

Seismic performance of URM walls retrofitted using FRP

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ABSTRACT: Recent earthquakes have shown repeatedly the vulnerability of Unreinforced Masonry (URM) buildings. Fibre Reinforced Plastic (FRP) composites can provide an retrofitting alternative for URM buildings. This paper presents results of dynamic tests investigating the in-plane behavior of URM walls retrofitted with FRP. Five half-scale walls were built, using half-scale brick clay units, and retrofitted on a single side. Two aspect ratios (1.4 and 0.7), two mortar types (M2.5, and M9), three composite materials (carbon, aramid, and glass FRP), three fibre structures (plates, loose fabric, and grids), and two retrofitting configurations (diagonal “X” and full surface shapes) were investigated. The test specimens were subjected to a series of synthetic earthquake motions on an uni-axial earthquake simulator. The retrofitting technique improved the lateral resistance of the URM walls by a factor of 2.9. However, the improvement in the lateral drift was less significant. Moreover, covering the full surface with composites worked better than the diagonal “X” retrofitting configuration.

1 INTRODUCTION

Existing unreinforced masonry (URM) buildings, many of which have historical and cultural importance, constitute a significant portion of existing buildings around the world. Recent earthquakes have repeatedly shown the vulnerability of URM buildings. Several conventional techniques are available to improve seismic performance of existing URM walls. Surface treatments (ferrocement, shotcrete, etc.), grout injections, external reinforcement, and centre core are examples of such conventional techniques. Several researchers (e.g., ElGawady et al 2004a) have discussed the disadvantages of these techniques: available space reduction, architecture impact, heavy mass, corrosion potential, etc. Modern composite materials offer promising retrofitting possibilities for masonry buildings and present several well-known advantages over existing conventional techniques. A recent literature review for retrofitting of URM walls using composites have been presented in (ElGawady et al 2004b). This paper presents pioneering dynamic in-plane tests carried out on half-scale single-leaf unreinforced masonry walls retrofitted with composites (URM-WRC). The objective of this study is to use dynamic tests to better understand the behavior of URM-WRC under in-plane seismic loading, and to investigate the effectiveness of composites as single-side, externally-bonded, retrofitting materials.

2 EXPERIMENTAL PROGRAM

2.1 Test specimens

Half-scale, single-leaf walls were constructed using half-scale hollow clay masonry units. The test specimens had two aspect ratios (Figure 1): slender walls and squat walls. Also, two mortar types were used: weak (M2.5) and strong (M9). In addition, different types of FRP (Table 1) and retrofitting configuration (Table 2) were used to retrofit the specimens. Anchorage failure of the FRP was prevented by clamping the FRP ends to the specimen’s footing and cap-beam using steel plates and screw bolts (since the anchorage problem is out of the scope of this research). Both the cap-beam and footing pad were of precast reinforced concrete (RC).

The test walls were tested twice. Firstly, the URM specimens were tested, as reference specimens, till a predefined degree of damage happened. Secondly, these reference specimens were retrofitted using composites and retested. The focus of this paper is on the behavior of the retrofitted specimens rather than the URM specimens. The behavior of the URM specimens is presented in a separate paper (ElGawady et al. 2003). The specimens were retrofitted on a single side only - since, in many retrofitting intervention scenarios, one-face retrofitting is frequently preferred over double-side ones, either for convenience of construction or to leave the exterior façade of the building unaltered.

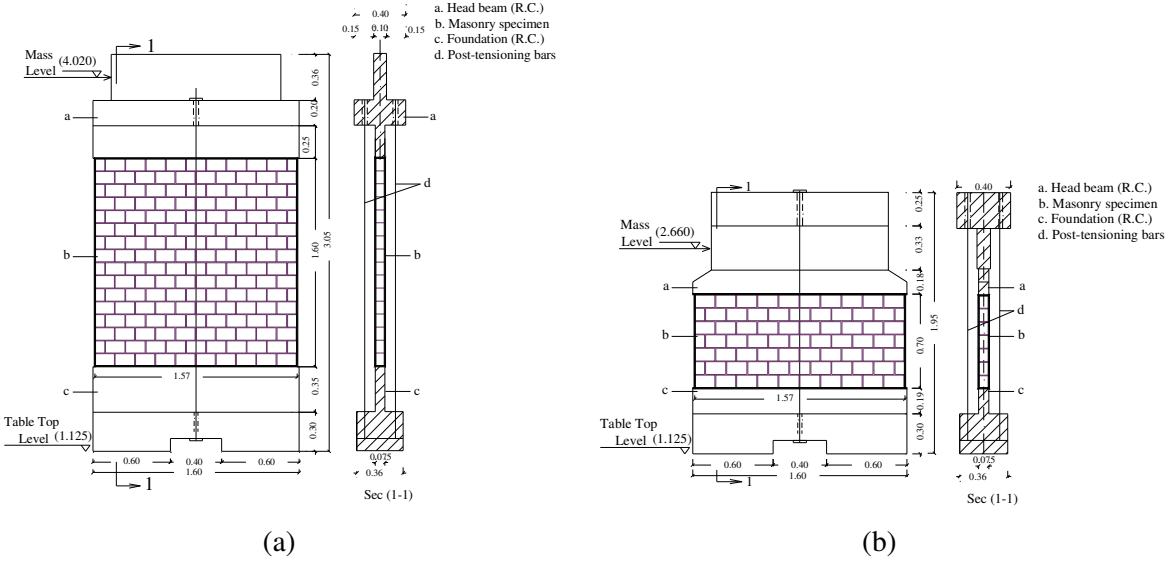


Figure 1. Specimens dimensions in metres, (a) slender and (b) squat

Table 1. FRP used in the experimental program

Commercial name	FRP [Fiber]	Warp _w [g/m ²]	Weft _w [g/m ²]	f _t [MPa]	E [GPa]	ε [%]
SikaWrap-400A 0/90	Aramid	205	205	2880	100	2.8
SikaWrap-300G 0/90	Glass	145	145	2400	70	3.0
MeC Grid G4000	Glass	139	119	3450	72	4.0
Sika CarboDur S512	Carbon	93	-	2800*	165**	1.7
Sika CarboDur T1.214	Carbon	26	-	2400*	135**	1.6

Warp_w and Weft_w: Weight of fibre in the warp and weft directions, respectively

f_t and E: Fibre nominal tensile strength and E-modulus, respectively

ε: Ultimate strain

*: Composite tensile strength

** : Composite E-modulus

2.2 Test set-up

The walls were tested on the uni-axial earthquake simulator of the Swiss Federal Institute of Technology in Zurich (ETHZ). A test specimen was fixed on a shaking table measuring 2 m by 1 m. It had a maximum displacement of ± 100 mm and was driven by a 100 kN servo-hydraulic actuator (Figure 2). The specimen was connected at its top to a 12-tonne substitute mass. At its top, the specimen was guided with a low-friction set-up to ensure that out-of-plane displacements were limited. More details about the test set-up are available in another paper (ElGawady et al 2003).

Table 2. List of the tested specimens

Tests Carried out on Slender Specimens with Type 1 Mortar	
L1-REFE	Reference specimen
L1-WRAP-G-F	Specimen L1-REFE after retrofitting with fabrics of glass fibres (SikaWrap-300G 0/90)
L1-LAMI-C-I	Specimen has been retrofitted with plates of carbon fibre and is considered as a reference specimen (Sika CarboDur S512)
L1-WRAP-G-X	Specimen L1-LAMI-C-I after taking off the carbon plates and re-retrofitting the specimen with fabrics of glass fibre (SikaWrap-300G 0/90)
Tests Carried out on Slender Specimens with Type 2 Mortar	
L2-REFE	Reference specimen
L2-GRID-G-F	Specimen L2-REFE after retrofitting with grids of glass fibres (MeC Grid G4000)
Tests Carried out on Slender Specimens with Type 1 Mortar	
S1-REFE	Reference specimen
S1-LAMI-C-X	Specimen S1-REFE after retrofitting with plates of carbon fibres (Sika CarboDur T)
S1-WRAP-G-F	Specimen S1-LAMI-C-X after taking off the carbon plates and retrofitting it with fabrics of glass fibres (SikaWrap-300G 0/90)
Tests Carried out on Slender Specimens with Type 2 Mortar	
S2-REFE	Reference specimen
S2-WRAP-A-F	Specimen S2-REFE after retrofitting with fabrics of aramid fibres (SikaWrap-400A 0/90)

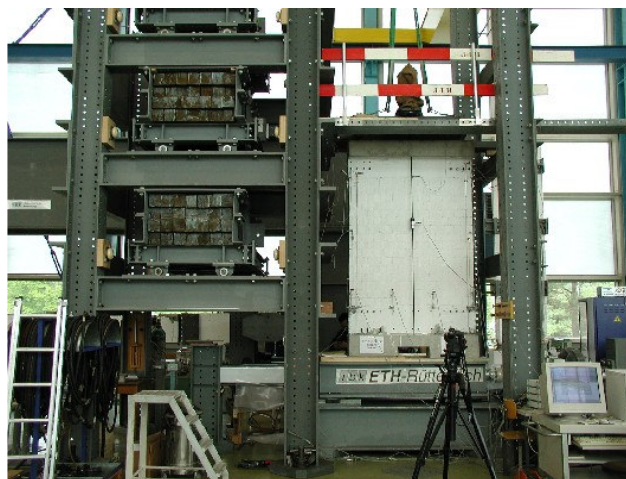


Figure 2. A slender specimen ready to test

2.3 Loading system

A test specimen was constructed on a precast RC footing. After allowing the specimen to cure (for 3-7 days), the precast RC cap-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 the wall top (due to the test

set-up), RC cap-beam, and masonry panel weight. This normal force corresponded to a stress of 0.35 MPa. During testing of specimens L1-WRAP-G-F and L1-WRAP-G-X, and due to an increase in the wall height as a result of opening of flexural cracks, the post-tensioning force increased many times; in the next specimens, two railcar springs were used with the post-tensioning bars. These springs prevent, to a certain extent, the increment in the post-tensioning force.

2.4 Dynamic excitations

The displacement inputs were based on synthetic acceleration time-histories compatible with Eurocode 8 (1994) for rock soil Type A and with a peak ground acceleration of 1.6 m/s^2 (Figure 3). The specimens were subjected to acceleration histories of increasing intensity until failure occurred. The tests started by subjected the specimens to an earthquake with acceleration of 10% of the reference earthquake acceleration, followed by an increment in the acceleration of usually 10% of the reference earthquake acceleration (ElGawady et al. 2003).

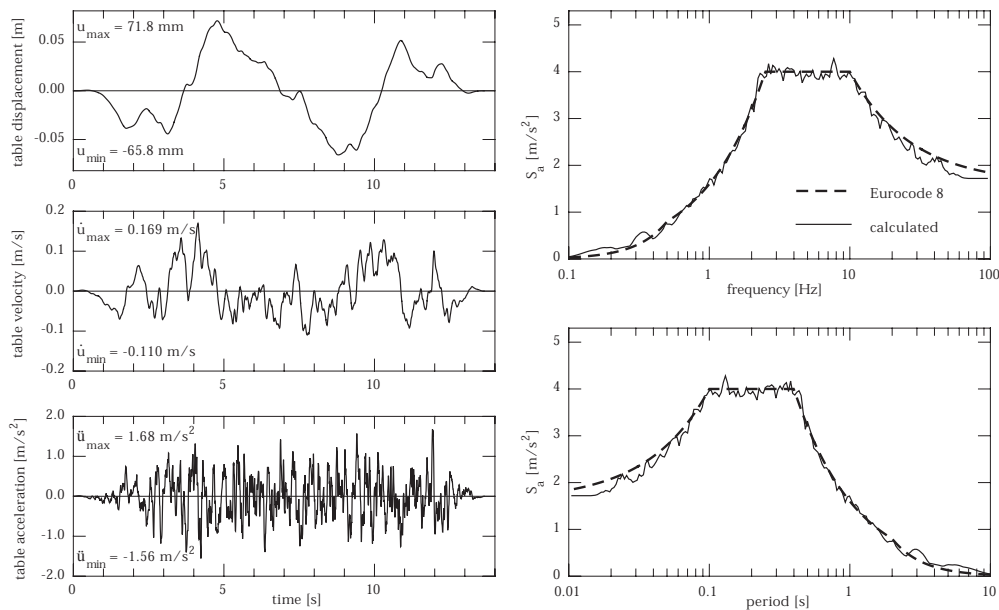


Figure 3 Spectrum-Compatible Synthetic Earthquake (UG1 for 100% intensity)

3 EXPERIMENTAL RESULTS

In this section, the experimental results of the test specimens are briefly discussed in terms of lateral strength, drift, and specimen asymmetry. Detailed results regarding URM specimens (i.e., specimens without composites) are available in another paper (ElGawady et al 2003).

3.1 Lateral strength and mode of failure

All the composite materials increased the lateral strength by a factor that ranged from 1.3 to 2.9. Different failure modes happened during the test; Figure 4 shows the test specimens at the end of the test. For slender specimens, the full-face retrofitted specimens (L1-WRAP-G-F and L2-GRID-G-F) developed a rocking mode - with masonry crushing at the toes, and fibre rupture at the heels. For the reference specimens, a rocking mode of failure was observed. However, in the case of retrofitted specimens, the failure happened at a level corresponding to the first brick course. This was not always the case for the reference specimens (ElGawady et al. 2003). For both retrofitted specimens and under a constant normal force of 57 kN, the retrofitting increased the lateral strength by a factor of 2.6 for fabric and 2.9 for grid reinforcing. A superposition of the hysteresis loops of a reference slender specimen (L2-REFE) and the corresponding retrofitted specimen (L2-GRID-G-F) is presented in Figure 5. For L1-WRAP-G-F and at the end of the test, the normal force tripled (due to increments of wall height as a result of opening of flexural cracks, and due to the absence of the railcar springs).

This increment in the normal force had insignificant effect on the specimen's lateral strength. Nevertheless, the lateral strength of the reference specimen (L1-REFE) approximately tripled when the normal force tripled. As a consequence, the enhancement in the lateral strength in the case of a high normal force reduced to 1.9 times the original lateral strength.

For squat specimens, the lateral strengths of the full-face strengthened specimens (S1-WRAP-G-F and S2-WRAP-G-F) were higher than the capacity of the shaking table hydraulic jack. At the end of the test, there were no significant signs of failure. In addition, the retrofitting increased the lateral resistance of the specimens by a factor of 2.6.

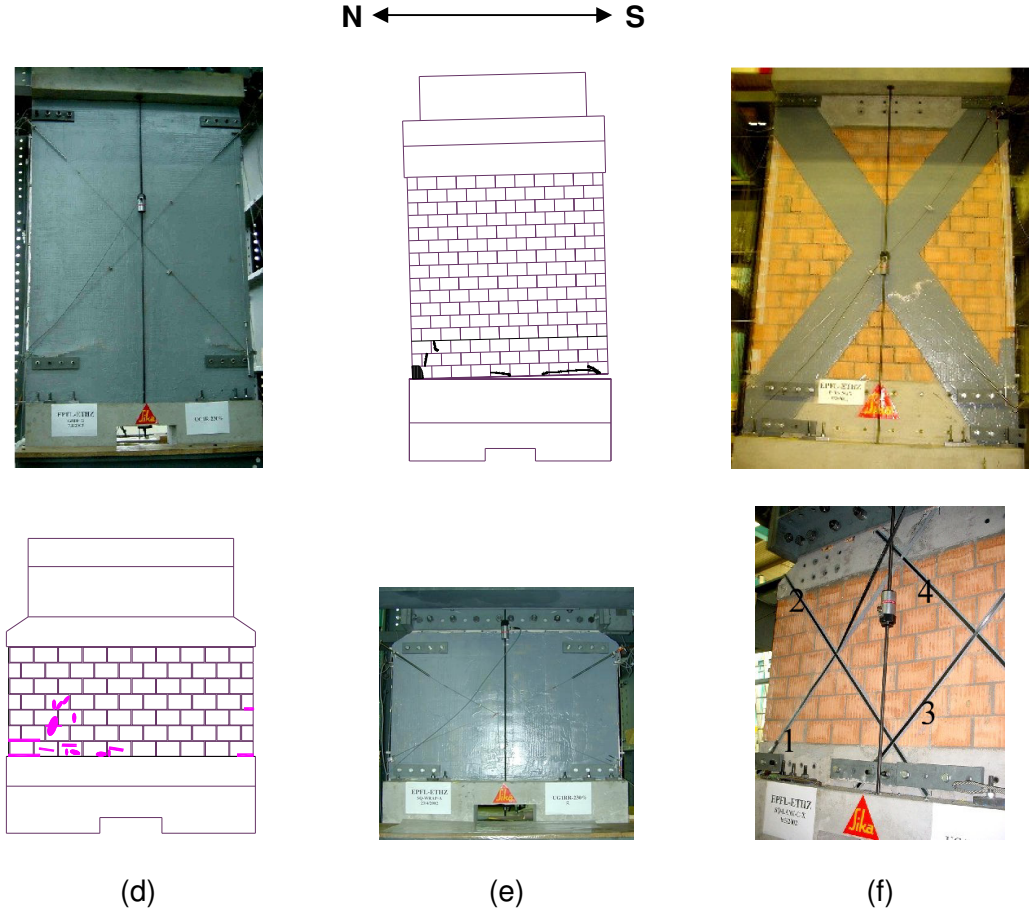


Figure 4 Failure Modes of Specimens (a) L2-GRID-G-F, (b) L1-WRAP-G-F, (c) L1-WRAP-G-X, (d) S1-WRAP-G-F, (e) S2-WRAP-A-F, and (f) S1-LAMI-C-X

Specimens that had been retrofitted with a diagonal shape (X) (L1-WRAP-G-X and S1-LAMI-C-X) were less successful. The behaviors of both specimens could be affected by the previous tests, which had been carried out on the specimens before retrofitting. Before retrofitting, L1-WRAP-G-X was tested as L1-LAMI-C-I, while S1-LAMI-C-X was tested as S1-REFE. These tests developed several cracks in both specimens. Therefore, the retrofitting could be considered as retrofitting of an URM wall that has been severely damaged during a recent real earthquake event. For L1-WRAP-G-X, and at failure, the FRP failed at the specimen's mid-height due to shear and flexural cracks which had developed first through mortar joints. For S1-LAMI-C-X and during the test, one plate failed due to anchorage failure at foundation level since no steel plates (which were used in the other specimens to prevent anchorage failure) were used in this specimen. Both retrofitting configurations enhanced the lateral resistance by a factor of 1.5 for L1-WRAP-G-X, and 1.3 for S1-LAMI-C-X. It should be noted that the cracks that existed in the specimens before the diagonal retrofitting influenced the results. However, this led to a conclusion to use such diagonal configuration only as retrofitting in the case of a real URM wall that has suffered severe damage in an earthquake.

Finally, as mentioned, the goal of retrofitting of one specimen using two vertical plates of CFRP was not to examine the effect of retrofitting; since in such kinds of retrofitting shear cracking is expected. As expected, this “retrofitting” system changed the wall mode of failure (from rocking to shear) and increased the specimen lateral strength by a factor of 1.75.

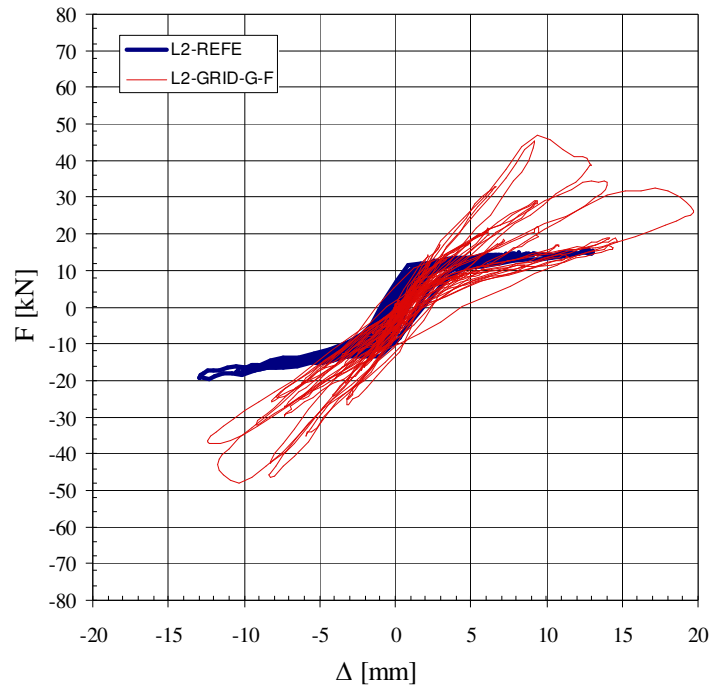


Figure 5 Superposition of the hysteretic loops of L2-REFE and L2-GRID-G-F

3.2 Lateral drift

The ultimate lateral drifts of retrofitted specimens were dependent on the aspect ratio, and mostly independent on the reinforcement ratio (ρ). For slender specimens (L1-WRAP-G-F, L2-GRID-G-F, and L1-WRAP-G-X), the ultimate drifts were approximately 1%. As an example, Figure 6 shows the envelopes of the hysteresis loops of all the test runs of specimen L2-GRID-G-F, and the corresponding reference specimen L2-REFE. The peak lateral force values are normalized by 128.7 kN, the sum of the weights of the 12-tonne mass, the head beam, half of the masonry panel, and the other test set-up steel elements at the top of the specimen. The envelope shows that approximately 80% of the drift was attributed to specimen rocking.

For squat (short) specimens (S1-WRAP-G-F, S2-WRAP-A-F, and S1-LAMI-C-X), it is difficult to trace the relationship between reinforcement ratio and lateral drift since the specimens (S1-WRAP-G-F, S2-WRAP-A-F) did not reach their ultimate state due to the test set-up capacity. However, the measured maximum drift for the squat retrofitted specimens ranged from 0.1% to 0.5%.

3.3 Plane section

Vertical deformations at the first brick course, along a specimen cross-section, were measured using four LVDs. The measured displacements were divided by the original measuring length (156 mm). This gave the strain time-history along the specimen cross-section. These measurements were used to verify the main assumption of the Bernoulli-Navier hypothesis (plane sections remain plane before and after deformations) for the slender URM-WRC. As an example of these strain distributions, measured strains during the several test runs of specimen L2-GRID-G-F are plotted in Figure 7. A salient feature of this figure is that the vertical strain distribution along the specimen cross-section is approximately linear - even at failure. The verification of this assumption of plane section is very important when using the usual linear elastic approach to calculate the lateral strength of an URM-WRC.

3.4 Specimen asymmetry

As mentioned earlier, all the test specimens were retrofitted on a single side only. As shown by other researchers (Schwegler 1994, Al-Chaar et al 1999), this system did not result in any asymmetry in the deformations, which may result in more complicated failure mechanism. In order to evaluate this issue for the tested specimens, a comparison between the vertical strains, calculated from measured displacements using LVD transducers on the masonry “bare face” and the retrofitted side was carried out. The comparison shows the following:

- For slender specimens, the retrofitting system succeeds in producing a complete symmetric response in the case of tension, while there was a little asymmetry in the case of compression. The strains indicate that the asymmetry increased with increasing the earthquake intensity. The rate of increase in the asymmetry during compression is many times larger than during tension. The maximum asymmetry in tension was recorded during testing L2-GRID-G-F. The average vertical strain along the masonry face was approximately 118% of the average vertical strain along the FRP face. In compression, the maximum asymmetry was recorded during the testing of L1-WRAP-G-F. The average vertical strain along the masonry face was approximately 50% of the average strain along the FRP face.

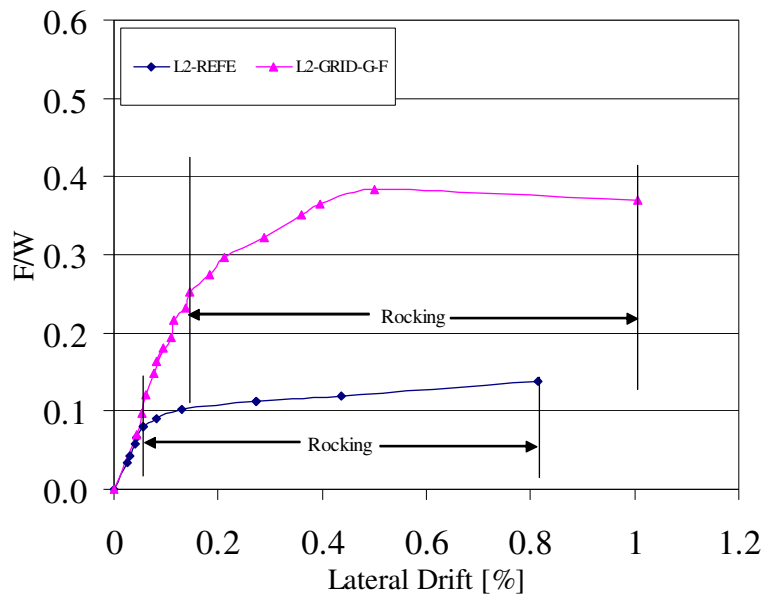


Figure 6. Normalized lateral force vs. wall drift for slender specimens (L2-REFE and L2-GRID-G-F)

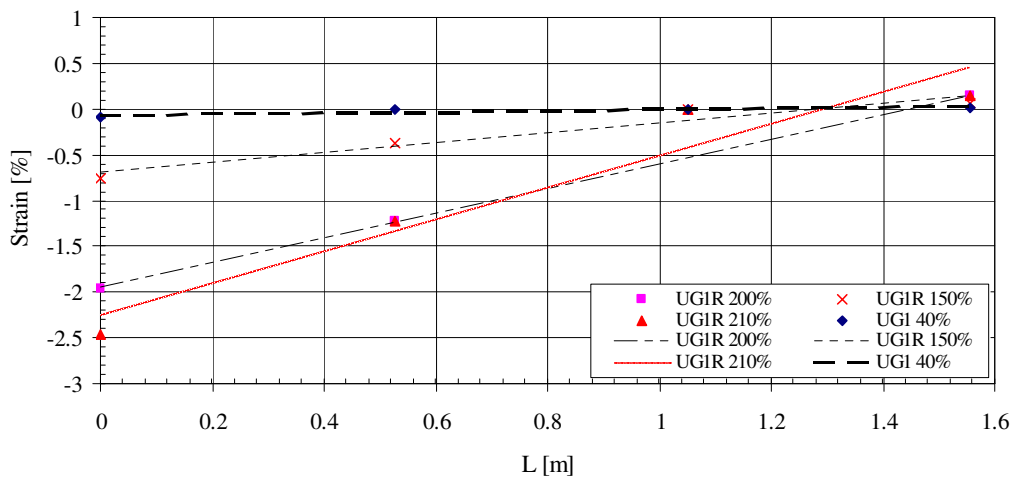


Figure 7. Vertical Strain Distribution along Specimen L2-GRID-G-F Cross Section

- For squat specimens, the retrofitting system did not succeed in producing a symmetric response. The maximum asymmetry in tension was recorded during testing of S1-WRAP-G-F. The average vertical strain along the masonry face was approximately 290% of the average vertical strain along the FRP face. In compression, the maximum asymmetry was recorded during testing of S2-WRAP-A-F. The average vertical strain along the masonry face was approximately 56% of the average strain along the FRP face.

4 CONCLUSION

Five half-scale URM walls were built using half-scale brick units. These five walls were dynamically tested as reference specimens. Then, these reference specimens were retrofitted using composites and retested. As a consequence, a total of eleven specimens were tested on the earthquake simulator of ETHZ. This experimental research led to the following findings:

- The retrofitting materials increased the specimens' lateral resistances by a factor of 1.3 to 2.9 compared to the reference (URM) specimens. As expected, the factor is higher for lower normal force: the lateral resistance of the reference specimen increases, approximately in a linear fashion, by increasing the normal force; the increase in the normal force has, nevertheless, little effect on the resistance of the retrofitted specimens.
- The enhancement in the ultimate drift for the slender retrofitted specimens was small, reaching up to 1.2. Furthermore, the ultimate drifts were independent of the reinforcement ratio and reinforcement type (grid or fabric). However, the ultimate drifts were dependent on the aspect ratio and the retrofitting configuration.
- Within the test conditions, retrofitting on a single side 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. However, further investigations are required for squat specimens in the ultimate range.
- The fabric prevented debris falling from the wall after failure - thus preventing possible injuries to occupants in the vicinity of the wall in the event of an earthquake in a real case.
- In general, the bi-directional, surface-type materials (fabrics and grids) applied over the entire surface of the wall (and correctly anchored) can help postpone the three classic failure modes of masonry walls: rocking ("flexural failure"), step cracking, and sliding ("shear failures"). Additionally, in some situations, they will postpone in-plane collapse by "keeping the bricks together" under large seismic deformations.
- Carbon plates or fabric strips used in a diagonal pattern (X or XX) were less successful. It was used in the retrofitting of two specimens. In both cases, "premature" failure developed (anchorage once, and shear-flexure another). In both cases, the retrofit pattern and reinforcement ratio could have been improved to prevent the premature failure. However, the tests indicate that these retrofits are less robust and have fewer redundancies.

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