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Retrofitting of squat masonry walls by FRP grids bonded by cement-based mortar

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Abstract. For seismic retrofitting of masonry walls, the use of fibre reinforced cement-based mortar for bonding the fibre grids can eliminate some of the shortcomings related to the use of resin as bonding material. The results of an experimental testing program on masonry walls retrofitted with fibre reinforced mortar and fibre grids are presented in this paper. Seven squat masonry walls were tested under unidirectional lateral displacement reversals and constant axial load. Steel anchors were used to increase the effectiveness of the bond between the fibre grids and the masonry walls. Application of fibre grids on both lateral faces of the walls effectively improved the hysteretic behaviour and specimens could be loaded until slip occurred in the horizontal joint between the masonry and the bottom concrete stub. Application of the fibre grids on a single face did not effectively improve the hysteretic behaviour. Retrofitting with fibre reinforced mortar only prevented the early damage but did not effectively increase deformation capacity. When the boundaries of the cross sections were not properly confined, midplane splitting of the masonry walls occurred. Steel anchors embedded in the walls in the corners area effectively prevented this type of failure.

Keywords: squat masonry walls; fibre reinforced mortar; fibre grids; experimental testing; seismic retrofitting; hysteretic behaviour; strength; energy dissipation capacity

1. Introduction

Extensive seismic damage of masonry buildings was recorded worldwide in recent years. In Europe, many authors reported about such damage. D'Ayala and Paganoni (2011) and Lagomarsini (2012) reported about the damage observed in L'Aquilla hystoric city center after the 2009 earthquake. Sorentino *et al*. (2014) and Penna *et al*. (2014) described the damage sustained by masonry buildings after the 2012 Emilia earthquake in Italy. Bruneau (2002) reported about the observed damage in weak concrete frames structures with masonry partitions or in unreinforced masonry structures after the 1999 Izmit (Turkey) earthquake. Similar damage were observed by Popa *et al*. (2013) after the 2011 earthquake in Van, Turkey. Failure of masonry walls caused the

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collapse of many un-engineered buildings in Bucharest (Romania) during the 1977 earthquake (Fatal *et al*. 1977).

Despite this high vulnerability of masonry buildings, retrofitting process develops very slowly in Europe (Spencer 2007). Erdik and Durakal (2008) explained the shortcomings that need to be addressed to significantly reduce the seismic risk in Istanbul area. Retrofitting of existing buildings is regarded as the most effective way to mitigate the risk but several shortcomings were identified: cost-effectiveness of the retrofitting works for each building if global social and economic implications are considered, temporary evacuation of the buildings during the construction works, tremendous effort to be spent as a large number of buildings need seismic assessment and retrofitting. Same situation is in Bucharest, where only an insignificant number of private buildings (less than 40) were retrofitted in the past decade, despite the subsidies offered by the central government. The reasons are similar with those observed by Erdik and Durakal: cost of the retrofitting works is around 60%-80% of the replacement cost and temporary relocation of the residents, usually for more than 1 year, is necessary.

Development of cost-effective retrofitting solutions for masonry buildings is necessary to speed up the retrofitting process. A large effort was spent worldwide to develop such techniques. Common solutions include jacketing with steel reinforced mortar, shotcrete or application of external steel reinforcement. The advantages and setbacks of these procedures were summarized, for example, by ElGawady *et al*. (2004). In Romania, retrofitting of multi-storey masonry buildings is done in most cases by erecting a new lateral resisting system consisting of concrete shear walls. Using such a retrofitting technique strongly disrupt the normal building operation. Temporary relocation of the residents is required. Moreover, in case of historical or architectural heritage buildings, additional constraints prevent the use of highly intrusive retrofitting methods with limited reversibility.

The use of composite materials for seismic upgrade of existing masonry structures is effective for increasing strength and deformability of masonry walls. Commonly, glass or carbon fibre reinforced polymers (FRP) are epoxy bonded to the lateral surface of the walls. The fibre reinforced polymers can be used as strips, usually aligned with the wall diagonals, or sheets covering the entire surface of the wall. Many authors reported about the seismic response of epoxy bonded FRP. Triantafillou (1998) reported about the increase of shear strength of masonry walls strengthened using bonded FRP laminates. Tomazevic *et al*. (2009) observed the high efficiency of seismic upgrade of masonry structures by confining with carbon fibre reinforced polymers strips. Saatcioglu (2005) observed that surface mounted carbon FRP sheets, having the fibres parallel to the wall diagonals, significantly improves the strength and stiffness of unreinforced masonry infills. Seki *et al*. (2008) observed that single or double layer carbon FRP sheets surface mounted on one or both sides of an unreinforced masonry wall greatly improves the hysteretic behaviour.

Papanicolaou *et al*. (2007) and Aldea *et al*. (2007) summarized the setbacks related to the use of fibre reinforced polymers applied using epoxy resin on one or both faces of the walls: low fire resistance, lack of vapour permeability, sensitivity to UV radiation, low compatibility of the resin with the support, irreversibility of the retrofitting works. The application of glass or carbon fibre grids embedded in a cement based mortar matrix represents an alternative solution. Some advantages of this solution are: fair fire resistance, good compatibility with the support, good permeability to moisture vapours and easy installation by medium skilled workers. Efficiency of the retrofitting works can be further improved if fibre reinforced mortar is used.

Papanicolaou *et al*. (2007) tested a number of middle scale masonry wallets made out of perforated bricks retrofitted by FRP bonded using cement-based mortar or epoxy resin. They observed that textile reinforced mortar jacketing is more effective than epoxy-bonded FRP jacketing in terms of lateral displacement capacity of masonry wallets. Walls' toe crushing was observed in some specimens but no special measures to prevent this failure mode were considered in the testing program. Similar positive conclusions regarding the strength and deformability of out-of-plane loaded masonry wallets were reached as well (Papanicolaou 2008). The textile reinforced mortar retrofitted walls outperformed the FRP counterparts when the failure was controlled by the damage in the masonry. In a subsequent study, Papanicolaou *et al*. (2011) studied the effectiveness of common "low-tech" grids, such as basalt-fibres grids, polyester-fibres grids or polypropylene grids, in retrofitting masonry walls for out-of-plane loading. Stone masonry walls retrofitted by basalt-fibres grids bonded by fibre reinforced mortar were tested for in-plan loading, as well. Positive outcomes regarding the use of textile reinforced mortar were reported.

Augenti *et al*. (2011) investigated in-plane lateral loading response of a perforated tuff masonry wall having the spandrel beam retrofitted on both sides using bidirectional alkali-resistant glass coated grids bonded by two-component fibre reinforced mortar. They observed that the applied retrofitting system increased the energy dissipation capacity of the spandrel beam and restored the load-bearing capacity of the wall. De-bonding of the fibre reinforced mortar jacket was not observed.

In this paper, the results of an experimental testing program on masonry walls retrofitted by fibre reinforced mortar and fibre grids are reported. The effectiveness of steel anchors in preventing splitting of the wall's toe was investigated.

2. Experimental program

The objective of the experimental testing program was to investigate the effectiveness of masonry retrofitting using different jacketing solutions based on fibre grids bonded with fibre reinforced mortar. The experimental testing plan included seven masonry specimens denoted W1-W7.

Specimens W1-W6 had rectangular cross-sections of 2.10 m×0.25 m and heights of 1.75 m. W7 was a masonry wall having a boundary masonry column at one end of the cross section. The boundary column was 0.25 m×0.25 m and the web of the cross section was 1.85 m×0.125 m. One face of the boundary column was aligned with the back face of the wall resulting an asymmetric cross section. Old solid bricks, recovered from a demolished building, having average compression strength of 12.65 MPa, and lime-cement mortar, with average compressive strength of 1.45 MPa, were used. Two reinforced concrete bottom and top stubs, having cross-sections of 0.30 m×0.30 m, were used for each specimen to ensure the load transfer between the reaction frame and the masonry wall. The stubs were connected to the reaction frame. Only translations of the top stub in the longitudinal and vertical directions, in the plane of the wall, were allowed. No rotation of the top stub was allowed. No ties were used to connect the stubs to the masonry walls.

Carbon Fibre Reinforced Polymers (CFRP) and Glass Fibre Reinforced Polymers (GFRP) grids were used for retrofitting. The GFRP grids were polymer impregnated. Each polymeric grid was embedded in a 15-25 mm thick Fibre Reinforced Mortar (FRM) layer. Jacketing was applied on a single face or both faces of the masonry walls. Two reference specimens were tested: W1 - an un-retrofitted masonry wall and W6 - a retrofitted masonry wall just by FRM jacketing on both sides.

The fibre reinforced mortar jacket was not connected to the bottom or top stubs of the specimens.

Table 1 Fibre grids characteristics

Fibre type:	Alkali-resistant coated fiberglass
Weight (g/m2):	125
Grid spacing (mm):	12.7×12.7
Modulus of elasticity (GPa)	72
Load resistant area per unit of width (mm^2/m)	23.5
Maximum load per unit length (kN/m):	25
Maximum stress (N/mm^2)	1276
Ultimate tensile strain (%):	3

Table 2 Carbon grids characteristics

Carbon fibre grids	
Fibre type	High-strength carbon fibre
Weight (g/m2):	170
Grid spacing (mm):	10×10
Modulus of elasticity (GPa)	252
Load resistant area per unit of width (mm^2/m)	48
Maximum load per unit length (kN/m):	225
Maximum stress (N/mm^2)	4688
Ultimate tensile strain (%):	2

The FRM used for jacketing the masonry walls had the following mechanical characteristics at 28 days: compression strength of 25 MPa, determined according to EN 12190 (1988), bending strength of 8 MPa, determined according to EN 196/1 (2005), and elasticity modulus of 11 GPa, determined according to EN 13412 (2006). It is a two-component, fibre reinforced, high-strength cement-based mortar. This mortar is impermeable to water but permeable to water vapours which make it suitable for the retrofitting of masonry buildings.

The characteristics of the fibre grids are given in Tables 1 and 2.

For some specimens, the mortar jackets were supplementary connected to the masonry wall using steel cords made from unidirectional high-strength steel fibres with tensile strength of 2086 MPa and elasticity modulus of 210 GPa. The equivalent dry section of each anchor was 40.6 mm^2.

A simplified representation of the specimens is given in Fig. 1. Specimen W1 was a reference unreinforced masonry specimen. This specimen was initially damaged by cyclic lateral loading under constant axial load. Subsequently, it was retrofitted by jacketing with one layer of glass fibre grid on each face. Before retrofitting, the wall was repaired by injection of the cracks with epoxy resin. FRM, which naturally bonds to the masonry, was used to connect the fibre grids to the wall. The jackets were supplementary connected by 7 steel anchors crossing the wall from on face to the other. This retrofitted specimen was denoted W2. Specimen W3 was an undamaged masonry wall retrofitted using the same technique as specimen W2. Specimen W4 was an undamaged masonry wall retrofitted by jacketing on one face with two layers of carbon fibre grids embedded in FRM. The jacket was supplementary connected by 7 steel anchors embedded in the wall.

Same retrofitting solution was used for specimen W5, but a different distribution of the steel

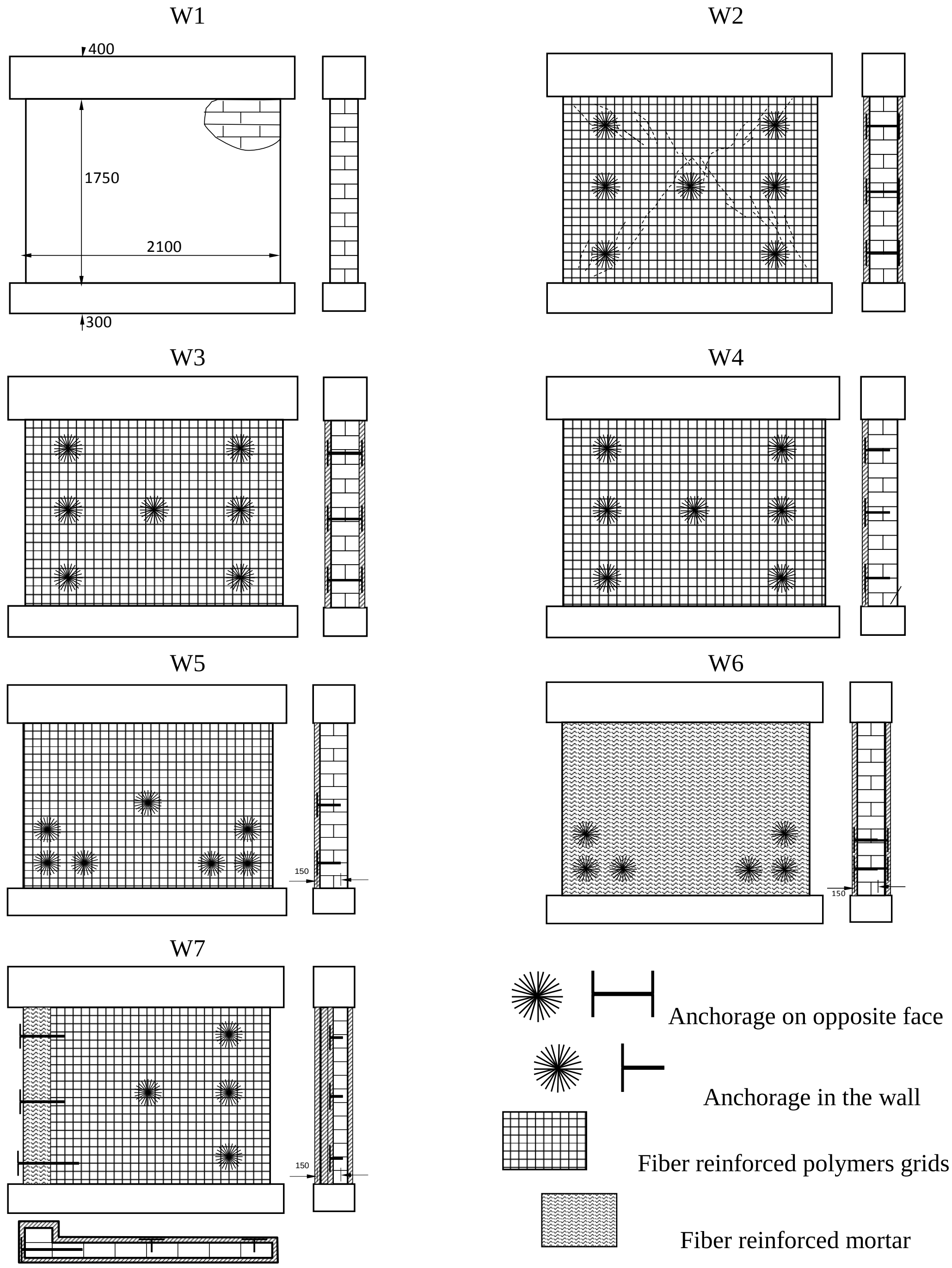

Fig. 1 Simplified representation of the specimens (all dimensions are in mm)

anchors was considered to prevent the midplane splitting of the wall at the bottom corners.

Specimen W6 was an undamaged masonry wall retrofitted just by jacketing with two layers of

FRM applied on each face of the wall. No fibre grids were used. Connection of the FRM jacket with the masonry wall was done similar to W5 specimen.

Specimen W7 was retrofitted by 2 layers of carbon fibre grids bonded by FRM on one face and 1 layer of FRM on the other face and the perimeter of the boundary column. Steel anchors were installed to prevent the midplane splitting of the wall at the cross section end with no boundary column. 3 steel anchors were used to improve the connection between the boundary column and the web of the cross section. Characteristics of all specimens are summarized in Table 3.

Each specimen was subjected to displacement based controlled unidirectional lateral load reversals. The testing protocol included one loading cycle at ±0.025% lateral drift and two loading cycles at ±0.05%, ±0.1%, ±0.2%, ±0.4%, ±0.6%, ±1.0% and ±1.5% lateral drift. Further on, a monotonically increased lateral displacement was considered up to the failure in sustaining the vertical load. This testing protocol is consistent with the recommendations of ACI374.2-R13 (ACI 2013) and FEMA461 (FEMA 2007). The lateral load protocol is represented in Fig. 2.

For each specimen, a mean vertical stress of 1.2 MPa was applied at the beginning of the test and maintained constant up to the end of the test. The corresponding axial force was 750 kN for all specimens except for W7 where the axial force was 420 kN due to the smaller cross-section.

Specimens were tested using the steel reaction frame of the Seismic Risk Assessment Research Centre (CERS) at the Technical University of Civil Engineering in Bucharest, Romania. The layout of the test setup in represented in Fig. 3. Using this reaction frame, the lateral load can be applied by two identical hydraulic jacks with 200 mm maximum stroke and ±1 MN loading capacity. The vertical load can be applied using a computer controlled hydraulic jack with 100 mm

Table 3 Characteristics of the specimens

	W1	W2	W3	W4	W5	W6	W7
Repaired:	NO	YES	NO	NO	NO	NO	NO
Retrofitted:	NO	YES	YES	YES	YES	YES	YES
FRM	NO	YES	YES	YES	YES	YES	YES
CFRP :		NO	NO	2 layers	2 layer	NO	2 layer
GFRP		2 layers	2 layers	NO	NO	NO	NO
Applied on:		Both faces	Both faces	One face	One face	Both faces	One face

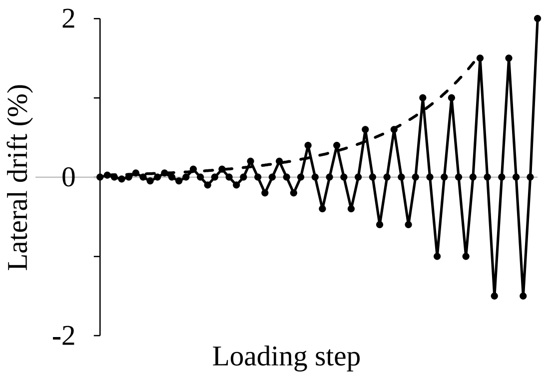

Fig. 2 Loading protocol

maximum stroke and 2 MN compression capacity. Three load cells, one for each hydraulic jack, were used to measure the horizontal and vertical loads. Ten linear displacement transducers were installed to measure the horizontal and vertical displacements between masonry wall and the concrete bottom stub. A schematic representation of the measurement system is given in Fig. 4.

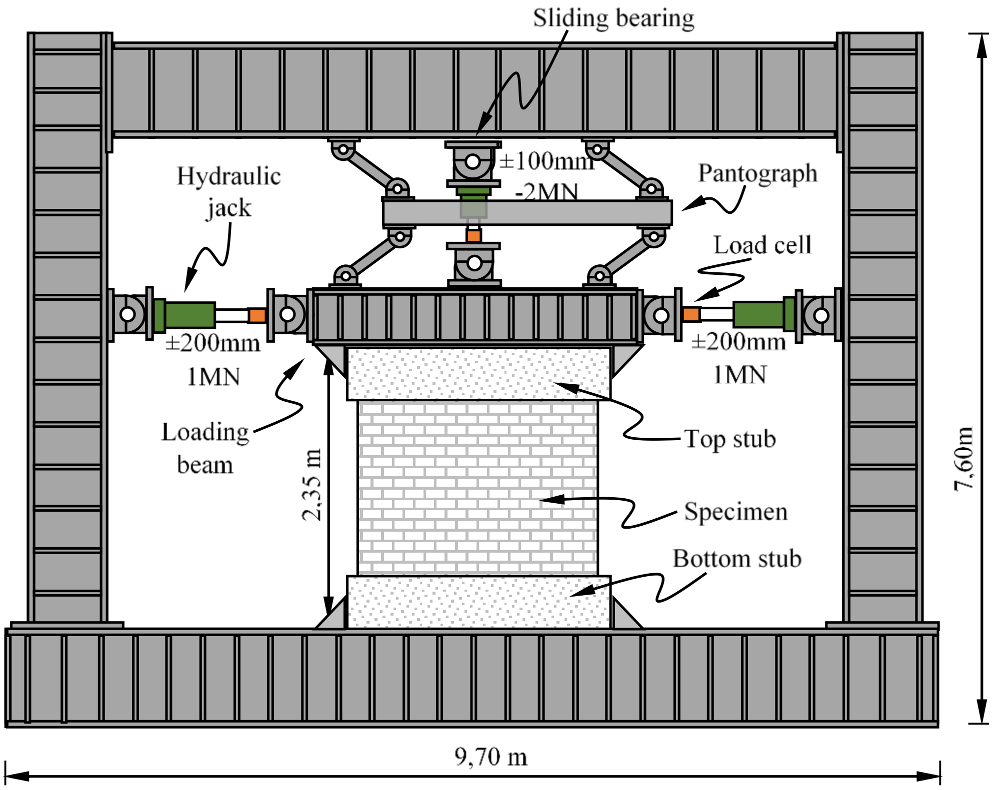

Fig. 3 Loading of the specimen

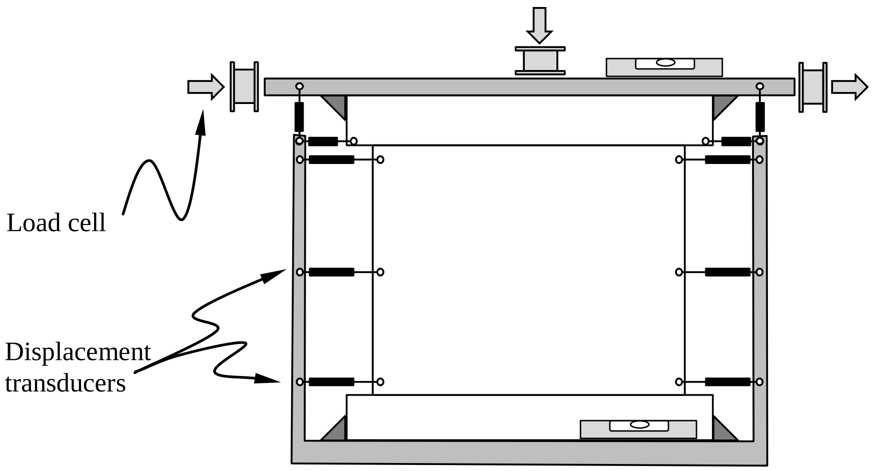

Fig. 4 Measuring: location of load cells and displacement transducers

3. Results

Damage state of each specimen at the end of the test is represented in Fig. 5. Maximum loads and displacements recorded during the tests are given in Table 4.

Specimen W1 responded essentially elastic up to 0.2% drift (Fig. 6). The diagonal cracking process initiated during the first deformation cycle at 0.4% lateral drift. In the subsequent cycle, cracks developed along both diagonals of the masonry wall. After two loading cycles at ±0.4% lateral drift cracks having the maximum width of around 2 mm, aligned with both diagonal directions, were observed (Fig. 5). Lateral loading was stopped considering that the damage state of the specimen should be limited to allow a proper repairing and retrofitting. A minor average vertical settlement of around 2 mm was observed at the end of the loading test (Fig. 7). Tests previously conducted on similar unreinforced masonry walls at the structural testing laboratory of CERS (Seki *et al*. 2010) showed that failure in sustaining the axial load occurs at approximately 0.6% lateral drift (Fig. 8). As observed in the previous experimental testing program, this type of masonry wall is unsuitable for seismic loading because of the limited displacement and energy dissipation capacity. Moreover, the severe damage state at the end of lateral loading makes unlikely any cost-effective retrofitting attempt. In case of specimen W1, after loading up to 0.4% specimen was repairable and suitable for retrofitting.

After the loading test, W1 was repaired and retrofitted and, subsequently, reloaded. The retrofitted specimen was denoted W2. First diagonal crack was noticed at the surface of the mortar jacket during the second loading cycle at -0.4% drift. This crack had different orientation in comparison with W1, starting from the midpoint of the upper side of the wall to the bottom-right corner. In the following loading cycle, a “symmetrical” crack starting from the left-bottom corner was noticed. Subsequently, in the following cycles at 0.6% and 1.0% drift inclined cracks along the main diagonals appeared. At 0.6% drift the maximum width of the inclined cracks was 0.25 mm. At 1.36% drift, slip was noticed in the horizontal joint between the masonry wall and the concrete bottom stub and the loading test was stopped.

Diagonal failure of specimen W3 was not observed during the loading test. At 1.0% drift slip occurred at the joint between the masonry wall and the bottom concrete stub. The corresponding lateral force was approximately 500 kN indicating an equivalent friction coefficient of 0.7. No cracks at the surface of the mortar jacket were noticed.

Specimen W2 and W3 showed a hysteretic response characterized by good deformation and energy dissipation capacities. Average vertical settlements at the end of the loading tests were around 2-3 mm. After the occurrence of slipping, the recorded lateral load was constant and the observed damage state was stable. The deformation and energy dissipation capacities of these specimens were similar despite the fact that specimen W2 was previously damaged (Fig. 9). This is due to the repairing of specimen W2 by injection of the cracks prior to retrofitting.

In case of W2 and W3, local crushing of the masonry at the bottom corners was noticed.

Table 4 Peak forces and displacements

	W1	W2	W3	W4	W7	W5	W6
Peak lateral displacement	-0.41%	1.36%	-1.03%	0.8%	0.61%	1.02%	0.62%
Peak positive lateral force (kN)	452	534	539	494	258	409	467
Peak negative lateral force (kN)	-415	-555	-470	-478	-206	-419	-491

Crushing was followed by local midplane splitting of the masonry, as can be seen in Fig. 10, a. Splitting occurred at 0.8% drift for W2 and 0.6% drift for W3. The rather unusual midplane splitting of the masonry could be caused by the technique used to anchorage the fibre grids. In both specimens the fibre grids were stopped right at the corner of the walls being bonded using

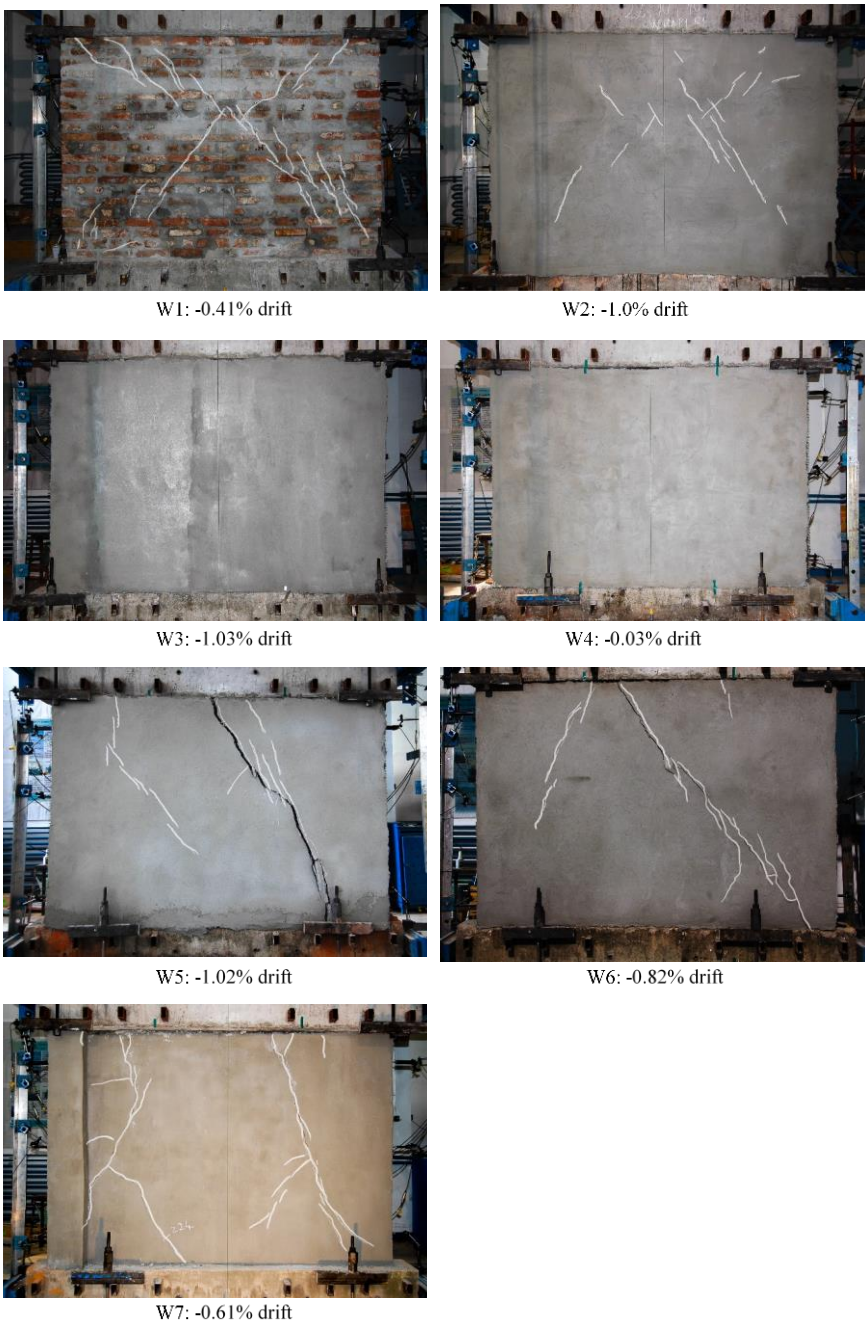

Fig. 5 Damage state of the specimens at the end of the lateral loading

fibre reinforced mortar and steel anchors penetrating the wall. No proper confinement of the boundary of the cross-section by turning the fibre grids around the corners was provided. Fibre grids jacketing prevented the diagonal failure of the wall and increased the diagonal compression force which lead to the failure of the wall at the corners, under compression stresses. Midplane splitting cracks were parallel to the compression stresses in the diagonal strut.

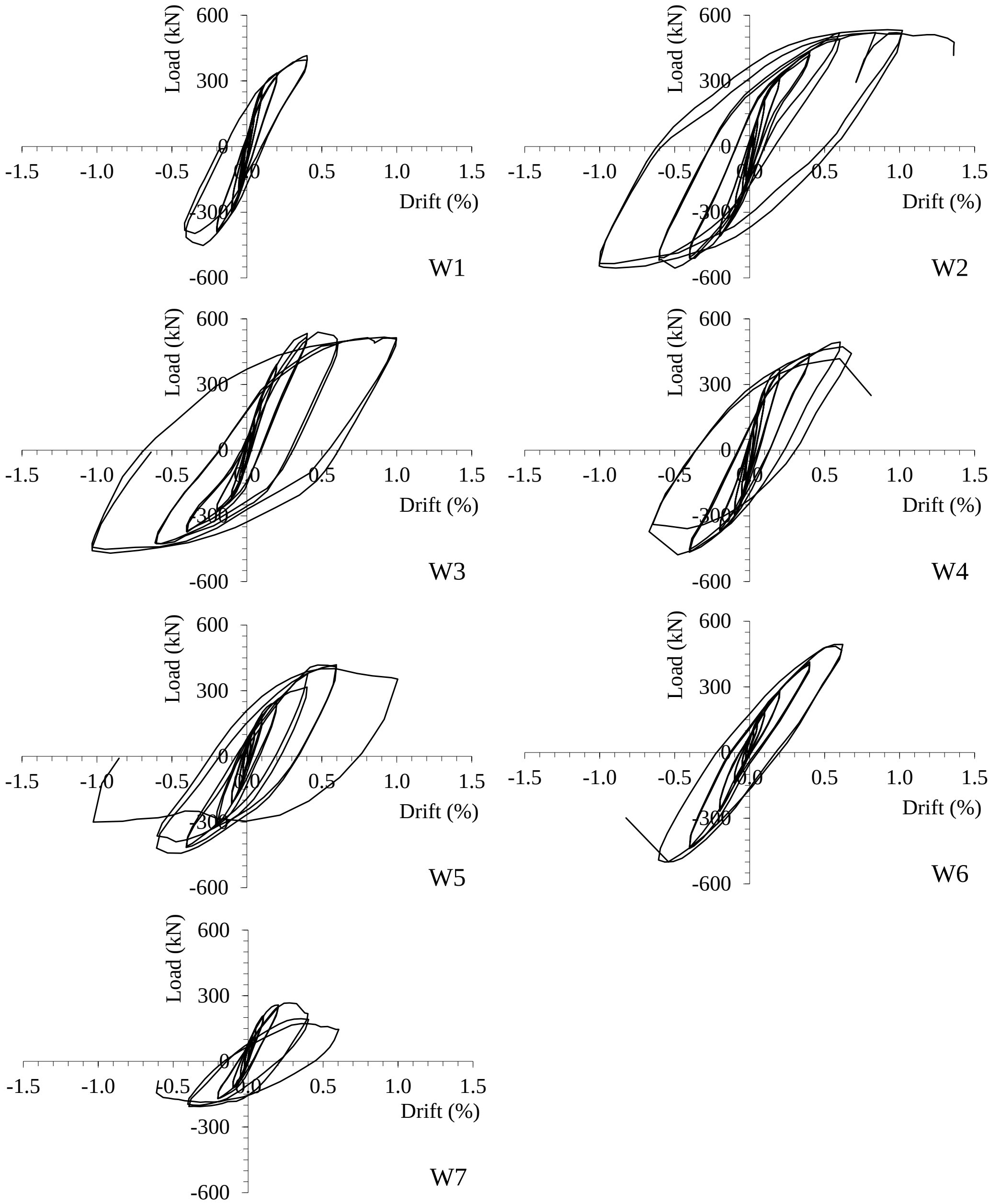

Fig. 6 Recorded lateral load - lateral drift hysteretic response

Anchoring the FRP grids on the opposite face by turning around the corners of the wall is hardly possible in practical retrofitting works because the masonry wall is usually confined by other structural boundary elements such as columns or walls. Using steel anchors penetrating the wall rather than turning the fibre grids around the corners of the wall is likely to reduce the retrofitting effectives but can facilitate the works.

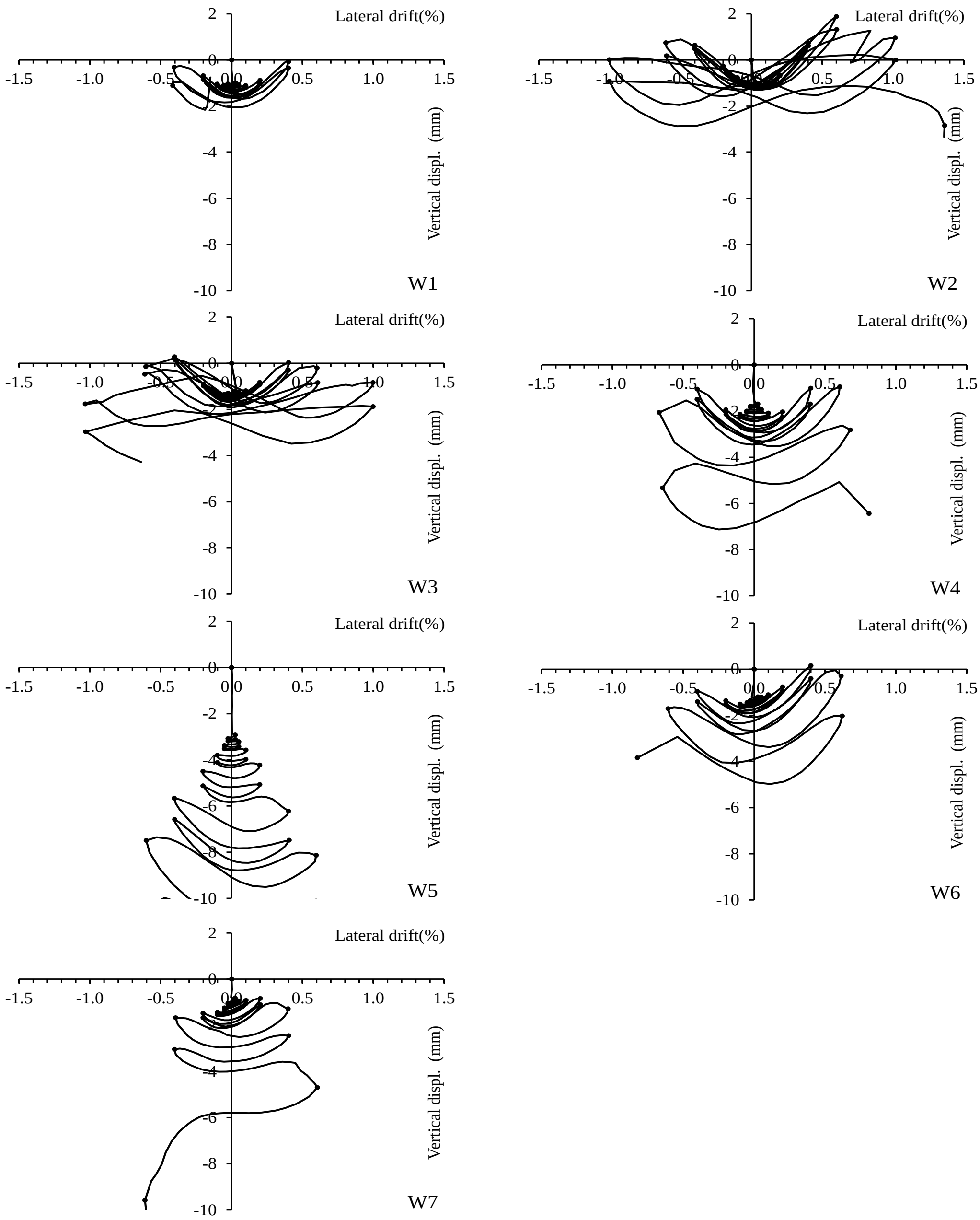

Fig. 7 Recorded lateral drift - vertical displacement hysteretic response

Loading of specimen W4 was stopped at 0.8% drift, during the first loading cycle to +1%. At +0.6% drift a sudden decrease of the lateral strength followed by a severe increase of the vertical deformation was recorded. No cracks could be seen at the surface of the FRM jacket. On the opposite side, at the second loading cycle at +0.4% drift, inclined cracks starting from the midpoint of the upper side to the bottom corners were noticed. After two loading cycles at 0.2% drift, splitting cracks appeared at the bottom corners. At -0.4% drift the maximum width of the diagonal crack was 0.45mm. It increased up to 1.0mm at 0.6% drift. Average vertical settlements steadily increased up to 7mm during the loading cycles. The recorded hysteretic response can be considered unsatisfactory due to the limited displacement capacity. Retrofitting of this specimen was not effective.

The first major fracture of specimen W5 occurred during the first loading cycle to -1.0%, at 0.6% drift. 30% lateral load decay was recorded. After this event, loading to 1.0% drift was continued. The failure to support gravity load was observed after the first loading cycle to 1.0% drift and the loading was stopped. A splitting crack at the upper-left corner occurred during the second loading cycle to 0.2% drift. The first diagonal crack occurred at -0.4% drift. In the same displacement cycle, a splitting crack in the bottom-right corner occurred. 10mm severe vertical settlement was recorded. Roughly the same values of the cumulated energy were calculated for specimens W4 and W5 (Fig. 9).

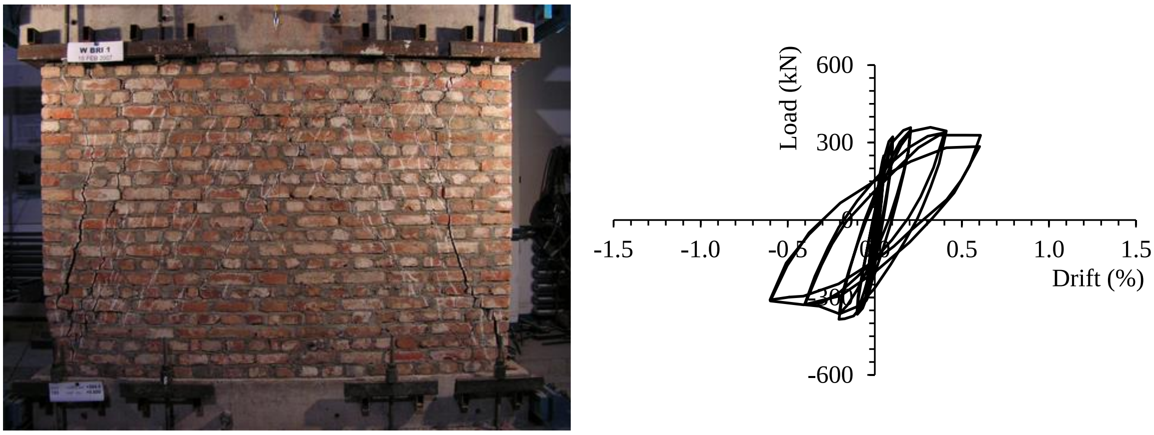

Fig. 8 Hysteretic response of an unreinforced masonry specimen previously tested at CERS

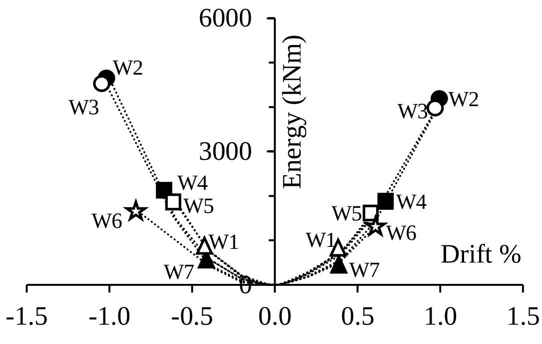

Fig. 9 Cumulated energy at maximum lateral displacement for all specimens

(a) midplane splitting at the bottom corner, specimen W2

(b) splitting in half of the boundary column, specimen W7

Fig. 10 Splitting of the masonry

W6 responded essentially elastic up to 0.4-0.6% drift. At the first loading cycle at -0.6% drift, first cracks were noticed in the diagonal direction. At the second cycle at -0.6% drift, failure of the wall by a diagonal crack starting from the midpoint of the upper side to the bottom-left corner was observed. No significant improvement of the energy dissipation capacity was observed despite the lateral strength increase by approximately 20%. The application of the FRM layers prevented the early damage of the masonry wall. The failure to sustain vertical load occurred at the same lateral displacement as in the case of the reference un-retrofitted specimen.

In case of W7, a vertical crack separating the web of the wall from the boundary column was noticed at 0.3, 0.4% drift (Fig. 10(b)). Subsequently, a 30% sudden decrease of the lateral load was recorded. Further loading up to 0.6% drift, amplified the wall damage and the loss of vertical load carrying capacity occurred. No damage of the FRP wrapped end of the wall was observed.

4. Conclusions

Retrofitting of masonry walls by epoxy bonded FRP sheets presents several shortcomings mainly related to the low fire resistance, low permeability to water vapours, high cost of resin and need of particularly skilled workers. Use of fibre grids bonded using fibre reinforced mortar can eliminate some of these shortcomings.

In this research program, several masonry specimens retrofitted with fibre grids and FRM were tested. Various retrofitting details were used.

Retrofitting by application of glass fibre grids bonded with fibre reinforced mortar effectively improved the hysteretic response of masonry walls. Best results were obtained when the fibre grids were applied on both lateral faces of the wall. In comparison with the un-retrofitted specimen, a roughly 25% increase of the lateral force was recorded in this case. Prior to the occurrence of slipping in the retrofitted specimen, a 66% increase of the peak displacement was recorded.

Repairing the damaged masonry wall prior to retrofitting, by epoxy injection of the cracks, proved to be effective in restoring the structural integrity of the wall. A hysteretic response similar to the undamaged retrofitted wall was recorded.

In retrofitting of masonry with FRP, special care has to be paid to the anchorage of the fibre grids at the end of the wall. Anchorage of the fibre grids on the opposite face of the wall by turning the fibres around the corners is desirable. If this is not possible, due to the wall intersections with boundary structural elements, steel anchors penetrating the wall proved to be a suitable alternative. Loss of bond between the jacket and the masonry was not observed.

Midplane splitting of the wall at corners occurred in some specimens because the fibres were applied only on the lateral faces of the masonry. The diagonal cracking was prevented by the application of the fibre grids, the compression stresses increased and midplane splitting cracks occurred. This caused the reduction of the lateral strength and stiffness of the wall. To prevent or limit such damage, transverse ties were effectively provided around the corners. In retrofitting by FRP jacketing, special care has to be paid to the confinement of the boundaries of the cross-sections especially at the corners of the walls. This can be done either by turning the fibres around the corners or installing steel or fibre ties penetrating the wall in the corners area.

Jacketing a single face of a masonry wall with carbon fibre grids bonded by fibre reinforced mortar and steel anchors penetrating the wall did not effectively improve the lateral strength or deformation capacity.

Retrofitting by application of a fibre reinforced mortar layer on each face of the wall, without fibre grids, did not improve the deformation capacity. Only the early damage of the masonry wall, at small lateral drifts, was prevented.

Acknowledgments

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