In-Plane Behavior of Confined Masonry Walls with Holes Retrofitted with GFRP and Subjected to Lateral Cyclic Loading

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SUMMARY:
Confined masonry walls are the most usual structural system in developing countries like Mexico for residential houses. Holes like windows are the more significance variable on the overall behavior of walls under lateral loads such as those due to seismic and differential settlements. It has been observed that due to ignorance of builders or deficiencies on the construction practice code requirements about the correct reinforcement around the windows are not satisfied. Experimental results of five confined masonry walls with holes are herein presented. Three were constructed with clay brick and two with concrete bock. The walls showed the same cracking strength, and the wall strengthened with GFRP reached the same strength and stiffness as well as the one constructed according to the specifications of the actual Construction Code. It can be concluded that the use of GRFP strips is a feasible alternative to restore lateral strength and stiffness capacity of walls.

Keywords: In-plane, cyclic, masonry, GFRP, confined

1. INTRODUCTION

Masonry is the most common construction system for housing in developing countries like México. The typical structural elements are load-bearing walls that may be confined or unconfined. However, due to actions such as seismic loadings and differential settlements many failures have been reported since masonry is weak in tension. It has been observed that due to ignorance of builders or deficiencies on the construction practice code requirements about the correct reinforcement around the windows are not satisfied. Such deficiencies induce poor behavior on these types of structural elements since they have strong influence in the overall behavior of load-bearing walls. Such openings are made for architectural reasons or for better function of masonry buildings. Due to these reasons, the main objective of this study is to find out an alternative to restore the strength en stiffness of deficient walls thought of the use of glass fiber composites materials such as GFRP.

Many alternatives are for restore de strength, deformability and ductility capacity for weak masonry structural elements such as those with openings. Among of such retrofitting methods are walls reinforced with steel mesh, walls with embedded beams and columns or walls strengthened with steel plates attached to the wall surface with bolts. These methods have the disadvantage of adding significant weight and time consuming. In the last two decades have been successfully used Fiber Reinforced Plastics for retrofitting and repairing masonry as well as reinforced concrete buildings. Several research reports have been written where composite materials were used in order to understand the behavior of masonry walls subjected to in-plane as well as out-of-plane loading (Saadatmanesh and Ehsani,1990, Schwegler and Kelterborn, 1996, Triantafillou, 1998, Velazquez-Dimas et al. 2000, Alcaíno and Santa-María 2008). All these studies had proved that composite material are a real alternative for load carrying capacity and deformability of masonry structures due to their main advantages such as the high strength-to-weight ratio, stiffness-to-weight ratio, corrosion resistance and easy to use.

In México, few studies have been conducted on this important field (Velázquez-Dimas, et al, 2007 and 2009) despite the advantage of composite materials and many failures on masonry buildings have been reported due to seismic loading or differential settlements. In this study, composite strips of GFRP are used to investigate their feasibility to improve or restore lateral capacity of masonry walls with holes. GFRP was selected because of is cheap (Weng, et al 2004) compared to other fiber such as Carbon and Kevlar and since is the same used for manufacturing in the local fishing industry.

2. MATERIALS

Masonry walls were constructed using hand-made solid clay brick and hollow concrete block. Materials properties of the units were determined according Mexican Standards and to the Complementary Technical Specifications for Masonry of the Mexico City Construction Code (NTCRDF). The brick units have nominal dimensions of 250x50x130 mm and the concrete block ones with 400x200x120 mm (thickness×height×width). In the Table 2.1 are listed the main mechanical properties of the units as well as masonry assemblages.

Table 2.1. Mechanical properties for materials used in masonry walls

Property	**Brick Walls** (MPa)	**Block Walls** (MPa)
Unit Compressive Strength (f_p)	7.80	7.68
Design Compressive Strength of Units (f^*_p)		5.12
Pile Compressive Strength (f_m)	3.70	5.65
Masonry Compressive Strength (f^*_m)	2.6	4.10
Average shear strength of wallets (v_m)	0.35	0.34
Design Shear strength (v^*_m)	0.27	0.22
Concrete compressive strength ($f'c$)	20.1	19.9
Mortar ($f'j$) compressive strength	6.4	3.8
Reinforcement yield strength, bar #3 (9.5mm)(nominal)	412	444
Mild wire yield strength	227.6	251
Static concrete elasticity modulus	21.41	21.41

Both set of walls were constructed with mortar Type III, since this is the most common in the local practice. Also the reinforcement for the confining elements was tested and this consisted of rebar # 9 and the stirrups #6 mild steel. The concrete used for confining elements en the transfer slab is a typical one for low rise buildings or houses. The properties of them are listed in Table 2.1.

For retrofitting and repairing purposes, strips of 140 mm width and a 1mm thick of composite material were used. The GFRP consisted of a 0°/90° glass fiber mesh and an epoxy resin. The fabric had a density of 8.76 N/m^2. These materials are popular in local fishing industry for constructing boats. The composite was tested in tension in order to obtain the tensile strength of 157 MPa and its elastic modulus of 16.7 GPa.

3. TEST SPECIMENS

3.1 Brick Masonry Walls

Two confined brick masonry walls were constructed with overall dimensions of 3.3 m long, 2.3 m height and 0.13 m thick. A whole representing a typical window was made in the middle of the wall. The window had dimensions of 1.0mx1.2m width and height, respectively. Ratio of the wall net area to the whole wall area was 0.85. The overall wall dimensions are the most common for load-bearing wall buildings. A foundation reinforced concrete beam was constructed at the wall base in order to attach it to the reaction slab. Also a transfer reinforced concrete slab was built at the top of the wall to allow the lateral load system. The Fig. 3.1 shows the wall general configuration.

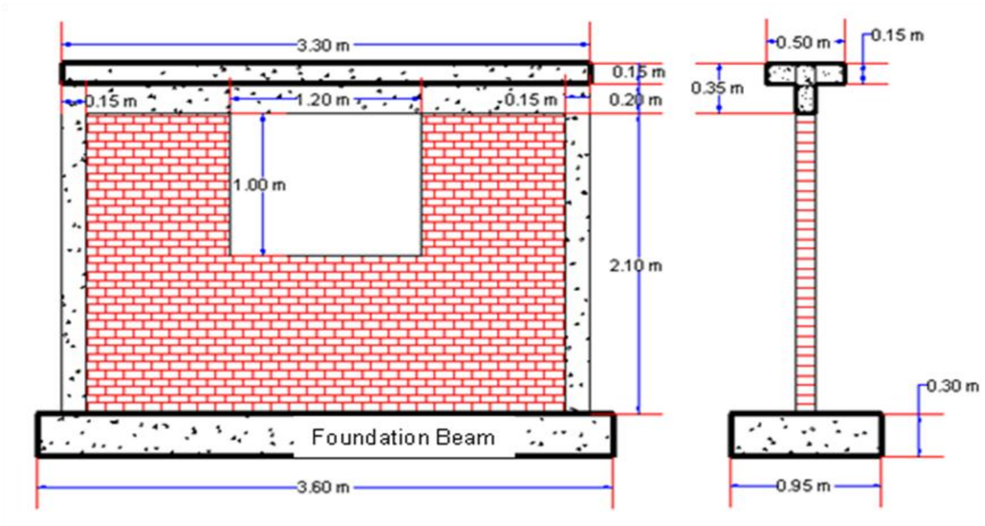

Figure 3.1. Brick wall specimen with overall dimensions

3.2 Block Masonry Walls

Two confined block masonry walls were constructed with overall dimensions of 3.3 m long, 2.2 m height and 0.12 m thick. A whole representing a typical window was made in the middle of the wall. The window had dimensions of 1.0mx0.80m width and height, respectively. Ratio of the wall net area to the whole wall area was 0.91. The overall wall dimensions are the most common for block load-bearing wall buildings. A foundation reinforced concrete beam was constructed at the wall base in order to attach it to the reaction slab. Also a transfer reinforced concrete slab was built at the top of the wall to allow the lateral load system. The Fig. 3.2 shows the wall general configuration. It is important to note that both set of specimens were made by a Mason in order to have field conditions as close as possible.

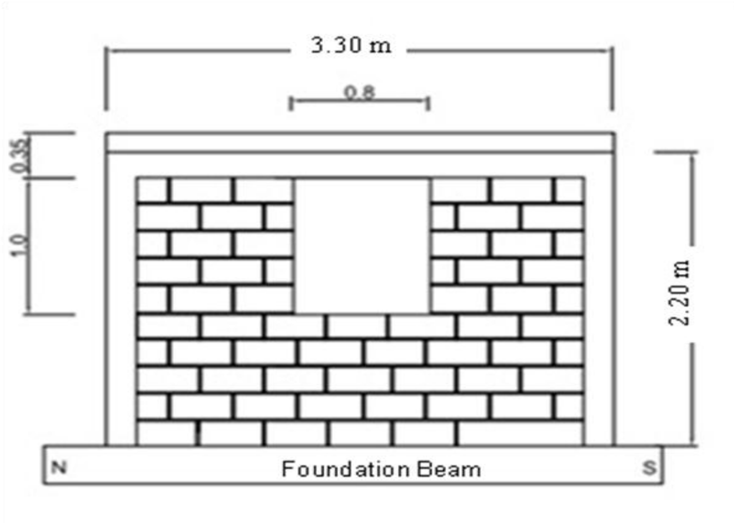

Figure 3.2. Block wall specimen with overall dimensions

4. TEST SET UP

In Fig. 4.1 are shown all parts of the reaction frame for the tested walls. Each specimen was laid on a foundation beam and this attached to the reaction slab. All walls were subjected to lateral load applied by a hydraulic actuator that was fixed to the reaction wall. Also each specimen was subjected to a constant axial load by means a vertical actuator. Both vertical and lateral load were applied to the wall throughout a steel transfer beam attached by bolts to the walls. Load Controlled and displacement controlled

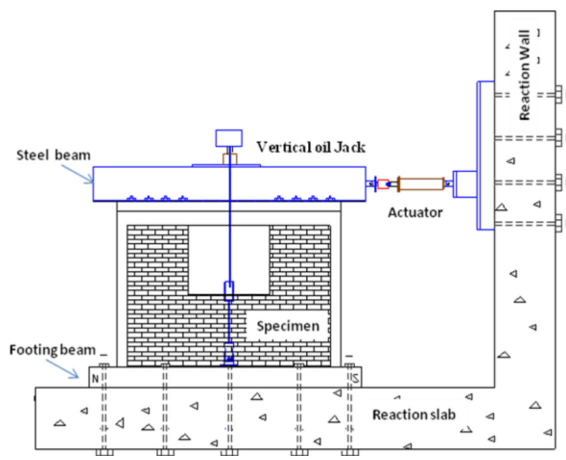

Figure 4.1. Test set up

The lateral load was applied to all specimens according to a load-history specified on the México City Code NTCRDF-2004. This consist of two stages the first one before a major crack named load-controlled and the second after that crack called displacement-controlled. As shown in Fig. 4.2 each level is given by a couple of cycles.

All experimental data were monitored by several devises such as two load-cells one for lateral load and the other for vertical load. Horizontal displacements were measured with LVDT and Dial Gages, as well as diagonal ones. Also many strain-gages were used for recording strains on steel reinforcement and composite strips.

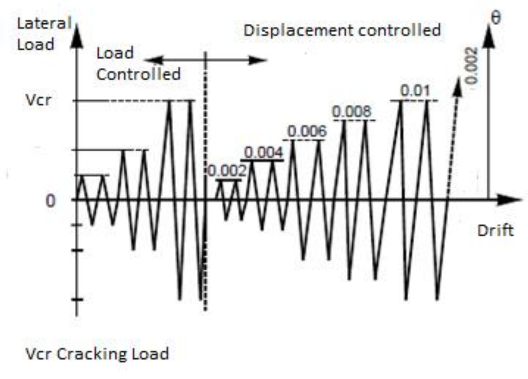

Figure 4.2. Load history

5. EXPERIMENTAL RESULTS

5.1 Brick Masonry Walls

The two brick masonry walls were constructed but three tests were done and described next. The first experiment was done in a confined wall without external reinforcement and this specimen was called brick masonry wall without reinforcement (BMWWR). The second one was called brick masonry wall retrofitted with vertical GFRP (BMWRV). And the last one was the original wall tested as a control specimen and repaired with diagonal composite strips (BMWRD). Therefore, a set of three tests was run for this part.

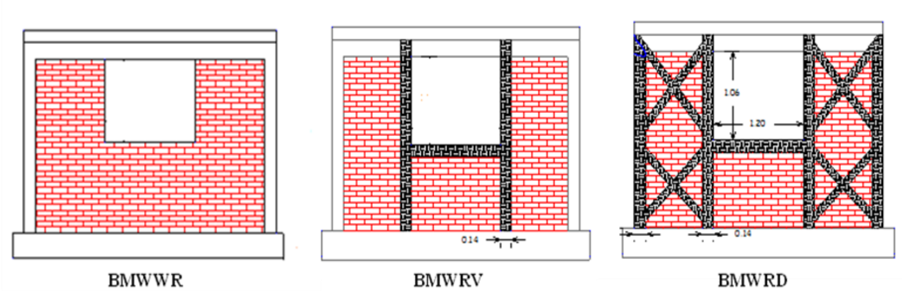

Figure 5.1. Brick wall configuration

5.1.1 Test Results

According to the tests done it can be pointed out that:

The wall BMWWR was loaded under a constant axial stress of 0.24 MPa. This load level is the equivalent to service load for a typical two stories load-bearing masonry building. The in-plane cyclic loading was applied according to the load history depicted in Fig. 4.2. From the observed behavior it can be said that the firs diagonal crack appeared at 5^{th} cycle for load level of 58.9 kN and a drift of 0.0006. At this point a crack sound was listened. In addition, flexural cracks appeared at lateral load of 56.6 KN and for a drift of 0.001. The last indicated that first flexural crack took place followed by diagonal ones. More cycles of lateral load were applied until 9^{th} cycle when the maximum load of 82.2 KN was reached for a drift of 0.0044. Also for this level the main diagonal crack width was about 5mm at North side. After this cyclic significant stiffness degradation took place. The test continued until the major crack width reached 11 mm on the south side and the crack penetrated to the confining reinforced elements. Then the test was terminated at 11th cycle when the lateral load reached 72 KN and for a drift of 0.006. At this level significant damage had occurred and it was decided to finish the test in such way that allowed repairing the wall. Fig. 5.2 shows the crack pattern and some observed damage. Also in the Fig. 5.3, it can be observed a hysteretic curve and the stiffness degradation. From figures it can be observed that the walls experimented significant energy dissipation at the same time of serious damage since it lost more than 60% of its initial stiffness for drift of 0.001.

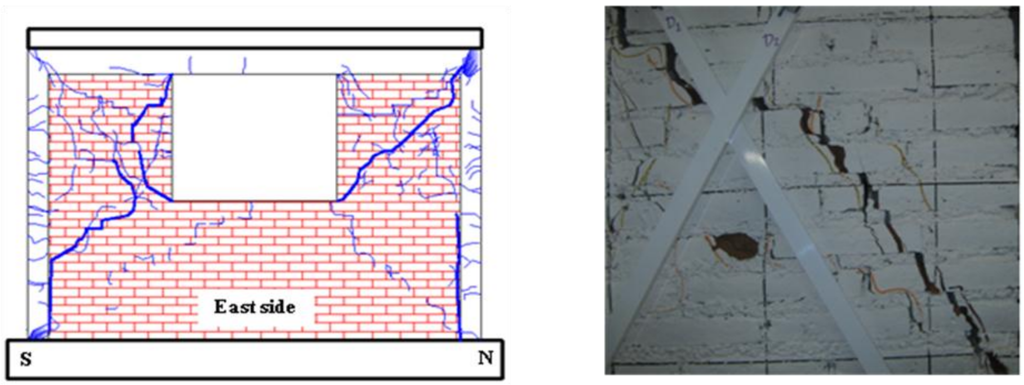

Figure 5.2. Crack pattern for the East Side and damage due to a diagonal crack

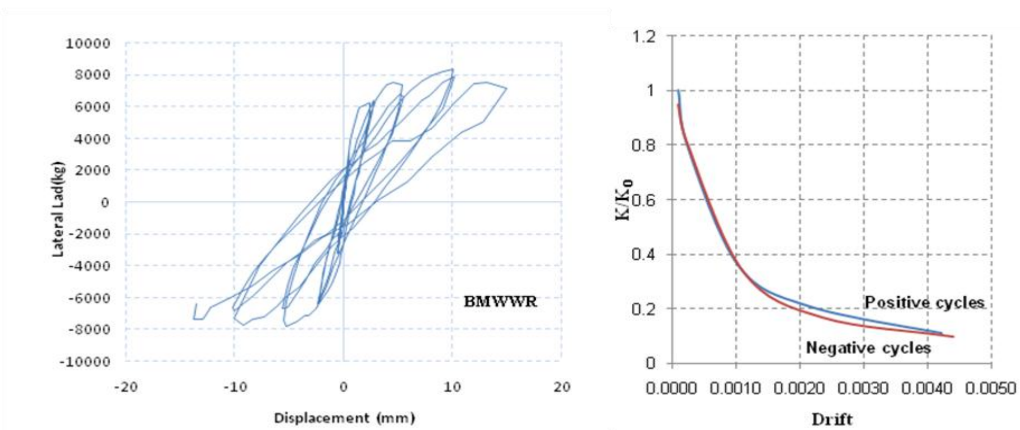

Figure 5.3. Hysteretic curve and normalized stiffness degradation curve for Wall BMWWR

In addition, the wall BMWRV was also subjected to the same constant axial stress that the BMWWR and also the same load history. The wall was retrofitted on both sides (as seen in Fig. 5.4) with vertical and horizontal GFRP strips around the window simulating the actual code (NTCRDF-2004) recommendations confined masonry walls. The composite strips were 140 mm wide and 1mm thick. This specimen was subjected to 12 cycles of in-plane loading. It was observed that the first visible inclined crack occurred at cycle 5th and for a lateral load of 62.5 KN, and a drift of 0.00046. Flexural cracks were observed during the puling stage of 6th cycle. For the 9th cycle a crack widths of 7mm (85 KN) and 11mm (110 MPa) were measured for the pulling and pushing stages, respectively. The maximum lateral supported load was 110 MPa for a drift of 0.0043. The first major delamination of the composite strip took place at 11th cycle and for a load of 99 MPa, drift of 0.006 and a crack width of 11mm. at this stage significant crush damage had occurred on bricks of the corners and diagonal crack had reached the thickness of the transfer slab. Test was conducted until the 12th cycle were full delamination occurred at the top part of the south side of the window and a crack width of 16 mm, load of 61 KN and drift of 0.0087 as can be observed in Figs. 5.4 and 5.5. No yielding stage for reinforcement was detected since the maximum steel stress was 136 MPa.

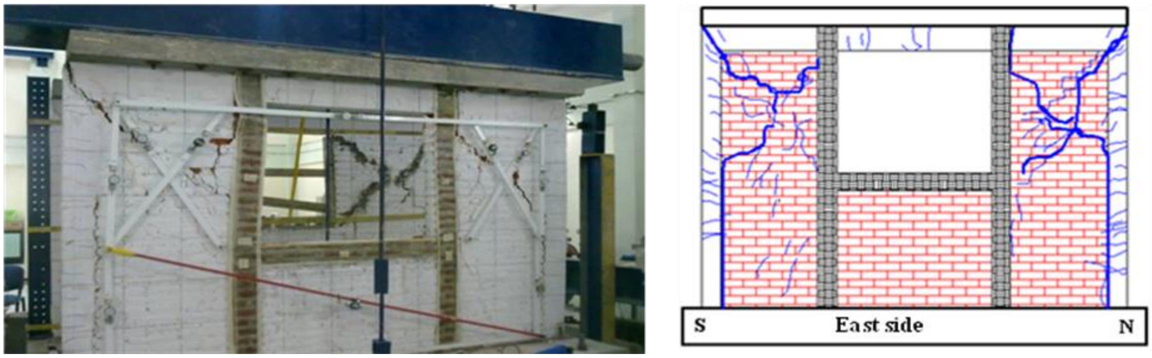

Figure 5.4. Damage due to a diagonal crack and crack pattern for the East Side

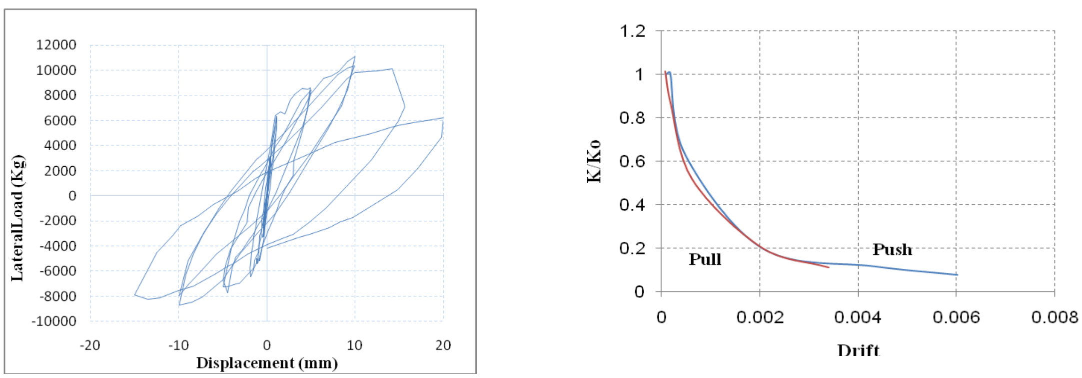

Figure 5.5. Hysteretic curve and normalized stiffness degradation curve for Wall BMWRV

The last wall of this set of tests is the one resulted from repairing the specimen BMWWR. This wall was named BMWRD, that is, diagonal composite strips were bonded to the wall surfaces as shown in Fig. 5.1 This wall was subjected to 13 cycles of in-plane loading and the main stages are described next. The first inclined crack was developed at 4th cycle where a previous one took place for the wall BMWWR, at load of 31KN and a drift of 0.00047. The test continued and at 8th cycle a crack width of 3 mm was measured for la load of 66 KN and drift of 0.0023. Also for a drift of 0.0047 and lateral load of 103KN delaminations occurred on several areas of the vertical composites strips. Highest lateral load was 120 KN and a drift of 0.0067, and crack width of 8mm also were measured at 11th cycle. The test was terminated at 13th cycle for a lateral load of 103 KN, drift of 0.009, crack width of 18mm. at this stage fully de-bonding of composite strip was observed. In the Fig. 5.6 are shown the behavior of both walls were the repaired wall exhibited better performance.

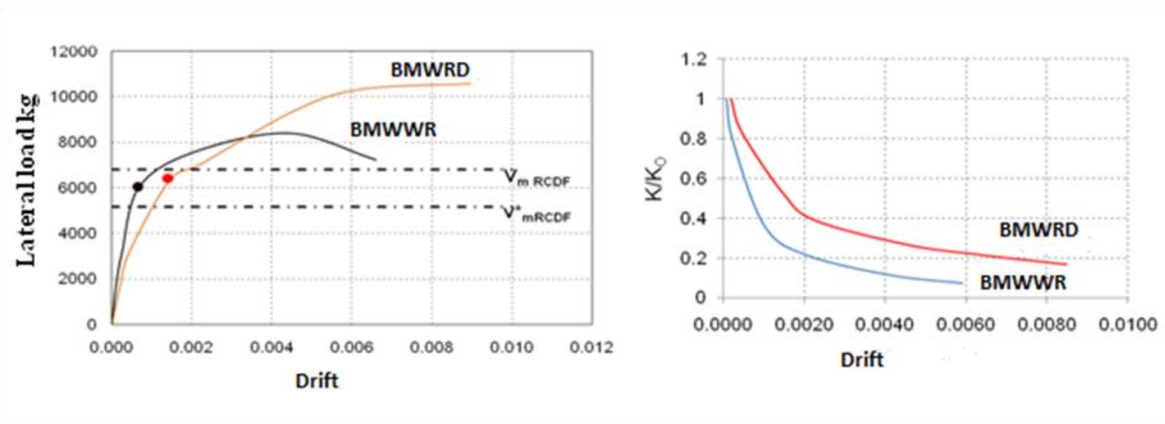

Figure 5.6. Peak values curves for pushing and
normalized stiffness degradation curve for Walls BMWWR and BMWRD.

5.2 Block Masonry Walls

Two tests were conducted on a constructed hollow block masonry wall without confining reinforcement around the window. The first wall was named as HBMW with dimensions of 3.3 m long, 2.2 m height and 0.12 m thick. The second one was called HBMWR, that is, a repaired hollow block masonry wall. Both walls were subjected to a constant axial stress of 0.19 MPa and to the same load-history shown in Fig. 4.2. In the Fig. 5.7 are shown both type of specimens.

Figure 5.7. Walls configuration

5.2.1 Test Results

The wall HBMW was subjected to 9 cycles of in-plane loading and the main findings are described next. The first inclined crack was observed at 5^{th} cycle for a lateral load of 77 KN and a drift of 0.00058. The test continued until 9^{th} cycle where a load a 73 KN was reached and a drift of 0.0039 and a main diagonal crack was developed. The test was terminated when a lateral load of 90 KN and a drift of 0.004 were measured and severe damage was observed. Also part of the wall around the window was separated from the main wall body.

Next, after that previous wall was tested it was decided to repair it with GFRP strips. This was done with the object to prove the feasibility of use composite material for restore the load-carrying capacity of weak block masonry walls subjected to in-plane cyclic loading. Is in this manner that the wall HBMWR was made. The retrofitting pattern system is depicted in the Fig. 5.8.

So, according to the experimental results it was observed that the first diagonal crack at 5th cycle for an in-plane loading of 73 MPa and a drift of 0.000438. In addition, a main inclined crack appeared for a load level of 136 MPa and a drift of 0.0046. The experiment was finished when la lateral load reached 136 MPa due to the severe damage concrete north bottom corner, and full GFRP delamination of both north vertical composite strips. In Fig. 5.8 are shown the curve for the peak values of both walls.

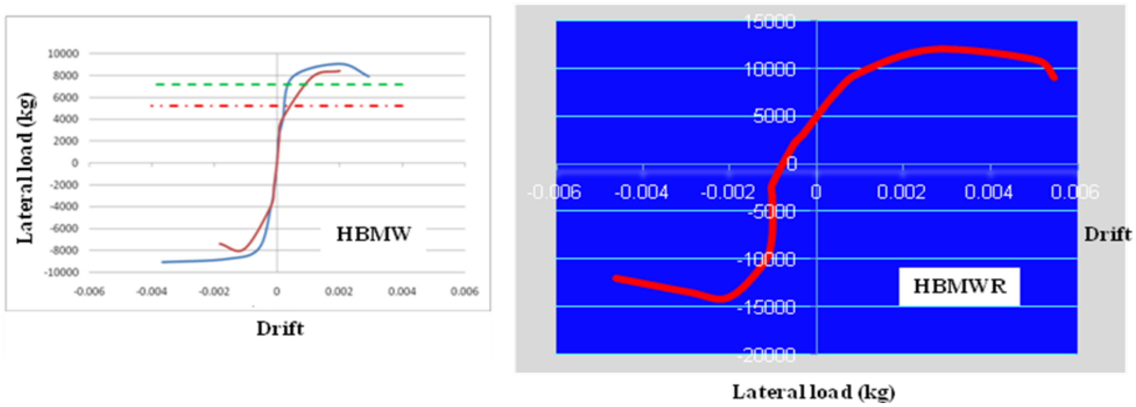

Figure 5.8. Peak values curves for pushing and pulling stage for walls.

6. CONCLUSIONS

Experimental results of five tested walls with whole and subjected to constant axial load and cyclic in-plane loading are presented. According to these, it can be concluded that:

In general it can be said that GFRP is a feasible retrofitting and repairing manner, not only to restore lateral strength and deformability capacity, but also, increasing them for masonry walls with holes constructed with poor code specifications for confined walls.

For the set of brick masonry walls it was observed that the retrofitted wall supported an ultimate lateral load almost two times the corresponding of the one without reinforcement around the window. The repaired wall also supported an ultimate load 50% larger than the original one. In addition, both walls retrofitted with GFRP strips exhibited superior deformation capacity allowing this to have more ductility capacity.

For the set of block masonry walls, the findings are similar to the set of brick masonry walls. The repaired wall supported 1.42 times in-plane-loading that corresponding to the reference one. In addition, de ultimate deformation of the repaired wall was little more than the one without reinforcement.

Research work is needed for more wall configurations with different aspect ratios and whole areas with respect to the total area of the wall.

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