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DYNAMIC VERSUS STATIC CYCLIC TESTS OF MASONRY WALLS BEFORE AND AFTER RETROFITTING WITH GFRP

Mohamed ELGAWADY[1], Pierino LESTUZZI[2], Marc BADOUX[3]

SUMMARY

An extensive experimental program for retrofitting of unreinforced masonry (URM) walls has been carried out in Switzerland. The program includes in-plane dynamic and static cyclic tests on URM walls before and after retrofitted with composites. This paper presents preliminary comparisons between the test results of the dynamic and static cyclic tests. The test specimens are half-scale specimens built using half-scale hollow clay masonry units and weak mortar. The specimens, before and after retrofitting, are subjected to a series of either synthetic earthquakes or static cyclic test runs. The tests show that the composites improve the cracking and ultimate load of the retrofitted specimen by a factor of 3 and 2.6, respectively. In addition, the method of testing has insignificant effect on the initial stiffness. The lateral resistance of the reference specimen measured in the static cyclic tests is 1.2 times the lateral resistance of the similar reference specimen measured in the dynamic test.

INTRODUCTION

Unreinforced masonry (URM) buildings represent a large portion of the buildings around the world. Based on modern design codes, most of the existing URM buildings need to be retrofitted (Bruneau [1]). In Switzerland, Lang [2] carried out vulnerability analysis of existing masonry buildings on a target area in Basel; the study shows that between 45% and 80% of the existing URM buildings will experience heavy damage or destruction during an earthquake of intensity VIII (MSK). Therefore, improving existing and developing better methods of upgrading existing seismically inadequate buildings is pressing. Numerous conventional techniques have been applied for retrofitting of existing masonry buildings. Potential disadvantages of these techniques (e.g. heavy mass, limited efficiency, etc.) have been reported (e.g. ElGawady [3], Hamid [4]).

Four years ago, a research program was started in Switzerland for retrofitting of URM. The experimental program includes a pioneer dynamic and a static cyclic in-plane investigation. The dynamic test includes several test parameters: aspect ratio (slender and squat), fiber type, fiber structure, retrofitting configuration, and mortar compressive strength. The dynamic study shows that composites could increase the in-plane ultimate resistance by a factor of 3. However, for squat specimens the test was stopped before

[1] Ph.D. Candidate, ENAC-IS-IMAC, Swiss Federal Institute of Technology at Lausanne (EPFL), Switzerland, mohamed.elgwady@epfl.ch
[2] Lecturer, ENAC-IS-IMAC, EPFL, Switzerland, pierino.lestuzzi@epfl.ch
[3] Former professor, ENAC-IS-BETON, EPFL, marc.badoux@epfl.ch

the ultimate resistance of the specimens was reached. As the ultimate resistance of the retrofitted squat specimens were higher than the force capacity of the shaking table hydraulic jack. Then, a second part of the project, including static cyclic tests on eleven squat specimens with two aspect ratios (0.67, 0.50), was carried out. Finally, the experimental results of the modern retrofitting "FRP" are compared to experimental results of a classical retrofitting scheme "shotcrete". This paper presents comparisons between the observed behavior of specimens before and after retrofitted using composites as well as between the behavior of similar specimens under dynamic and static cyclic loading. The entire test results of the tests are presented in ElGawady [5, 6].

EXPERIMENTAL PROGRAM

This paper presents the preliminary results of the following specimens:

- S2-REFE-ST: an unreinforced masonry reference specimen was subjected to a static cyclic test
- S2-WRAP-G-F-ST: specimen S2-REFE-ST after retrofitting on one face with one layer of glass fiber reinforced plastic (GFRP) was subjected to a static cyclic test
- S1-REFE: an unreinforced masonry reference specimen subjected to a dynamic test
- S1-WRAP-G-F: specimen S1-REFE after retrofitting on one face with one layer of GFRP was subjected to a dynamic test

Description and construction of the test specimens

The test specimens are representative of an unreinforced clay masonry wall in the upper floors of a typical Swiss building of the 1950's (Figure 1). Half-scale squat masonry walls were built by experienced masons using half-scale Hollow Clay Masonry (HCM). The walls were constructed in a single wythe, in a running bond pattern with a mortar joint of 5 mm thickness, which is consistent with the half scaled bricks. The nominal dimensions of the walls are 710 mm height, 1570 mm length, and 75 mm width. Both the head beam and foundation pad were precast concrete. The main geometric features of the constructed walls are illustrated in Figure 2.

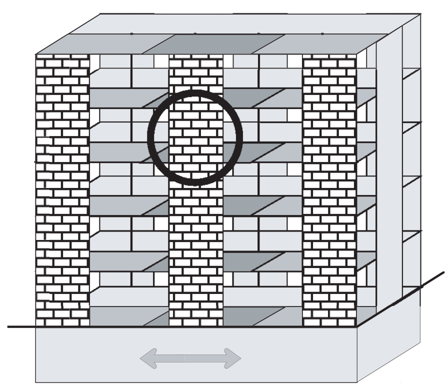


Figure 1: Typical building and investigated URM wall

Bricks and mortar

The original HCM unit is 300 X 150 X 190 mm; this resulted in a scaled brick nominally measuring 150 X 75 X 95 mm. A commercial firm produced the scaled HCM units. The specimens were built using two mortar types. Type 1 had an average cub compressive strength of 9.0 MPa and a standard deviation of 0.40 MPa. Type 2 had an average cub compressive strength of 3.2 MPa and a standard deviation of 0.35 MPa. In the dynamic phase, both types of mortar have been used in the construction of the test specimens; however, the specimens presented in this paper are constructed using type 1. In the static cyclic part, only type 2 was used in the construction of the test specimens.

Retrofitting procedure

After testing of the reference specimens until a predefined degree of damage, the specimens were retrofitted using a layer of bidirectional glass fiber (SikaWrap-300G 0/90). Table 1 gives the fiber

characteristics according to manufacture's data. The composites were applied on one face of the masonry specimen using two-component epoxy Sikadur-330 mixed in a ratio of 4:1 by weight.
The application of the wrap material was a simple and rapid operation. The surface was roughened by grinding, cleaned with high air pressure. It was then coated with a thin layer of Sikadur-330. To ensure that anchorage failure did not occur, steel plates were used to anchor the GFRP to the reinforced concrete head beam and foundation pad.

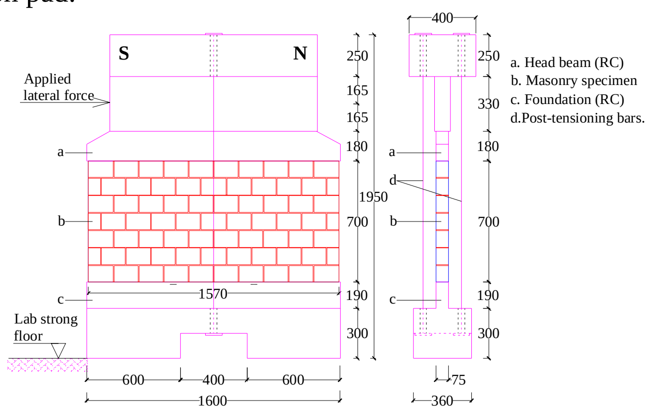


Figure 2: Specimen dimensions [mm]

Table 1: GFRP characteristics

Commercial name	FRP [Fiber]	$Warp_W$ [g/m^2]	$Weft_W$ [g/m^2]	f_t [MPa]	E [GPa]	ε [%]
SikaWrap-300G 0/90	Glass	145	145	2400	70	3.0

$Warp_w$ and $Weft_w$: Weight of fiber in the warp and weft directions respectively
f_t , E, and ε: Fibers nominal tensile strength, Young's modulus, and ultimate strain respectively

Test set-up

Dynamic tests

The specimens were tested on the uni-axial earthquake simulator of the Swiss Federal Institute of Technology in Zurich (ETHZ). The test set up is illustrated in Figure 3, it includes the following features:

- The test specimen is fixed on a shaking table measuring 2 m by 1 m. It has a maximum displacement of ± 100 mm and is driven by a 100 kN servo-hydraulic actuator.
- The specimen is connected at its top to a 12-ton substitute mass placed on bearing wheels with a low coefficient of friction in the order of 0.5%. This substitute mass simulates the inertia mass of the floor, the dark gray area in Figure 1.
- At its top, the specimen is guided with a low friction set-up to ensure that out-of-plane displacements are restricted.

Static cyclic tests

The specimens are tested in the lab of the Structural Institute (IS) of the Swiss Federal Institute of Technology in Lausanne (EPFL). The test set up is illustrated in Figure 4, it includes the following features:

- The test specimen is fixed to the lab strong floor.
- At the specimen top, two 100 kN hydraulic jacks are used alternatively to apply the lateral forces
- At its top, the specimen is guided with a low friction set-up to ensure that out-of-plane displacements are restricted.

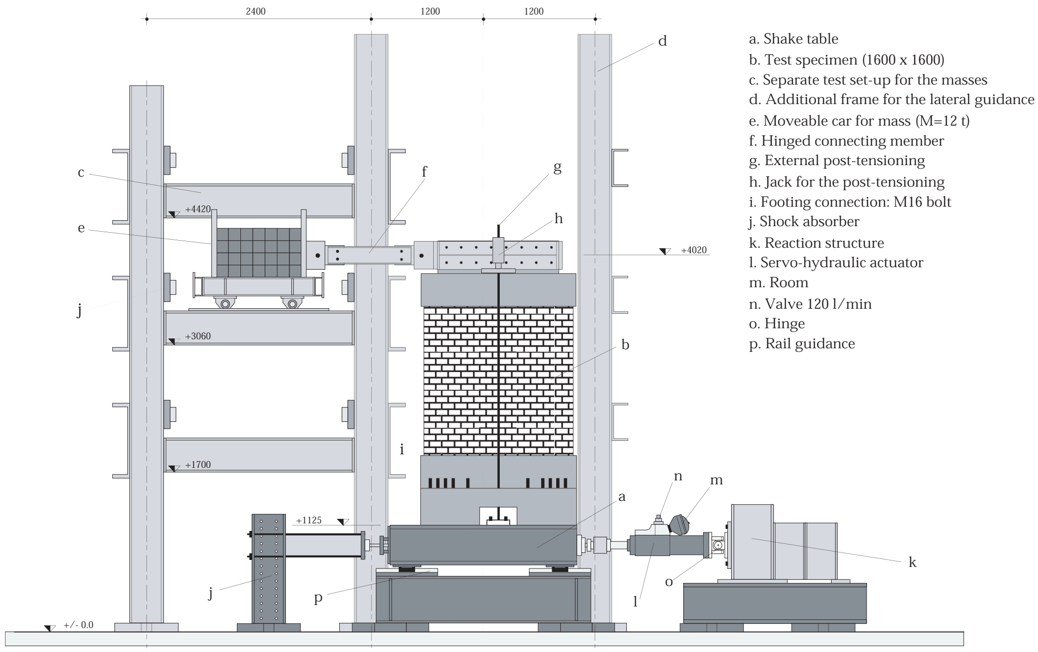


Figure 3: Dynamic test set-up with a slender test specimen [mm]

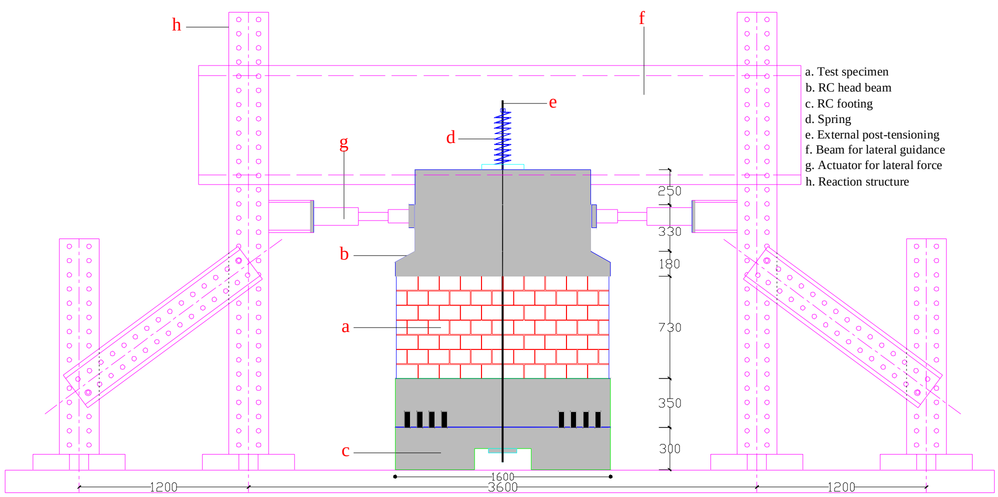


Figure 4: Static cyclic test set-up [mm]

Loading

A test specimen was constructed on a precast reinforced concrete footing. After allowing the specimen to cure (from 3-7 days), the head beam was fixed to the top of the specimen using strong mortar (M20). 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), reinforced concrete head beam, and masonry panel weight. This normal force corresponded to a stress of 0.35 MPa. Railcar springs were used with the post-tensioning bars to avoid increment in the post-tensioning force due to bars elongation. The post-tensioning bars elongate due to the increment in the specimen height as a result of opening of flexural cracks. Later on, the specimen was fixed on the shaking table platform or lab strong floor and subjected to either a dynamic or static cyclic loading. The specimens can be considered cantilever walls, i.e. fixed at the base and free at the top with an effective aspect ratio of 0.67 (height of the horizontal force above the base of the masonry wall of 1.00 m and width of 1.6 m).

Dynamic tests

The displacement input for the shaking table was based on artificial time histories generated from a spectrum shaped according to Eurocode 8 (rock soil type A) and with a peak ground acceleration of 1.6 m/s^2 (seismicity zone 3b of the current Swiss building code). Each acceleration history had duration of approximately 15 seconds. Figure 5 shows the time histories and spectra of the artificial earthquake used for the test of S1-WRAP-G-F and S1-REFE. The specimens were subjected to acceleration histories of increasing intensity, until failure occurred or a predefined degree of damage was obtained. The increment was usually 10% of acceleration.

Static cyclic tests

The horizontal load was applied to the reinforced concrete head beam, which in turn distributes the force to the masonry wall. The load was applied manually using two hydraulic jacks and hand pumps.

The specimens were subjected to a sequence of test runs (Figure 6): each test run is a half cycle. 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 complete cycle (i.e. two consequent test runs). After cracking (displacement control), the first ram (test run in the cracked direction) was controlled by a predefined sequence of displacements (Figure 6), 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.

The predefined sequence of displacements was similar to that proposed in the ICBO (1997). At first cracking, the measured relative displacement at wall top was used to mark the “first yield displacement”. As shown in Figure 6, at each ductility level the specimens were subjected to three complete cycles.

Instrumentation

The specimens were instrumented with several devices as shown in Figure 7. The displacements and deformation of the specimen were measured with linear variable displacement transducers (LVDTs). The forces in the post-tensioning bars as well as the lateral forces at the wall top were measured using load cells. During the static cyclic tests, the horizontal strains in the FRP were measured using electrical strain gages (Figure 7 (b)). In addition, for the dynamic tests, the specimen’s instrumentation included several accelerometers for vertical and horizontal acceleration. Figure 8 and Figure 9 show S1-WRAP-G-F and S2-WRAP-G-F-ST ready to test.

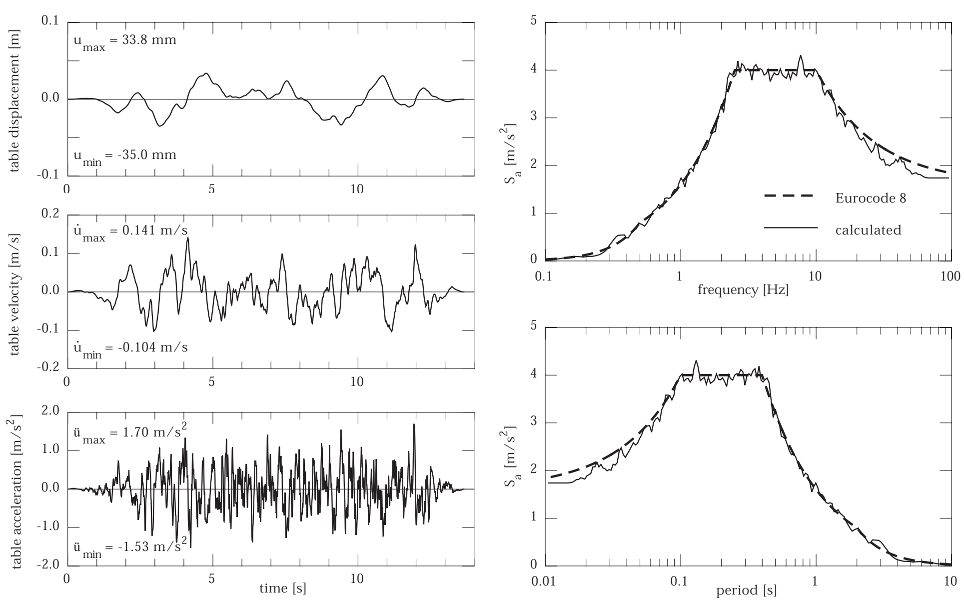


Figure 5: Time histories (displacement, velocity, and acceleration) and response spectra of the spectrum-compatible synthetic for dynamic loading

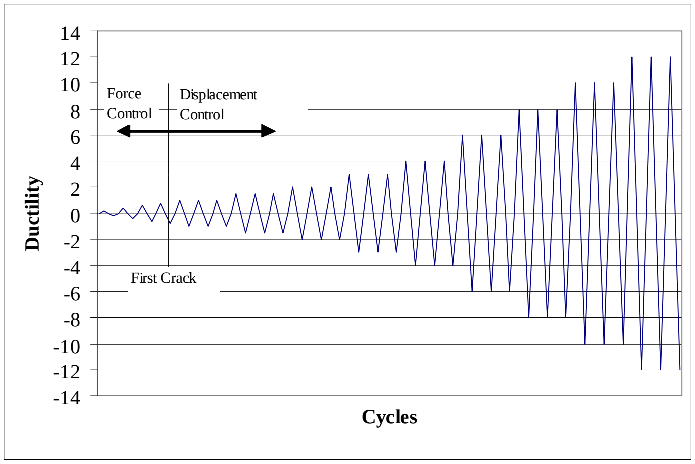
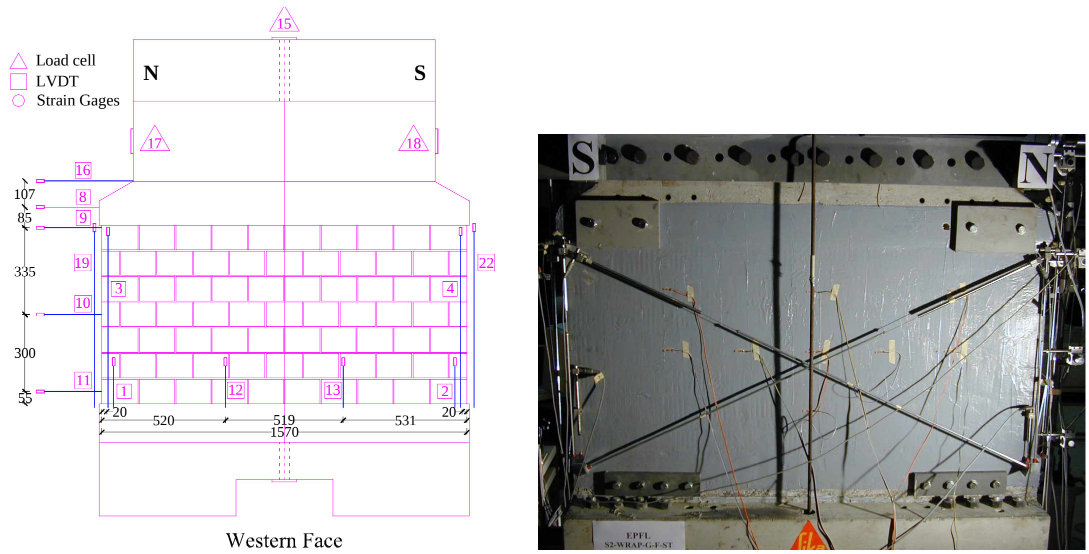


Figure 6: Loading sequence for static cyclic loading



(a) (b)

Figure 7: Specimen S2-WRAP-G-F-ST instrumentations on the (a) western face and (b) eastern (retrofitted) face (for the static cyclic test)

TEST RESULTS

Brief descriptions of the experimental results are presented in Table 2; the entire results and measurements are presented in ElGawady [5, 6]. Table 3 and Table 4 present a summary of the test procedure, the measured lateral forces, and drifts for selected test runs. Figure 10 to Figure 12 show the test specimens at the test end and during the test. These tables and figures complemented by the following comments:

- For S1-REFE (dynamic) and after test run 25, the test was interrupted in order to preserve the specimen for retrofitting and retest.
- Before S1-WRAP-G-F (dynamic) was tested as S1-WRAP-G-F, it was tested two times: first it was tested as reference specimen S1-REFE until a predefined degree of damage. It was then retrofitted with diagonal plates of carbon fiber reinforced plastic CFRP. After the specimen with the CFRP failed, the CFRP plates were taken off and a new retrofitting with GFRP was applied.

Figure 8: Retrofitted specimen ready to test in the dynamic part

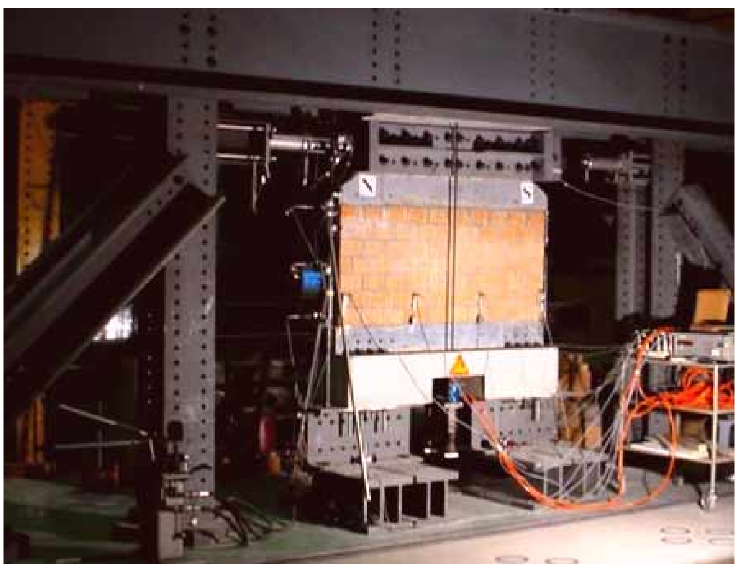


Figure 9: Retrofitted specimen ready to test in the static cyclic part

- For S1-WRAP-G-F and after test run 35, no deterioration was observed either in the composite fabrics itself or the masonry panel. The test was interrupted because the maximum force capacity of the shaking table hydraulic jack was reached.
- For S2-REFE-ST (static cyclic) and after test run 75, the specimen reached its ultimate state with heavy damage at the toes. Also, sliding was recorded.
- Prior to retrofitting of S2-REFE-ST using GFRP, new bricks replaced the damage bricks at the toes. However, the test results of S2-WRAP-G-F-ST influenced by the replacement of bricks as well as heavy damage of S2-REFE-ST.
- For S2-WRAP-G-F-ST (static cyclic) and after test runs 57 and 59, the specimen reached its ultimate state with heavy damage at the toes and GFRP tearing.

COMPARISON OF TEST RESULTS

Figure 13 shows the hysteretic behavior of each test specimen. The axes are the relative horizontal displacement between the top and base of the masonry wall and the horizontal load at top of the wall. In addition, Figure 14 and Figure 15 show superposition of the backbone curves for the reference specimens and the retrofitted specimens as well as the dynamic and static cyclic tests. The following comments complete the comparison between the specimens:

Comparison of test specimen S1-REFE and S1-WRAP-G-F (dynamic)

- The retrofitting increased the cracking load by a factor of at least 3; as no cracks were visually observed in specimen S1-WRAP-G-F until the test end.
- At the test end, the lateral resistance of S1-WRAP-G-F was at least 2.6 times the lateral resistance of S1-REFE.
- The retrofitting delayed the ultimate damaging deformations from 193% to, at least, 467% of the reference earthquake.
- The initial stiffness in the retrofitting specimen was higher than the initial stiffness of the reference specimen. At a drift of approximately 0.15%, the stiffness of the retrofitted specimen equaled the initial stiffness of the reference specimen.

Table 2: Overview of test results

Event	Type	Run*	Position	Notes
S1-REFE				
First crack	Flexural	16	Between the masonry panel and the foundation pad	
Test end	Compression failure	24-25	Toe	Characteristic rocking
S1-WRAP-G-F				
First crack	--			
Delamination	White spots and lines	19-35	Several points	
Test end	--			
S2-REFE-ST				
First crack	Flexural	5	Between the masonry panel and the foundation pad	Runs 45 to 52 produced a flexural crack extended between the fourth and third bed joints
Test end	Compression failure	65-75	Toes	Characteristic rocking
	Sliding	66-67	Between the masonry panel and the foundation pad	Sliding of about 2.5 mm
S2-WRAP-G-F-ST				
First crack	Flexural	15	In the masonry substrate behind the GFRP	Extended instantaneously over 300 mm length
GFRP tearing	Flexural	21	The level of the first mortar joint	Extended instantaneously over 400 mm length
Delamination	White spots	39-40	Several points	
Test end	Compression failure	39-56	Toes	Characteristic rocking
	Sliding	58-59	Between the masonry panel and the foundation pad	Sliding of about 7.0 mm

* See tables 3 and 4 for corresponding lateral forces and drifts

Table 3: Loading history and main test results for the dynamic tests

			North-south direction		South-north direction	
Run	Earthquake [%]	P [kN]	F [kN]	Drift [%]	F [kN]	Drift [%]
S1-REFE						
16	140	30.8	19.6	0.09	24.3	0.11
17	150	31.1	20.5	0.10	25.1	0.14
18	160	31.4	21.3	0.13	25.9	0.15
22	200	34.2	24.9	0.21	27.6	0.25
24	220	36.3	27.4	0.29	28.6	0.32
25	230	37.6	**28.4**	0.35	**28.6**	0.33
S1-WRAP-G-F						
1	60	28.7	10.6	0.02	11.6	0.02
19	360	29.2	36.0	0.10	43.8	0.11
23	380-2	30.0	40.9	0.15	51.0	0.15
29	440	30.2	47.9	0.16	52.5	0.19
32	470	30.3	49.3	0.19	51.3	0.18
34	300-3**	32.5	**72.7**	0.29	**75.5**	0.33

R.I.: Earthquake Real Intensity
P: Maximum prestressing force
F: Lateral force
** Special earthquake with 250 Hz

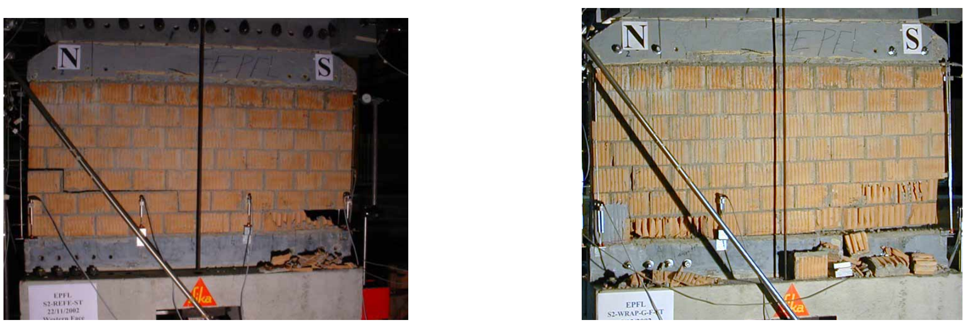
Table 4: Loading history and main test results for the static cyclic tests

North-south direction						South-north direction					
Run	Control	Target	P [kN]	F [kN]	Drift [%]	Run	Control	Target	P [kN]	F [kN]	Drift [%]
S2-REFE											
5	F.C.	15.0 kN	30.1	15.1	0.02	6	F.C.	15.0 kN	29.9	15.2	0.02
7	D.C.	Δ=1.0 Δ_y	30.0	14.7	0.05	8	F.C.	14.7 kN	29.9	14.9	0.02
29	D.C.	Δ=4.0 Δ_y	30.8	25.0	0.15	30	F.C.	25.0 kN	29.8	24.9	0.05
51	D.C.	Δ=10.0 Δ_y	31.4	30.8	0.35	52	F.C.	30.8 kN	29.9	30.7	0.20
63	D.C.	Δ=16.0 Δ_y	30.7	31.5	0.53	64	F.C.	31.5 kN	27.9	31.2	0.31
65	D.C.	Δ=20.0 Δ_y	33.4	33.7	0.70	66	D.C.	Δ=30.0 Δ_y	34.9	37.3	1.02
67	D.C.	Δ=25.0 Δ_y	31.8	30.8	0.69	68	D.C.	Δ=25.0 Δ_y	31.4	34.2	0.73
71	D.C.	Δ=35.0 Δ_y	34.4	27.6	1.08	72	D.C.	Δ=35.0 Δ_y	33.6	33.0	1.00
75	F.C.	18.0 kN	31.4	18.1	1.46						
S2-WRAP-G-F-ST											
15	F.C.	45.0 KN	30.2	45.0	0.17	16	F.C.	45.0 kN	30.3	45.0	0.16
21	D.C.	Δ=1.5 Δ_y	31.1	**47.0**	0.28	22	F.C.	47.0 kN	30.3	47.0	0.17
23	D.C.	Δ=1.5 Δ_y	30.9	35.0	0.26	24	D.C.	Δ=1.5 Δ_y	31.1	**55.0**	0.28
37	D.C.	Δ=3.0 Δ_y	33.0	17.0	0.51	38	D.C.	Δ=3.0 Δ_y	33.9	35.0	0.55
39	D.C.	Δ=4.0 Δ_y	33.7	17.0	0.56	40	D.C.	Δ=4.0 Δ_y	36.8	36.0	0.84
55	D.C.	Δ=10.0 Δ_y	35.3	13.0	1.58	56	D.C.	Δ=10.0 Δ_y	35.8	27.0	1.84
57	D.C.	Δ=14.0 Δ_y	30.7	11.0	1.91	58	D.C.	Δ=14.0 Δ_y	37.6	26.0	2.35
						59	D.C.	Δ=18.0 Δ_y	31.1	17.0	2.80

F.C., D.C.: Force control, and displacement control respectively
P., F: Measured peak post-tensioning and peak lateral forces

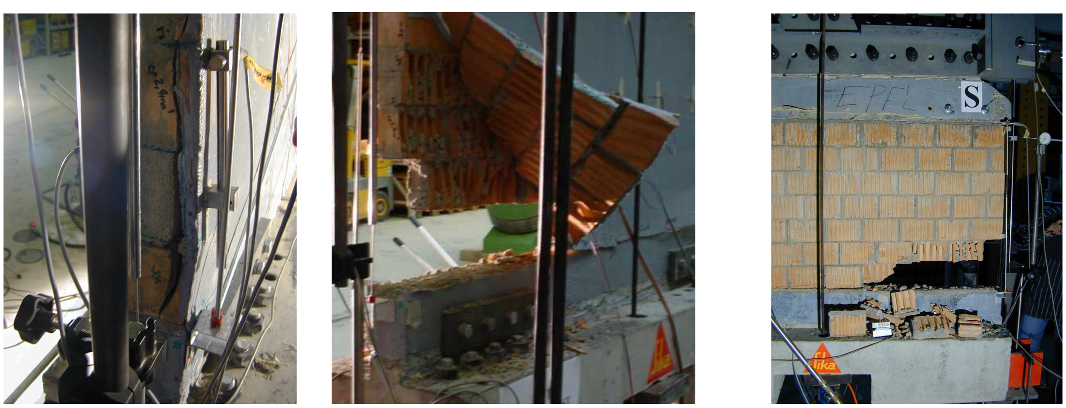
(a) (b)

Figure 10: Specimens (a) S1-REFE and (b) S1-WRAP-G-F at the test end of the dynamic tests



(a) (b)

Figure 11: Specimens (a) S2-REFE-ST and (b) S2-WRAP-G-F-ST (unreinforced face) at the test end of the static cyclic tests



(a) (b) (c)

Figure 12: S2-WRAP-G-F-ST (a) propagation of the first crack in the southern side, (b) rupture of GFRP at the test end, and (c) crushing of masonry at the test end

Comparison of test specimen S2-REFE-ST and S2-WRAP-G-F-ST (static cyclic)

- Both specimens developed a rocking mode and a significant lateral deformation capacity.

- The retrofitting forced a move of the “rocking crack” from 2nd and 3rd course (S2-REFE-ST) to the base of the masonry wall (S2-WRAP-G-F-ST).
- At initiation of rocking, the lateral load in S2-WRAP-G-F-ST is about 3 times that in S2-REFE-ST. However, this high improvement is a consequence of the very weak tensile strength of masonry.
- At ultimate lateral load, the lateral resistance of S2-WRAP-G-F-ST was about 1.5 times the lateral resistance of S2-REFE-ST. This limited improvement was mainly due to the heavy damage in the reference specimen before retrofitting.
- After more than 30 and 20 rocking cycles for S2-REFE-ST and S2-WRAP-G-F-ST respectively, both specimens slide over the reinforced concrete foundation.
- During sliding, the coefficient of friction was not the same in both specimens. For S2-REFE-ST, the coefficient of friction was about 1.0 while for S2-WRAP-G-F-ST was about 0.7. This reduction in the coefficient of friction is due to very heavy damage suffered by S2-REFE-ST before retrofitting.
- In spit of the heavy damage of specimen S2-REFE-ST at the test end, the retrofitting was able to recover its initial stiffness (Figure 14 (b)).
- After GFRP rupture, a high rate of the specimen lateral resistance degradation happened (Figure 14 (b)). After few cycles of GFRP rupture, the lateral resistance dropped to a value corresponding to the lateral resistance at the test end of the reference specimen.
- Although S2-WRAP-G-F-ST had a high lateral drift at the test end, no debris falls down. This preventing, in a real earthquake event, possible injury to occupants in the vicinity of a wall.

Comparison of dynamic and static cyclic test results

Note that the dynamic test was stopped before the ultimate state of the specimens was reached. This happened due to different reasons. In case of the reference specimen, the test was interrupted in order to preserve the specimen for retrofitting and retest. In case of the retrofitted specimen, the test was interrupted because the maximum force capacity of the shaking table hydraulic jack was reached.

- For the reference and retrofitted specimens, the testing method has insignificant effect on the initial stiffness.
- Although the higher resistance of the mortar used in specimen S1-REFE, specimen S2-REFE-ST has a lateral resistance 1.2 times the lateral resistance of S1-REFE. This difference in lateral resistance is probably due to the test method.
- S1-WRAP-G-F has a lateral resistance 1.5 times the lateral resistance of S2-WRAP-G-F-ST. However, the authors believe that the high difference in the lateral resistance between the retrofitted specimens in the static cyclic and dynamic tests is not because of the test method. The difference is mainly due to the state of the reference specimens before retrofitting.
- The ultimate drift reached in the static cyclic was much higher than the reached drift in the dynamic test. However, it is not possible to drawn a conclusion from that as the dynamic test was stopped before the ultimate drift of the specimens was reached.
- Until the end of the dynamic test, the behavior and mode of failure of the reference specimens was the same regardless of the testing method. However, at the end of the static cyclic sliding happened. This sliding was not possible to confirm for the dynamic test.

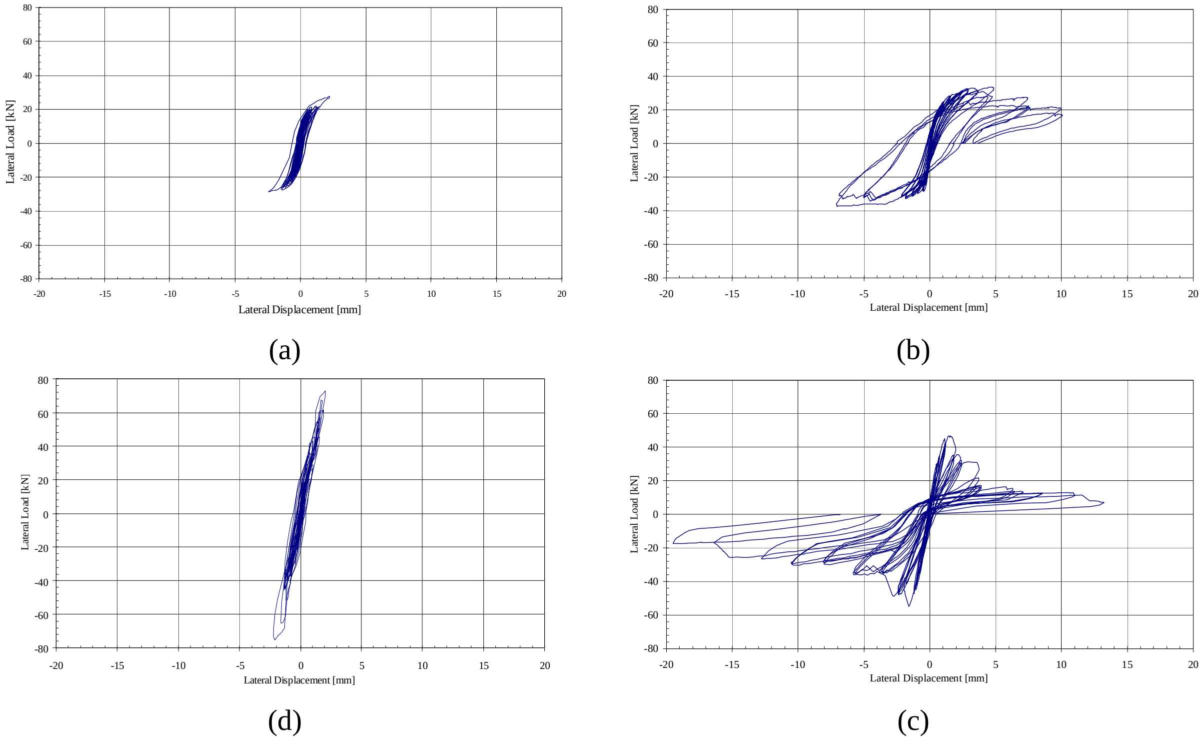


Figure 13: Lateral forces vs. relative top wall displacements for (a) S1-REFE (dynamic), (b) S2-REFE-ST (static cyclic), (c) S1-WRAP-G-F (dynamic), and (b) S2-WRAP-G-F-ST (static cyclic)

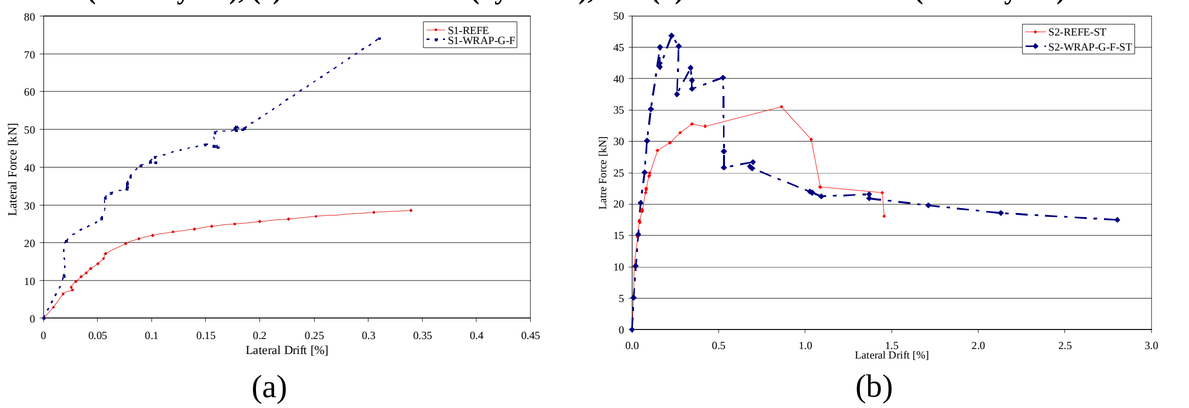


Figure 14: Backbone curves, comparison between reference and retrofitted specimens for (a) dynamic, and (b) static cyclic tests

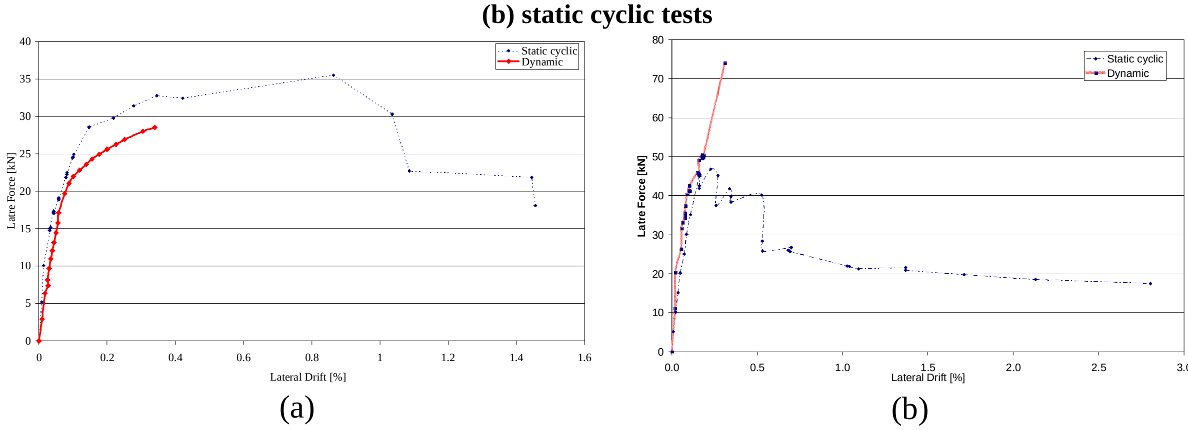


Figure 15: Backbone curves, comparison between dynamic and static cyclic tests for (a) reference, and (b) retrofitted specimens

SUMMARY

Two half-scale URM walls were tested before and after retrofitting using GFRP. Each wall was subjected to either dynamic or static cyclic loading. The tests lead to the following findings:

- The one-sided retrofitting with glass fiber wrap is promising; GFRP improved the specimen cracking load and lateral resistance by a factor of about 3 and 2.6 respectively. It also doubled the acceleration corresponding to the onset of nonlinear behavior, thus providing a significant improvement from a "continued operation" limit state point of view.
- After composite rupture, the retrofitted specimen behaved in the same way as the reference specimen.
- These tests confirm that wall rocking can be a stable non-linear response in unreinforced masonry walls, providing significant lateral deformation capacity.
- In spite of relatively poor mortar, the specimen friction coefficient exceeded 1.0. However, after heavy damage and a drift of about 2% the specimen coefficient of friction reduced to 0.7.
- The initial stiffness for the reference and retrofitted specimens was approximately the same in the static cyclic and dynamic tests.
- The lateral resistance of the reference specimen in the static cyclic test is approximately 20% higher than the lateral resistance in the dynamic test.

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