Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 193 (2017) 66 – 73

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on Analytical Models and New Concepts in Concrete and Masonry Structures AMCM'2017

Seismic behavior of strengthened URM masonry – an overview of research at ZAG

Petra Triller[a], Miha Tomaževič[a], Marjana Lutman[a], Matija Gams[a,]*

[a]*ZAG - Slovenian National Building and Civil engineering Institute, Dimičeva 12, 1000 Ljubljana, Slovenia*

Abstract

Four experimental campaigns performed at ZAG over almost a decade and dealing with strengthening of masonry using FRPs are briefly presented. The campaigns show in-situ tests on strengthened walls in an actual building, the cyclic shear laboratory tests where different materials and FRP layouts were explored, use of innovative flexible materials instead of mortar or epoxy, and finally the test of a full scale building model where all aspects of strengthening a building using FRPs are investigated.

Keywords: FRP; masonry; seismic strengtening; in-stu tests; laboratory tests; full scale tests;

---

1. Introduction

Various technologies of strengthening the unreinforced masonry (URM) buildings are available. Although effective, the traditional strengthening techniques are time consuming and require that the users temporarily move out of their buildings. Therefore, strengthening methods based on using fibre reinforced polymers (FRP), which

---

* Corresponding author. Tel.: +386 1 2804 458; fax: +386 1 2804 484.
E-mail address: matija.gams@zag.si

doi:10.1016/j.proeng.2017.06.187

provide a simpler, faster and cleaner application, are replacing the traditional ones and their use is on the rise [1,2,3]. Additionally, the cost of many FRP materials has been steadily dropping and has become affordable.

An FRP coating consists of the fibres of the reinforcing FRP material which normally have high tensile strength. Different materials are used for the fibres (e.g. glass, carbon, aramid, basalt, etc.). The fibres themselves are inside a coating, which acts as the protecting cover for the FRPs and as the adhesive to the masonry. Despite its function as the adhesive, anchors for fixing the coating to the masonry are normally used. As in case of fibres, different materials are used for coating (e.g. epoxy resin, cement based mortar or even flexible polymers). The strengthening can be applied to different types of masonry (stone masonry, brick masonry, hollow clay masonry, etc.). Finally, the layout of the fibres on the surface of the wall can have many different configurations (vertical, horizontal, diagonal, it can be applied to one side or to both sides of the wall and there can be different densities anchors for anchoring the coating to the wall). The coating, the fibres and the masonry together constitute a complex composite system and the number of combinations of FRP materials, materials for coating and of layouts is virtually inexhaustible. The complexity of the composite system and high number of possibilities is perhaps one of the main reasons, why research in this field is so active and there is a lot of research in papers and conferences on this topic. Furthermore, some combinations appear to not work well together and are best avoided (e.g. coating without wrapping with glass or carbon fibres in epoxy on brick masonry [4]).

There has been a substantial amount of experimental research performed on this subject over several years at Slovenian National Building and Civil Engineering Institute (ZAG). In this paper this research will be briefly presented along with the main lessons learned. The research can be chronologically divided into four phases, and the structure of the paper follows these phases. The first tests were performed in-situ in a building that was about to be demolished [5]. It was a brick masonry building from 1935. Two walls were strengthened by wrapping them in carbon fibre fabric and using epoxy resin as the adhesive. In the second phase, presented in third section, a large series of walls were tested in laboratory using the cyclic shear tests. Different materials and especially different layouts of the FRP materials were used [4,6]. In the third phase, an innovative solution for gluing the fibres to the wall was used. A deformable material (called polymer PM) with elastic modulus of about 4 MPa was used and results were surprising [7]. Finally, a three storey model of a building was built in full scale and tested next to a reaction wall. The model was first tested in unstrengthened state up to considerable, but still repairable damage and then strengthened using glass fibre grids and cement based mortar. The model was then tested again, this time up to collapse. Similar laboratory experiments on multistorey buildings were performed by e.g. [7,8].

In the conclusions, the summary of the four experimental campaigns is presented.

2. In-situ cyclic shear tests [5]

A building in Ljubljana from 1935 (Fig. 1a) was about to be demolished and prior to the demolition the owners allowed us to perform destructive tests on the building. The walls of the building were built from so-called normal size (25 x 12 x 6.5 cm) solid bricks and lime mortar with small amount of cement. The building had reinforced-concrete slabs above the cellar, while all the stories above had timber floors. The thickness of the longitudinal walls was 51 cm in ground floor and 38 cm in floors above, whereas the transversal walls were 38 cm thick in the ground floor and 25 cm thick in floors above. The 12 cm thick partition walls were built of solid bricks. The construction is typical in Slovenia for the era between both world wars.

Compressive strength of bricks was measured on couplet specimens (11.3 MPa). Compressive strength (2.24 MPa) and elastic modulus (790 MPa) of masonry were measured on two full scale wall samples retrieved from the building.

Two walls (denoted as H1 and H2 in Fig. 1b) were selected for shear tests. First, the walls were tested in their original state using the test setup shown in Fig. 2a). The load was applied in the form of prescribed lateral displacements at mid-height of the walls. The walls were loaded and unloaded and the loading was gradually increased. The vertical load in the walls was estimated to 0.61 MPa and 0.44 MPa for walls H1 and H2, respectively. During the first phase of testing, the walls developed clear shear damage (Fig. 2b).

Then the walls were strengthened using carbon fabric and epoxy resin. Both walls were wrapped by three horizontal strips. In addition, wall H1 had diagonal strips on both sides, whereas wall H2 only had diagonal strips on one side of the wall. The layout of the fabric is shown in Fig. 2c. The strengthened walls were labelled H1w and H2w.

The strengthened walls exhibited a significant improvement in seismic resistance, although the displacement capacity was not increased (Figs. 3b and 3c). The improvement in resistance was 42 % and 60 % for walls H1 and H2, respectively. At first, the strengthened walls developed shear damage as shown in Fig 3a. The final failure mechanism of the walls, however, changed significantly due to the strengthening. The connection of the wall to the rest of the structure above and below, which was undamaged before, developed damage and was the point of final failure.

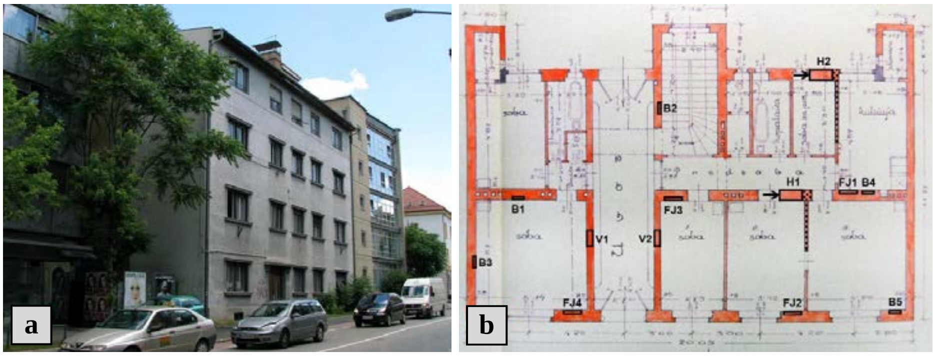

Fig. 1. View of the building (a); floor plan with test sites [2] (b).

Fig. 2. Test setup on wall H1 (a), shear damage of wall H2 (b) and strengthened wall H1 (c).

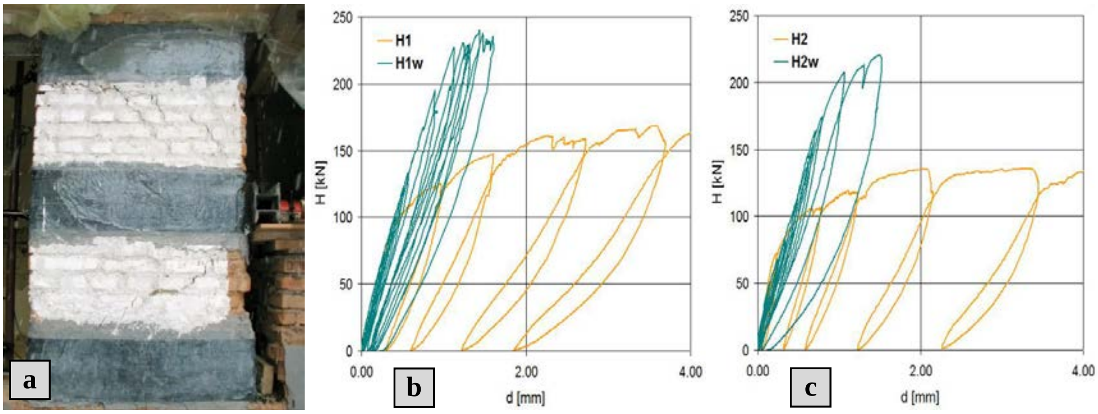

Fig. 3. Shear damage of wall H2w (a), response of wall H1 and H1w (b), and response of wall H2 and H2w (c).

The conclusion of this research campaign was that wrapping of walls is an extremely effective technique, but the connection between the wall and the rest of the structure needs to be strengthened as well. The increase of shear and bending capacity of the wall should be designed appropriately and possible brittle mechanisms should be prevented. Additionally, it was seen that wrapping requires prior removing of windows and demolishing of the facades, which raises doubts about the simplicity of such application of FRP.

3. Laboratory cyclic-shear tests [4]

A large experimental campaign, in which 28 brick walls were tested in cyclic shear, was partly inspired by the experience of the in-situ tests, but also largely motivated by the desire of the industrial partner to test techniques which would apply coating (strengthening) to only one side of the wall or at least without wrapping. All tests were performed on full scale walls with dimensions length x height x width = 100 x 150 x 25 cm. Four major groups of FRP layouts were used, but in this paper we will focus on only three (Fig. 4). The fourth used stiff carbon fiber strips which is a somewhat different concept due to lack of coating. In the tests different variations were studied, such as amount of anchors, effect of mortar thickness, strengthening previously damaged or undamaged walls, using single or both sided strengthening and using carbon or glass fabric.

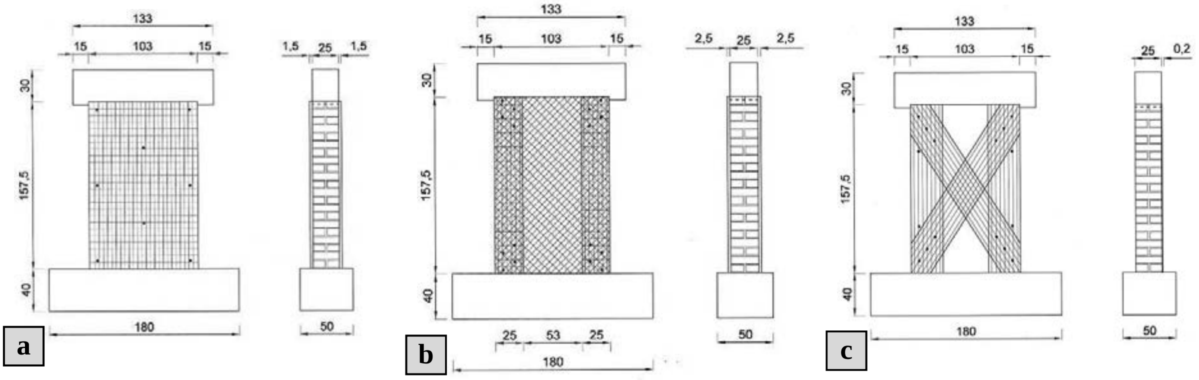

Fig. 4. Groups of FRP layouts: mesh over the entire surface (a), mesh over the entire surface with additional reinforcement at the sides (b) and lateral bracing layout with vertical strips at the sides (c). Black dots denote anchors.

The walls were built from strong normal format solid bricks with nominal compressive strength of 20 MPa (29 MPa was determined by testing). Cement-lime-sand mortar with volumetric proportion 0.25:1:8 was used, as this resembles the composition of historic mortars in Slovenia. Compressive strength of mortar was 1.14 MPa and the compressive strength of masonry according to EN 1052-1 was 4.1 MPa.

The tests were performed in the so-called cyclic shear test setup (Fig. 5), where the wall is tested under constant vertical load (stress), amounting to 30 % of compressive strength and with lateral load in the form of prescribed, cyclic and increasing horizontal displacements. The lateral load is repeated three times at each intensity level before increasing it to observe the strength degradation.

Two walls were tested in their original (un-strengthened) state for reference and they responded in shear, as can clearly be seen from Fig. 5b.

The response of the walls can be divided into two distinct phases regardless of the material for strengthening and the layout of the FRPs: in the first phase the masonry and the coating acted as a strong composite element. The first phase ends at the onset of debonding and delamination of the coating. Once this process starts, it rapidly spreads over the most stressed areas. Eventually, the separation occurs over a large enough area and the unsupported part of the coating either buckles, or even peels off with millimeters thin layer of masonry. When the bond is lost over sufficient area, most of the resistance is provided only by the original wall.

In case the coating was based on cementitious mortar and if there were no anchors, the coating could detach completely (Fig. 6a). The connection was partly lost at the bond between the coating and the masonry, and partly due to tensile failure of masonry, which essentially peeled off. In case epoxy resin was used (Fig. 6b), the connection was lost exclusively due to tensile failure of masonry, which again peeled off. In case of such debonding, the effect of strengthening on seismic resistance of the wall was negligible. In case of mortar based coatings, the problems with delamination can be alleviated by using anchors (carbon anchors were used in our study). Different densities of anchors were used, and the response of the highest density (13 anchors per 1.5 m^2) is shown in Fig. 6c. Despite relatively high density, there were still problems with delamination, but the seismic resistance was improved compared to reference walls (Fig. 7a).

One of the hypothesis at the time was, that the problems with debonding occur due to incompatibility of materials for coating and masonry. The difference in stiffness of masonry and the coating produced high demand on the bond when the wall started to shrink under vertical load and damage due to lateral loads. A couple walls were therefore tested with very thin (0.5 cm) mortar coating. The experiments showed that the coating was not thick enough for the composite system to work well together and improvement in resistance was less than in case of coating with normal thickness.

By first testing walls up to damage and then strengthening them gave us an opportunity to compare the effectiveness of strengthening damaged walls compared to undamaged walls. The results showed that walls that were first damaged and then strengthened exhibited slightly higher resistance than those that were damaged in unstrengthened state. This was due to the fact that the cracks were diligently filled with mortar and all damage repaired before the walls were strengthened. The effect on displacement capacity was inconclusive.

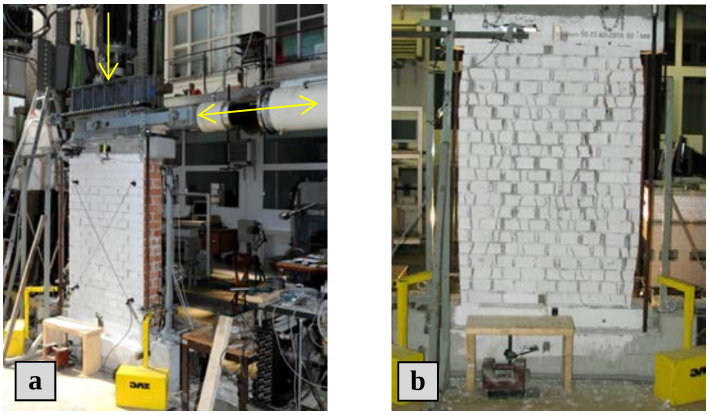

Fig. 5. Test setup for laboratory cyclic shear test (a) and shear damage of reference wall (b).

Fig. 6. Coating separated from the wall (a), delamination of epoxy based coating (b) and failure of anchors at highest density (c).

Only in one case the coating failed due to tensile fracture of the FRP material (Fig. 7b). This was the case of coating based on GFRP grid in cementitious mortar in a layout shown in Fig. 4b. In this case, the coating was very strong and thicker at the sides due to the second layer of the grid. It was also very strongly connected to the wall. In this case the resistance of the wall was increased more than two fold and there was also an increase in the displacement capacity (Fig. 7c).

The conclusions at the end of this experimental campaign were that seismic strengthening can be very effective, but only if the strengthening is very well designed. The difference in stiffness of materials was considered to be the biggest problem and it was thought that materials with more compatible characteristics would reduce difficulties.

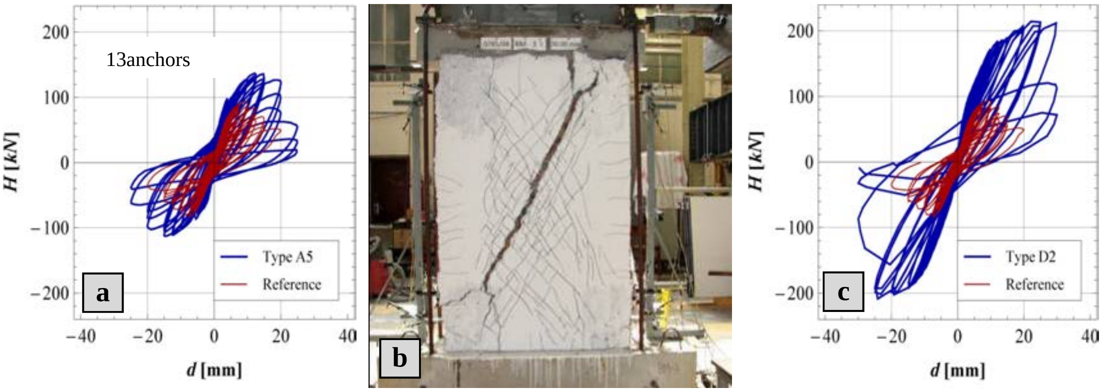

Fig. 7. Coating separated from the wall (a), shear failure of coating from GFRP grid in cementitious mortar with additional vertical strips and strong anchoring (b), and hysteretic response of wall shown in b (c).

4. Strengthening using flexible polymers

A new material for bonding the FRPs to masonry was developed by Polish researchers [10] and is called the polymer PM. It is a two component polyurethane adhesive with patented additives with the following properties: Young's modulus E = 4.5 MPa, tensile strength f_t = 1.95 MPa, ultimate strain ε_u =150%. In collaboration with the Polish team an idea to use this material to apply the GFRP mesh over the entire surface was tested by performing cyclic shear tests [7]. The walls used for strengthening had the same dimensions as shown in the previous section and were built using the same materials. The test setup and testing program were also the same. Because the walls were covered by the flexible layer, it was not possible to observe the cracks on the surface. The wall beneath the coating did crack, and we could observe the damage distribution using an optical image correlation system.

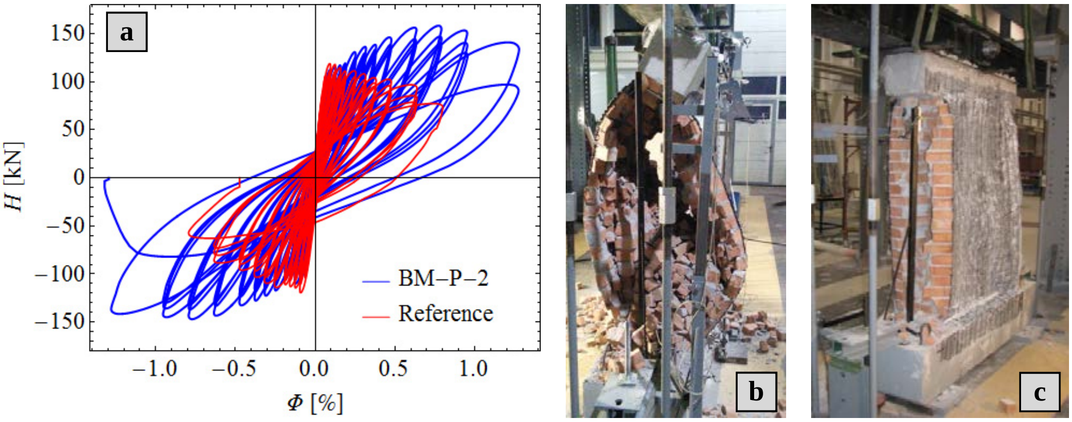

Fig. 8. Hysteretic response of wall strengthened by polymer PM (a), the contact between coating and masonry was not lost even at collapse (b), wide opened crack at the side of the wall during test (c).

The key observations during testing were two: (i) the coating did not lose the contact with the masonry at any time and even at extreme deformations (Figs. 8b and 8c), and (ii) the behavior of the strengthened walls was much better than that of reference walls (Fig 8a). The strengthened walls exhibited higher strength (up to 40 %), almost double energy dissipation and maximum resistance at many times higher displacement (rotation).

5. Tests on a strengthened full scale building model [11]

Despite the vast experience gained in the previous three campaigns there was still something missing. An entire building with piers, lintels, openings, shear and cross walls was still to be tested. The opportunity to fill the gap came as a large reaction wall was completed at ZAG, which enabled testing up to 6 m high models.

The multistorey model was built from hollow clay units (compressive strength 15 MPa) and general purpose mortar (compressive strength 1.8 MPa). The compressive strength of masonry according to EN 1052-1:1998 was 3.8 MPa. The building model was made of two 0.19 m thick three storey shear walls with openings, which were connected to cross walls in order to provide out of plane stability. Floor structures were 12 cm thick reinforced concrete slabs. The model can be seen in Figs. 9a and 9b.

Before the model was strengthened, it was tested up to the point where significant damage developed. Then it was strengthened and retested up to near collapse. At the beginning of each test the vertical load, which simulated a typical stress state in the walls of five storey unreinforced masonry residential building, was applied. Average compressive stress in the bottom storey was of about 0.90 MPa. After that lateral loads at the floor levels were applied in a way that triangular distribution of seismic forces along the height of the specimen was provided. At each amplitude level three loading cycles were performed.

The walls were strengthened using FPR reinforced coating. The fibers were a glass fiber grid, laid in fiber reinforced cementitous mortar. The scheme in Fig. 10a and 10b shows the layout of the FRP grid. First, the vertical strips were placed over the entire storey height and anchored to the bottom and top floors. Then the horizontal strips were applied over the entire length of the shear walls and finally the middle piers were wrapped.

The strengthened model responded in shear and a clear storey mechanism was observed. In the first floor, there was typical diagonal shear crack pattern in the piers (Fig 9c). Some of the cracks appeared also above and below the openings. In the phase when maximum resistance was attained, the delamination of the coating of the middle pier was observed. This test was terminated at the first storey drift of 1.4 %, when large damage appeared and there was fear of actual collapse.

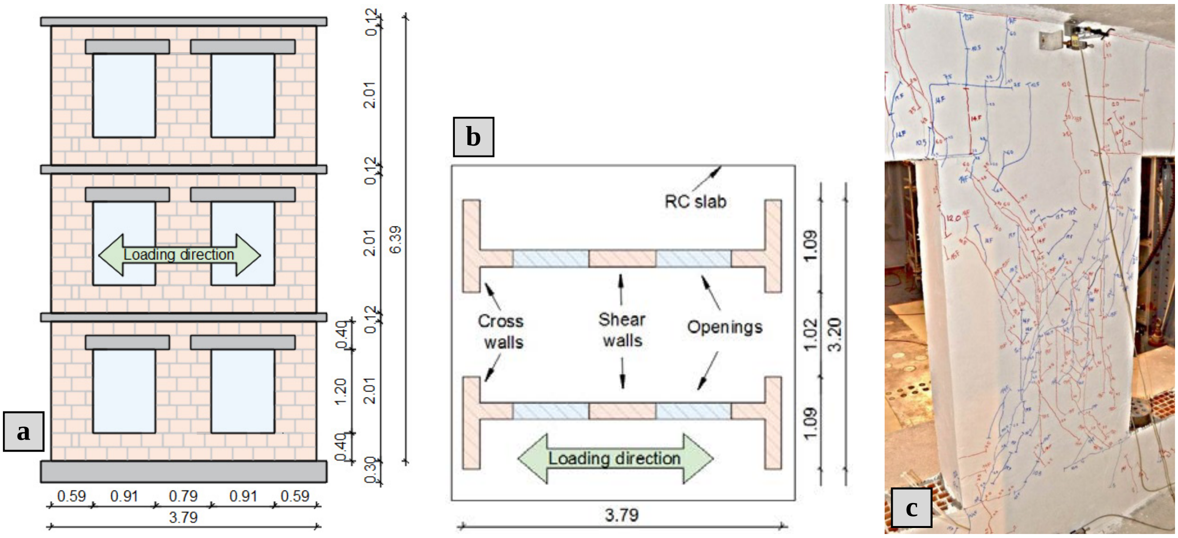

Fig. 9. View of the model (a), floor plan (b) and damage pattern on a pier (c).

The comparison of the seismic resistance of the original and strengthened specimen is shown in the hysteretic curves in the Fig. 10c. The red curve shows the response of the original model and the blue one shows the response of the strengthened one. The majority of the damage and energy dissipation is concentrated in the first floor. The efficiency of strengthening is reflected by maximum resistance, which increased by 45 % and the displacement capacity, which has tripled, while the elastic stiffness of the specimen remained almost the same.

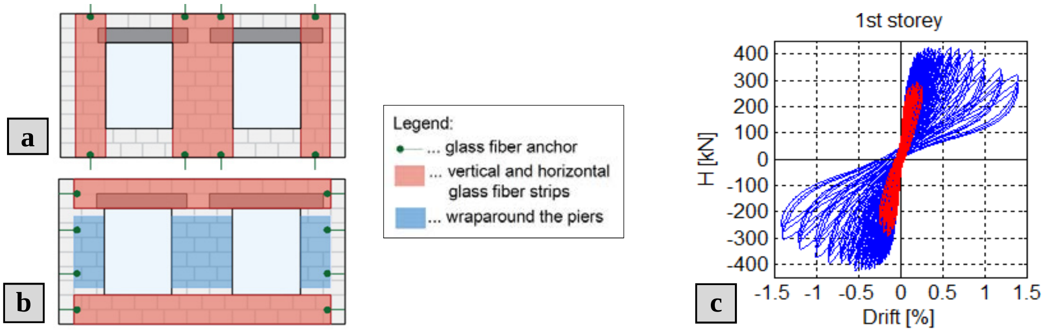

Fig. 10. Gird layout layer 1 (a), gird layout layer 2 (b), and hysteretic response of the 1st floor (c).

6. Conclusions

Four experimental campaigns are briefly presented. The first one shows the experience of in-situ tests of strengthened walls in an actual building, and demonstrates the efficiency of wrapping, but exposes the problem of sufficient connection of the strengthened wall to the rest of the structure. The second campaign deals with different materials and FRP layouts and shows the difficulties with the bond between a strong coating and the weak masonry wall if there is no wrapping. The third campaign explores the use of innovative flexible materials (polymers) as the matrix for the FRPs. Finally, in the fourth campaign, a full scale building model was strengthened using the experience of the first three campaigns, and tested in the laboratory. The results show that seismic behavior of masonry structures can be substantially improved with proper use of FRPs.

References

[1] S. Babatunde, Review of strengthening techniques for masonry using fiber reinforced polymers, Composite Structures 161 (2017) 246-255.

[2] M. Corradi et al., Shear strengthening of wall panels through jacketing with cement mortar reinforced by GFRP grids, Composites Part B: Engineering. 64 (2014) 22-42.

[3] J. Proença et al., Development of an innovative seismic strenghtening technique for traditional load-bearing masonry walls. Bulletin of earthquake engineering. 10 (2012) 113–133.

[4] M. Tomaževič, M. Gams, T. Berset, Seismic strengthening of brick masonry walls with composites: an experimental study, SEWC, Structural Engineers World Congress 2011, April 4th - 6th, Villa Erba, Como, Italy.

[5] M. Lutman, U. Bohinc, M. Gams, M. Tomaževič, In situ tests for the assessment of seismic strengthening historic brick masonry walls with carbon fiber fabric. 15th World Conference on Earthquake Engineering : 24 to 28 september 2012, Lisbon, Portugal. Lisbon: Sociedade Portuguesa do Engenharia Sísmica: International Association for Earthquake Engineering, 2012

[6] M. Tomaževič, M. Gams, T. Berset, Strengthening of stone masonry walls with composite reinforced coatings. Bulletin of earthquake engineering. 13(7) (2015) 2003-2027.

[7] M. Gams, A. Kwiecień, B. Zając, M. Tomaževič, Seismic strengthening of brick masonry walls with flexible polymer coating. P.B. Lourenço (ed.), B. Haseltine (ed.), G. Vasconcelos (ed.). 9th International Masonry Conference, Guimarães, 7-9 July 2014 : book of abstracts. Guimarães: International Masonry Society, 2014.

[8] P. Heerema, M. Shedid, W. El-Dakhakhni, Seismic response analysis of a reinforced concrete block shear wall asymmetric building. Journal of structural engineering. 141 (2014) 7.

[9] T. Wang, X. Zhong, XF. Xu, Performance of a seismically repaired masonry building. 16th World Conference on Earthquake Engineering : 9 to 13 January 2017, Santiago, Chile: Chilean Association of Seismology and Earthquake Engineering: International Association for Earthquake Engineering, 2017.

[10] A. Kwiecień, Polymer flexible joints in masonry and concrete structures (in Polish). Monography No. 414, Wyd. Politechniki Krakowskiej, Seria Inżynieria Lądowa, Kraków, 2012.

[11] P. Triller, M. Gams, M. Tomaževič, Seismic behavior of multistorey strengthened URM masonry shear walls with openings: an experimental study. 16th World Conference on Earthquake Engineering : 9 to 13 January 2017, Santiago, Chile: Chilean Association of Seismology and Earthquake Engineering: International Association for Earthquake Engineering, 2017.