.M.: failure mode (R: Rocking, RS: Rocking and Shear, and MF: Masonry compression failure and fiber rupture)

Regarding the retrofitted specimens, all the retrofitting techniques increased the lateral resistance by a factor that ranged from 1.7 to 5.9 (Figure 7). For S2-WRAP-G-F-ST and S2-WIRE-S-ST, both specimens developed a rocking mode with masonry crushing at toe (Figure 6(b)). In both specimens, before the specimens reached their ultimate resistances a vertical crack passed through the masonry substrate behind the retrofitting material (Figure 6(c)). A FRP rupture or local buckling of Hardwire followed this vertical crack. The retrofitting increased the lateral resistance by a factor of 1.7 for S2-WRAP-G-F-ST and 2.33 for S2-WIRE-S-F-ST. It is worth noting that, although specimen S2-WIRE-S-F-ST was retrofitted using a unidirectional material oriented in the vertical direction no shear failure happened during testing the specimen. Limited shear cracking (cracking in the mortar joints and diagonal cracking in the epoxy at the toes) appeared at a lateral resistance of 63 kN. For S2-WRAP-G-F-ST, the limited increment in the lateral resistance was influenced by the heavy damage in the reference specimen prior to retrofitting. To illustrate, superposition of the hysteretic loops of a reference specimen (S2-REFE-ST) and the corresponding retrofitted specimen (S2-WRAP-G-F-ST) at the test end is presented in Figure 8.

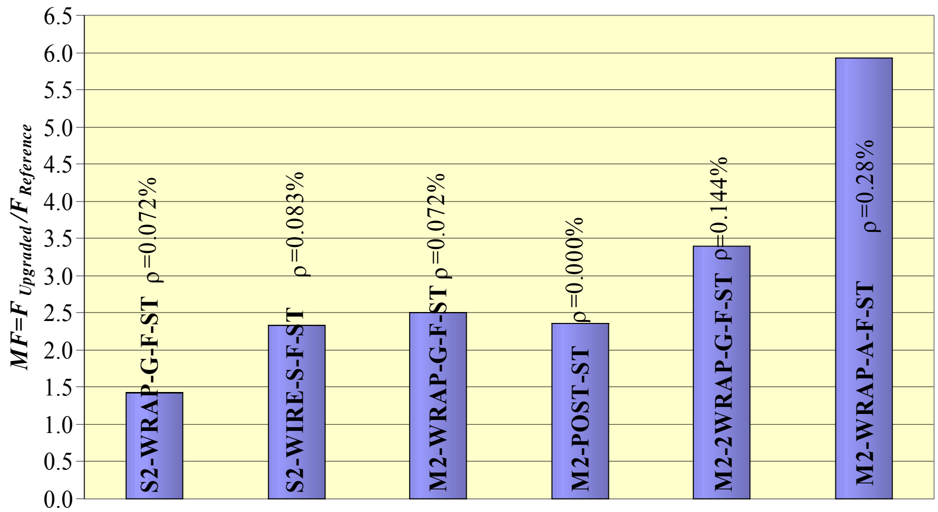

Figure 7 – Improvements in the Lateral Resistance of the Retrofitting

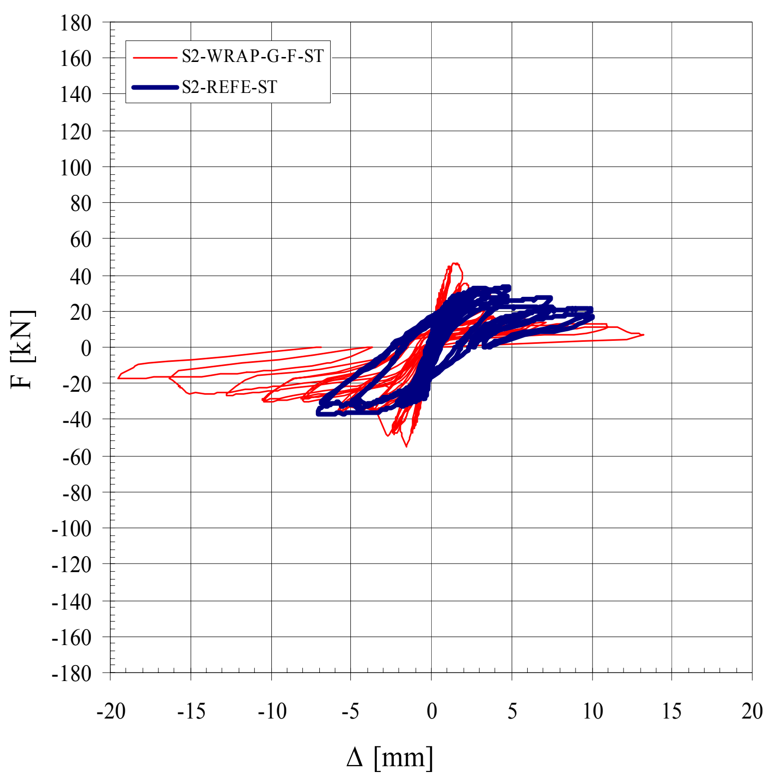

Figure 8 – Superposition of the Hysteretic Loops of S2-REFE-ST and S2-WRAP-G-F-ST

For M family specimens, the specimen that was retrofitted using post-tensioning (M2-POST-ST) reached approximately the same lateral resistance as the one that was retrofitted using one layer of GFRP (M2-WRAP-G-F-ST). Both retrofitting techniques increased the lateral resistance by a factor of approximately 2.5. To illustrate, a superposition of the hysteretic loops of M2-REFE1-ST and M2-WRAP-G-F-ST is presented in Figure 9. Doubling the number of layers of GFRP in specimen M2-2WRAP-G-F-ST increased the lateral resistance by a factor of 3.4. Finally, the lateral resistance of specimen M2-WRAP-A-F-ST where AFRP was used as retrofitting material was increased by a factor of approximately 5.9. All the M family retrofitted specimens failed in flexural with either masonry compression and/or FRP rupture. In specimen M2-WRAP-G-F-ST and after FRP rupture, the masonry panel slid over its RC foundation.

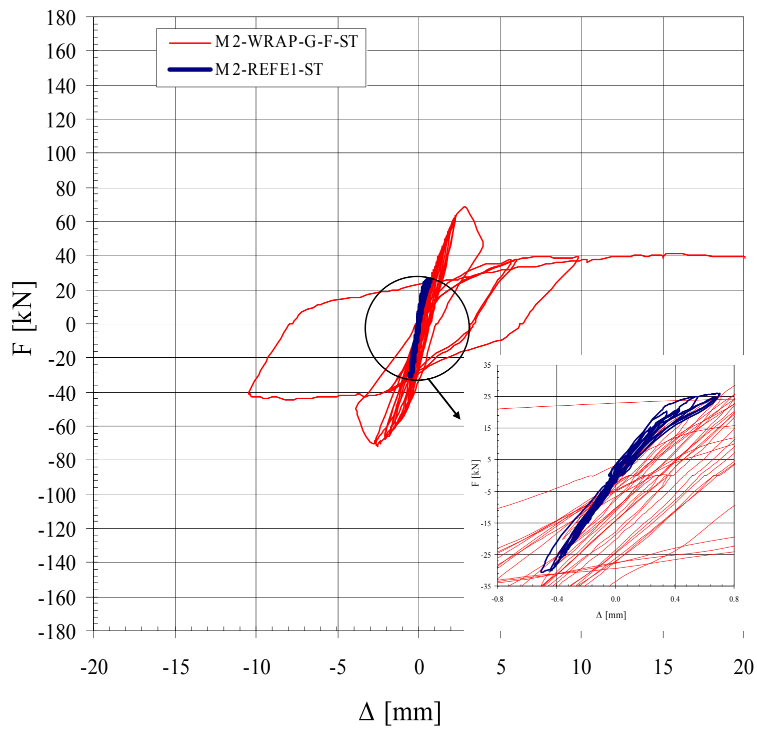

Figure 9 – Superposition of the Hysteretic Loops of M2-REFE1-ST and M2-WRAP-G-F-ST

As demonstrated by Figure 8 and Table 2, the retrofitting changed the ultimate lateral drift. The retrofitting material changed the lateral drift by a factor of 0.5 and 1.5 in case of specimen S2-WRAP-G-F-ST and S2-WIRE-S-F-ST, respectively. It should be noted that these factors were determined in the post peak region when the lateral resistance dropped by 20%. However, in case of S2-WRAP-G-F-ST (south-north direction), after GFRP rupture the specimen behaved in the same manner as the reference specimen (Figure 8). For M family specimens it is difficult to determine the effect of retrofitting on the lateral drift, as the reference specimens was not tested until its ultimate drift was achieved. However, Table 2 shows that the specimens that are retrofitted using either post-tensioning, one layer of GFRP, or 2 layers of GFRP reached approximately the same lateral drift. This means that the reinforcement ratio did not influence the lateral drift, since specimen M2-2-WRAP-G-F had double the reinforcement ratio of specimen M2-WRAP-G-F-ST and both reached the same ultimate drift. Finally, specimen M2-

WRAP-A-F-ST had a lateral drift approximately two times the other retrofitted specimens (M2-WRAP-G-F-ST and M2-POST-ST). However, it is believed that this increment in the lateral drift was due to the movement of the diagonal crack, which formed during testing the reference specimen (M2-REFE-ST).

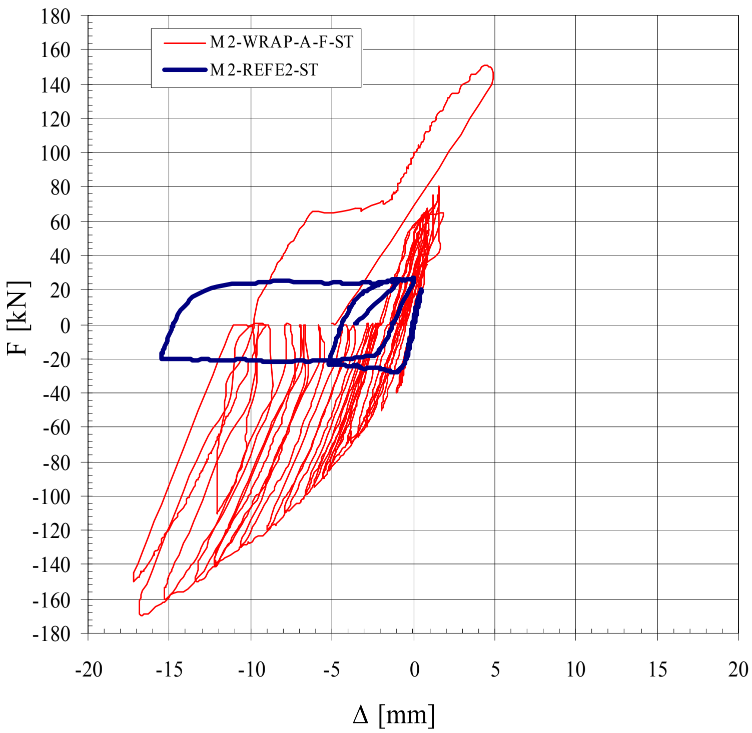

Figure 10 – Superposition of the Hysteretic Loops of M2-REFE2-ST and M2-WRAP-A-F-ST

Regarding the specimen's stiffness, although there was a high degradation of the stiffness of the reference specimen at the tests' end; it should be noted that all the retrofitting techniques succeeded in recovering the initial stiffness of all the specimens. However, the initial stiffness of specimen S2-WIRE-S-F-ST was less than the initial stiffness of specimens (S2-REFE-ST and S2-WRAP-G-F-ST). This could be attributed to the expected variations in the masonry panel itself.

SUMMARY

The static cyclic experimental testing of URM-FRP specimens, led to the following findings:

- The retrofitting materials increased the specimens' lateral resistances by a factor of 1.7 to 5.9 compared to the reference (URM) specimens.
- By defining the ultimate drift as the drift attained when the lateral resistance is reduced by 20%; the GFRP reduced the ultimate drift of the retrofitted specimen by a factor of 0.5. Furthermore, the ultimate drifts were independent of the reinforcement ratio.
- Using post-tensioning as retrofitting approximately doubled the lateral resistance of the reference specimen and was approximately equivalent to use a single layer of GFRP from both lateral resistance and drift point of view.

- Doubling the reinforcement ratio did not produce double the lateral resistance; the lateral resistance in the case of two layers of GFRP was approximately 1.4 times the lateral resistance in the case of a single layer of GFRP.
- Using Hardwire material increased the lateral resistance and drift, with respect to the reference specimen, by a factor of 2.3 and 1.5, respectively. In addition, despite the unidirectional Hardwire oriented in the vertical direction only, no shear failure was observed either in the masonry itself or in Hardwire.
- Within the scope of testing, single-sided retrofitting appears to produce good behavior. No out-of-plane or uneven response of the specimens was observed. Small asymmetries in the transducers were recorded in the case of squat specimens.
- The fabric prevented falling of debris from the wall after failure; thus, preventing possible injuries to occupants in the vicinity of the wall in the event of a real earthquake.

ACKNOWLEDGMENTS
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