CYCLIC SHEAR TESTS ON PLAIN AND FRP RETROFITTED MASONRY WALLS

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ABSTRACT :

Retrofitting of existing vulnerable buildings in seismic areas represents a high priority for the structural engineer community worldwide. In Romania the issue of seismic rehabilitation is focused on some vulnerable buildings typologies such as high rise gravity designed RC structures and plain masonry structures. Given the seismic risk of Romania and the large vulnerable building stock, JICA Technical Cooperation Project on the Reduction of Seismic Risk in Romania was implemented since 2002 by National Center for Seismic Risk Reduction. Many building collapses in 1940 and 1977 Vrancea earthquakes were triggered by the shear failure of the masonry walls. These walls were not designed and detailed to withstand the shear force due to lateral seismic loading. The seismic evaluation and retrofitting of masonry walls is tributary to available and accurate input data. These data are made available solely by structural experimental tests. The employment of worldwide available experimental data is misleading because of scattered materials characteristics and construction practice. To implement accurate and appropriate retrofitting solutions it is necessary to conduct tests following local state of the practice. The paper describes a series of four masonry walls specimens subjected to cyclic shear test. Two of the specimens represent the existing plain masonry walls and the other two FRP retrofitted ones. One of retrofitted specimens is enforced using one layer of FRP sheet applied on both sides and the other one by using two layers applied on one side.

KEYWORDS: Masonry, shear, retrofitting, FRP

1. TESTING PROGRAM

1.1. Specimens

The paper contains information about a series of 4 tests on masonry walls requested by Building Research Institute, Tsukuba, Japan to Technical University of Civil Engineering, Bucharest (UTCB) & National Center for Seismic Risk Reduction, (NCSRR) Romania. The test program started in January 2007 and was finalized in April 2007. The test consisted of 4 masonry walls subjected to increasing cyclic lateral loads up to the failure. The specimens are made of old solid bricks with average compression strength of 10 MPa and of mortar with average compression strength of 2.5 MPa. The nominal dimensions of the solid brick used in the tests are: 240x115x63 mm. The layout of the tested specimens is given in Figure 1 and Figure 2. Two walls are made of plain old masonry and the other two walls are prepared in the same way but are retrofitted using FRP sheets, carbon fiber sheets more precisely. The overall amount of carbon fiber is the same, but for specimen three, WBRI3 the amount is distributed evenly on both faces of the wall and for specimen four, WBRI4 the amount is placed only on one face of the wall.

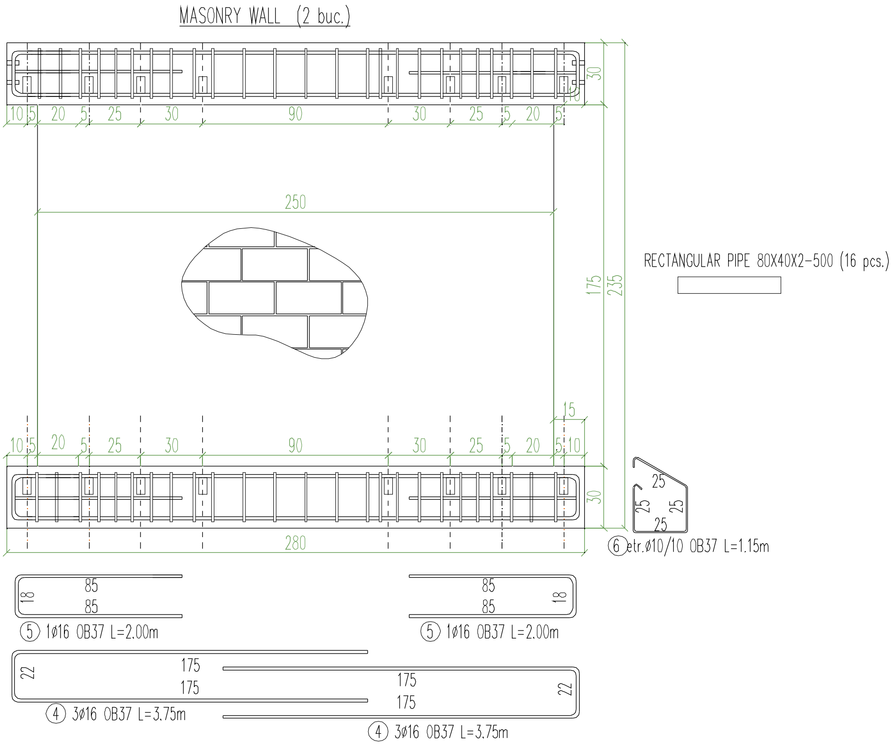


Figure 1. Elevation view of the masonry wall and of the studs

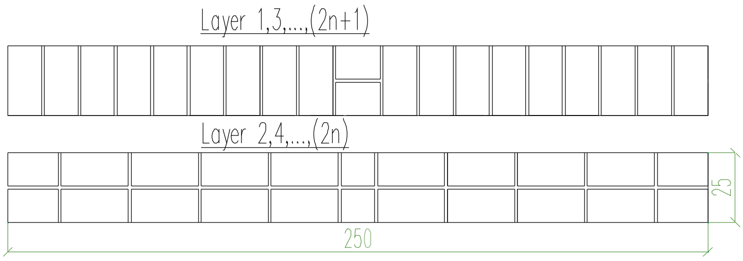


Figure 2. Bird eye view of the bricks layer

More details about the tested specimens are given in Table 1. The purpose of the test is to investigate the effectiveness of FRP retrofitting and the robustness of application of the sheets only on one face, as it is the case of historical buildings where no intervention on the façade is allowed.

Table 1 – Characteristics of tested specimens

Wall	Vert. Reinf.	Hor. Reinf.	Carbon fiber sheets	σ_0 [MPa]	Applied Axial Force [kN]
WBRI1	No	No	No	1.20	750
WBRI2	No	No	No	0.60	375
WBRI3	No	No	Yes – on both faces	1.20	750
WBRI4	No	No	Yes – on one face	1.20	750

Observation: the axial mean stress (σ_0) corresponds to the average specimen's sectional dimensions (length = 2500mm; width = 250mm)

The specimens are tested in double curvature and correspond to “squat walls” because of the height to length ratio less than one. For this type of walls the lateral behavior is controlled by the shear force, as opposed to the regular walls controlled by bending with axial force. This is why the results and conclusions of the tests cannot be extrapolated to regular walls.

1.2. Loading Equipment

The structural testing equipment consists of a steel reaction frame, loading control device, data acquisition and processing systems. The structural testing facility worthy of approximately 1 million US$ was donated by JICA to the NCSRR and installed in April/March 2004 at the UTCB/NCSRR site, Bucharest (Figure 3 and Figure 4).

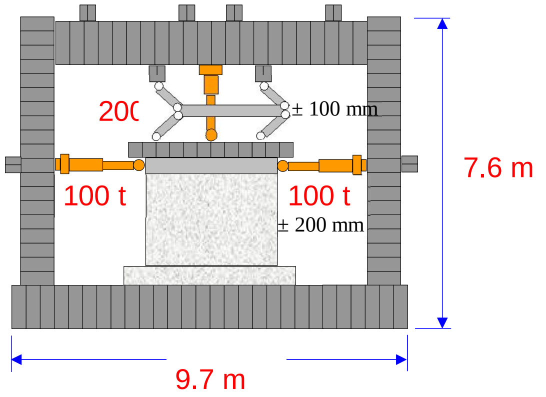


Figure 3. Overall dimensions, force and stroke capacities of loading system

Figure 4. Reaction frame

1.3. Loading Scheme and Loading Protocol

The loading begins with the application of the vertical (axial) force (first step) kept constant during the test. The axial force applied with the vertical cylinder is uniformly distributed by the rigid steel beam of the pantograph. Due to the pantograph, the rotation of the upper beam is constrained and the specimens are tested in double curvature. In the second step the cyclic lateral force is applied under constant axial load. The cyclic load (second step) is controlled in displacements due to the inelastic behavior envisaged for the tested specimens. The loading scheme is presented in Figure 5 and the loading protocol is presented in Figure 6.

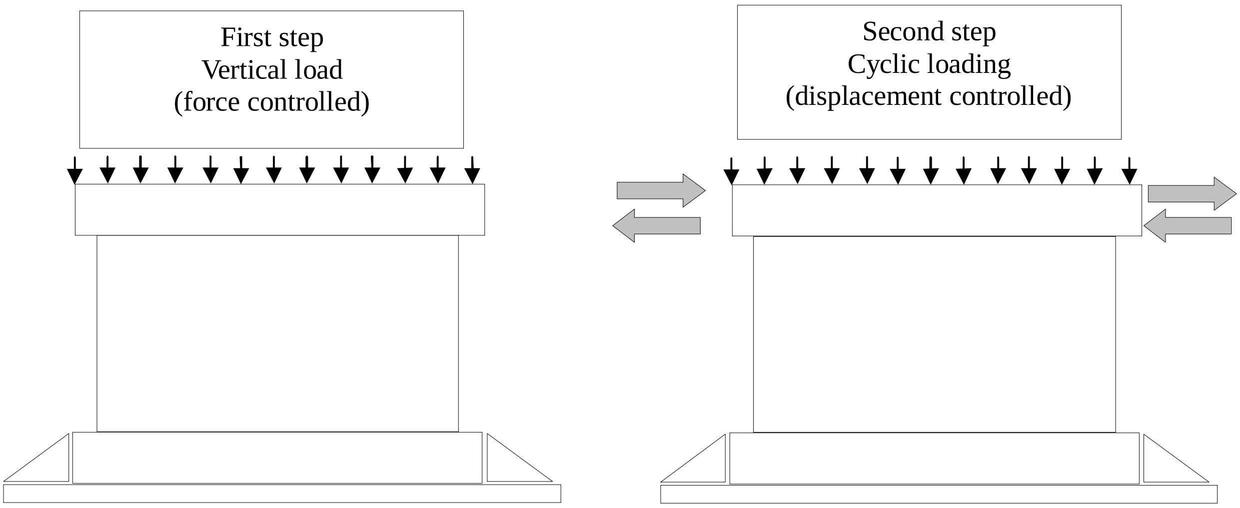


Figure 5. Loading scheme

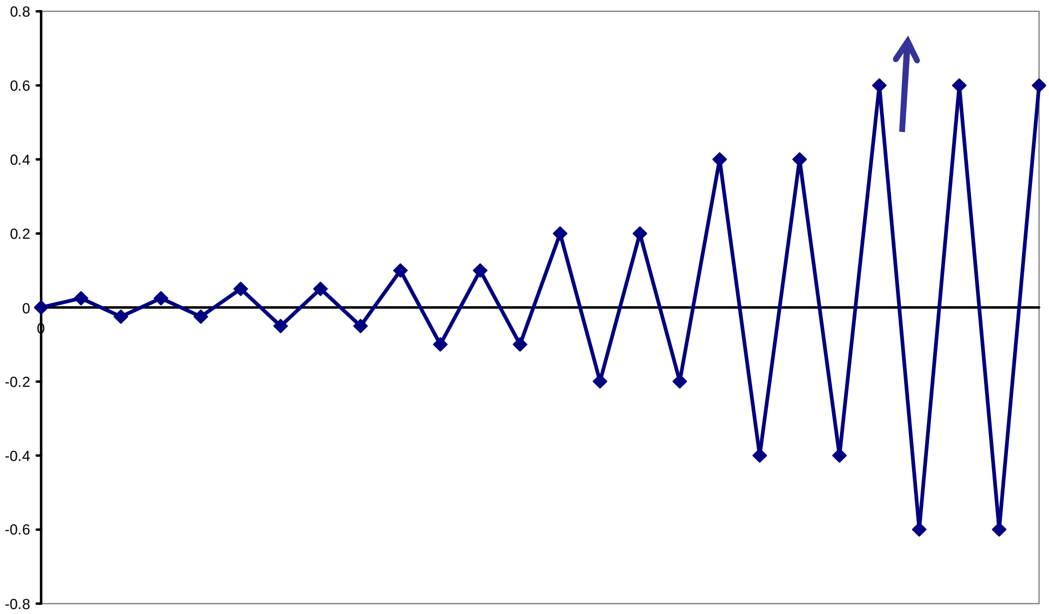
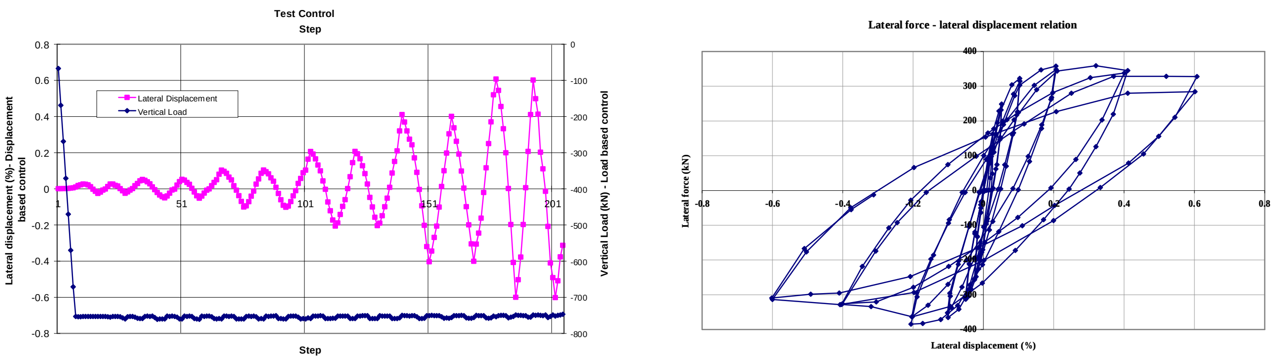


Figure 6. Loading protocol (step vs. relative drift)

The loads were measured using three load cells (two for the horizontal load "LC2 and LC3" and one for the vertical load "LC1"). The displacements were measured with digital transducers. All the data were transferred to the computer through the data logger (TDS300).

2. TESTS' RESULTS

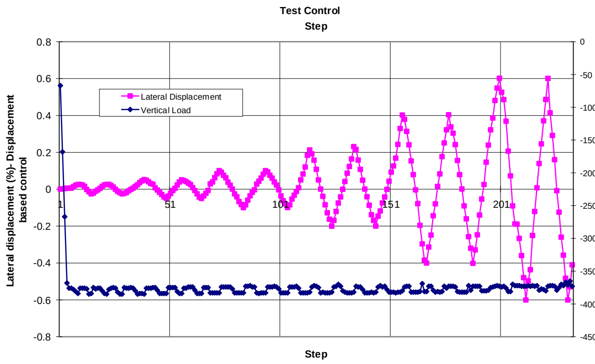
The main result of each test is the recorded lateral force – lateral displacement (drift) curve. It may be used to quantify the strength, the stiffness and the "ductility" of the specimen and the reduction of strength and stiffness due to cyclic loading. Some of the test results are presented in the following, Figures 7…10. The data used in the charts are calculated directly from the test data. The damage state of the specimens at the onset of collapse is presented in Figure 11. The onset of collapse corresponds to the sudden drop of capacity in sustaining vertical loads.



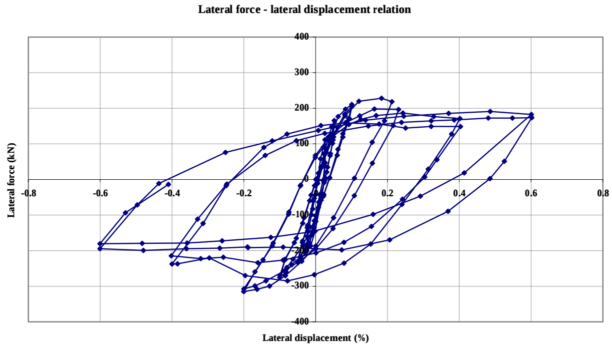
Variation of the lateral drift (%) (red line) and applied vertical load (kN) (blue line)

Lateral force (kN)-lateral drift (%) curve

Figure 7. Test results for WBRI1

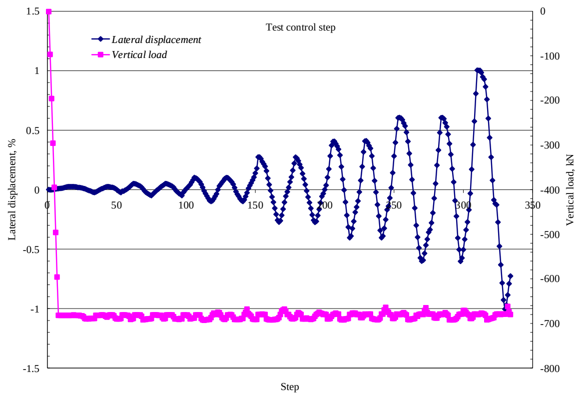


Variation of the lateral drift (%) (red line) and applied vertical load (kN) (blue line)

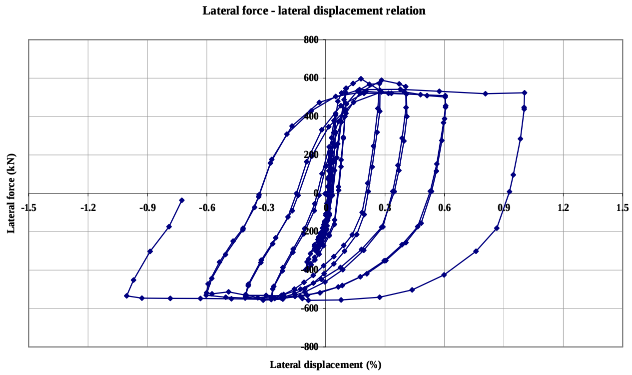


Lateral force (kN)-lateral drift (%) curve

Figure 8. Test results for WBRI2

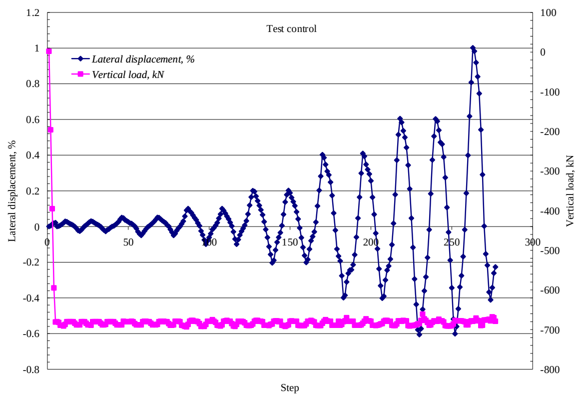


Variation of the lateral drift (%) (red line) and applied vertical load (kN) (blue line)

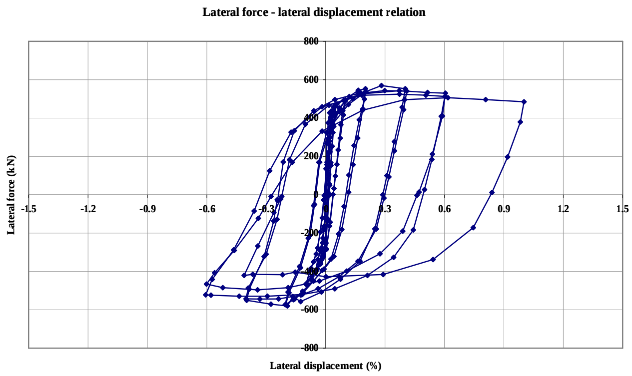


Lateral force (kN)-lateral drift (%) curve

Figure 9. Test results for WBRI3

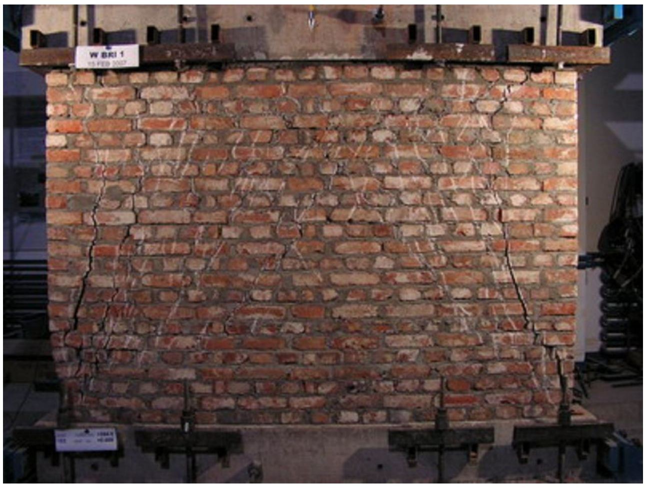


Variation of the lateral drift (%) (red line) and applied vertical load (kN) (blue line)

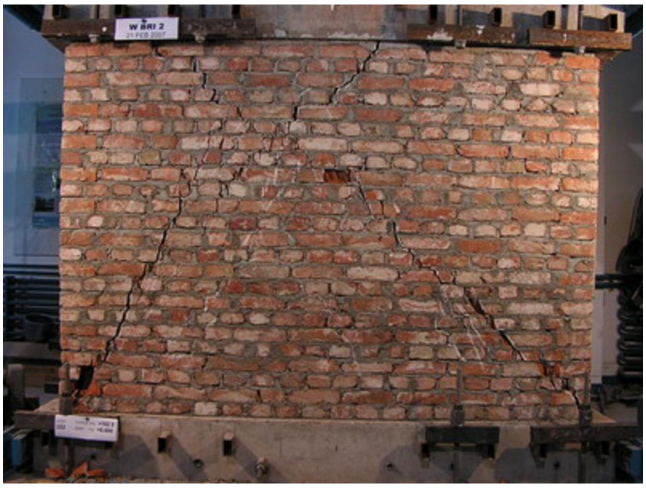


Lateral force (kN)-lateral drift (%) curve

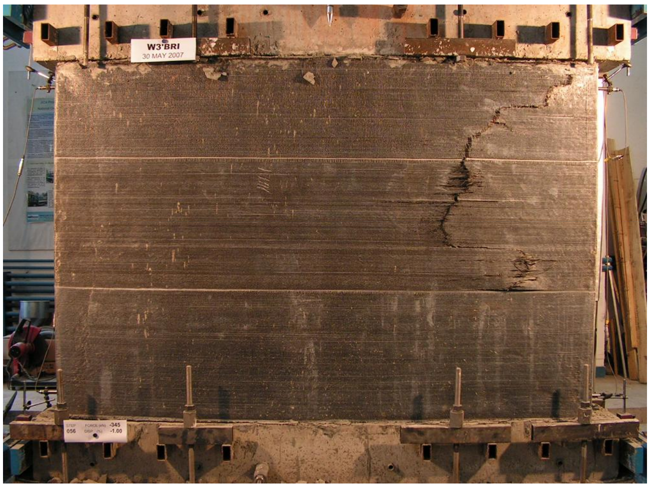
Figure 10. Test results for WBRI4



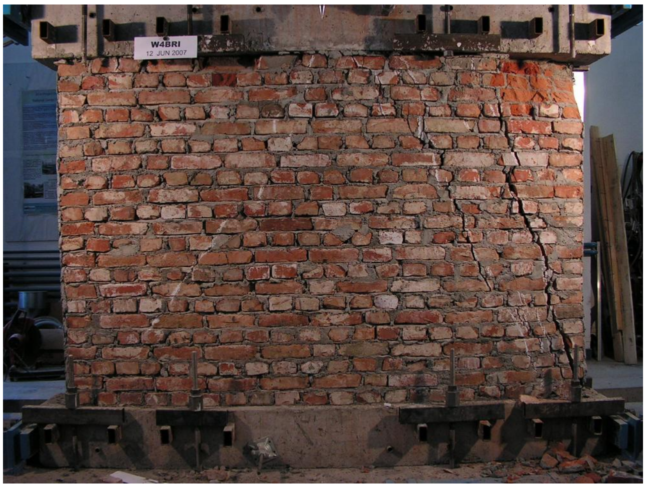
WBRI1



WBRI2



WBRI3



WBRI4 – face w/o carbon fiber

Figure 11. Damage state of the specimens at the onset of collapse

3. COMPARISON OF TESTS' RESULTS

The lateral force-lateral drift curves are compared in Figures 12…15.

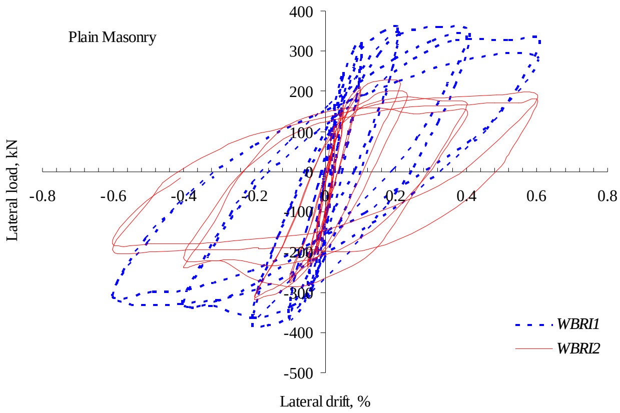


Figure 12. Lateral force – lateral drift curves
Plain Masonry

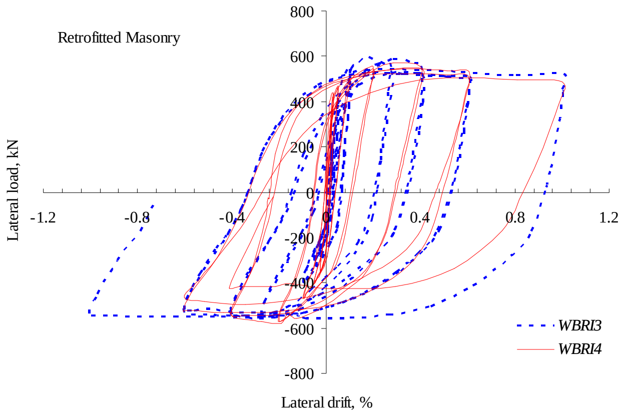


Figure 13. Lateral force – lateral drift curves
Retrofitted Masonry

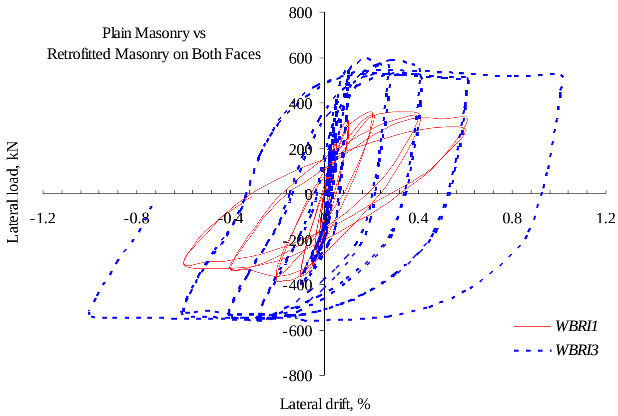


Figure 14. Lateral force – lateral drift curves
Plain Masonry vs. Retrofitted Masonry on Both Faces

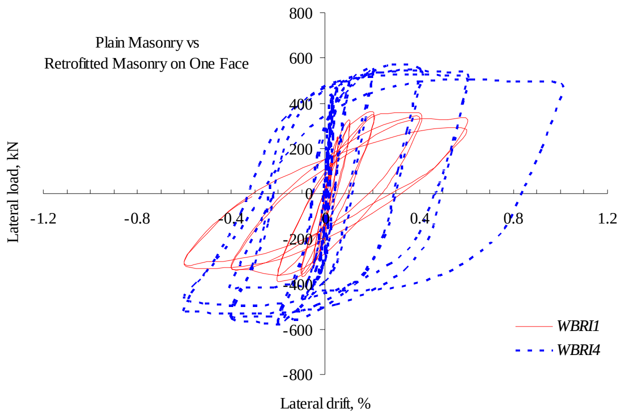


Figure 15. Lateral force – lateral drift curves
Plain Masonry vs. Retrofitted Masonry on One Face

The influence of vertical force is noticed in Figure 12 since WBRI1 has larger strength capacity than WBRI2 due to higher vertical force. The provision of the same amount of carbon fiber sheets on one face or on two faces does not significantly influence the strength and deformability capacity of the walls. Meanwhile, the stiffness and the hysteretic behavior stay close for both cases, but one can notice a higher capacity of dissipating seismic energy for specimen WBRI3 (two-side coated with carbon fiber) than for WBRI4 (one-side coated with carbon fiber). This is because the failure mechanism is controlled by in plane shear for the wall coated on both faces (WBRI3) and it is controlled, in the final stage, by out-of plane forces for the wall coated on both faces (WBRI4). For WBRI3 the carbon sheets confined and impeded the masonry to move out of plane and for WBRI4 the presence of the carbon fiber on only one face and the large cracks triggered the out of plane movement of the masonry.

The hysteretic energy dissipated within the cycle is proportional to the area of the hysteretic loops. Table 2 shows the ratio of the areas of hysteretic loops for the tested walls.

Table 2. Hysteretic loops area ratios

Wall i/ Wall j	Hysteretic loop area ratio
i=WBRI1; j=WBRI2	1.57
i=WBRI3; j=WBRI4	1.18
i=WBRI3; j=WBRI1	2.49
i=WBRI4; j=WBRI1	2.12

From Table 2 one can notice that the energy dissipation capacity of two-side coated wall is almost 20% higher than the capacity of one-side coated wall. This is because of the failure mechanisms. Meanwhile, the retrofitting of the masonry walls with carbon fiber sheets increases the energy dissipation capacity of the wall more than two times, thus enabling a much better expected seismic performance of the retrofitted walls.

The value of maximum positive (F_{max+}) and negative (F_{max-}) forces along with the corresponding lateral drift are reported in Table 3. In the same table the cracking forces (both positive and negative – F_{c+} si F_{c-}) are reported; the cracking force is considered to correspond to a lateral drift of 0.05%. One can notice from Table 3 that the carbon fiber reinforcement of the wall increases the strength capacity of the wall no matter if the carbon sheets are distributed on one face or on both faces. Meanwhile, the deformability of the wall at the onset of collapse is increased.

Table 3. Lateral maximum and cracking forces and corresponding drifts

Wall	F_{max+} kN	Lat. drift + %	F_{max-} kN	Lat. drift - %	F_{c+} kN	F_{c-} kN
WBRI1	359	0.32	384.5	0.206	248.5	313
WBRI2	228	0.183	315	0.2	165.5	234
WBRI3	596.5	0.178	556.5	0.315	416	300
WBRI4	569.5	0.282	579.5	0.193	468.5	401.5

4. CONCLUSIONS

The results of the test series show that the retrofitting solution of masonry walls with carbon fiber sheets is effective irrespective if the same amount of overall coating is placed on one face or evenly distributed on two faces. Still, the retrofitting solution with carbon fiber sheets is more expensive than the classical solutions (coating with reinforced concrete or mortar) and should be applied when a shorter construction time is envisaged or when a less severe and painful structural intervention is to be considered.

5. ACKNOWLEDGEMENTS

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