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CYCLIC LOADING OF MASONRY WALLS AND ITS ANTI SEISMIC REINFORCING

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Abstract: *The damage of structural masonry walls is one of the most widespread harming injuries and cause of loss of serviceability and seismic capacity for a building. Therefore a research into possibilities which would improve these characteristics have been carried out within the 7th EC Framework programme project NIKER. The retrofitting approach is constrained by conservation requirements of minimum interventions which should not severely change the structural behavior and the structural appearance, and should prefer solutions without a necessity of total structural disassembling. This article provides an overview about the research that led to applications of the steel wire ropes and geo-nets onto adobe brick walls.*

Keywords: ***Seismic retrofitting, Adobe, Brick wall.***

1. Introduction

In the laboratory of ITAM were tested total 5 samples. Onto every the sample was applied various reinforcing except the first sample which was unreinforced. Overview of the tests shows Table 1.

Tab. 1: Overview of the test.

Title	Description
ABW_1	Unreinforced sample
ABW_2	Reinforced sample by wire ropes
ABW_3	Reinforced sample by PET geo-nets
ABW_4	Retrofitting ABW_1 by PET geo-nets
ABW_5	Reinforced sample by PP geo-nets

The specifications of the material and physical properties of the geo-nets and the wire steel ropes, which were used for the reinforcement of the walls, are summarized in Table 2.

The overall dimensions of the tested walls were 240 mm in thickness, 1050 mm in width and 1295 mm in height. The specimens have been walled up on steel-supported channels with fixtures that enabled the specimens to be lifted by a crane and positioned into the testing rig. The three types of unreinforced masonry considered in tests are depicted in Figure 1.

For the reinforced specimens a polyethylene TENCATE geo-nets and polypropylene TENAX geo-nets externally applied onto the wall surfaces have been used. After they have been mechanically fastened, the walls were rendered with about 2 cm thick plaster made with lime mortar.

The second reinforcement method is represented by means of steel wire ropes placed diagonally and in two directions on the wall surfaces. The wire ropes were installed in three grooves per direction previously produced on the surface of the wall and adequately anchored at their extremities by means of mechanics fasteners.

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Tab. 2: Material specifications.

Title	ρ [kgm3]	Tension strength [MPa]	μ [/]	E [GPa]	Compression strength [MPa]
Adobe brick (CLAYTEC)	2000	0	0,35	3,5	5,5
Mortar – adobe (CLAYTEC)	1900	0,2	-	0,023	1,5

Title	E [GPa]	Ø [mm]	Tensile strength	Mesh sizes [mm]
Wire ropes	210	4	1770 MPa	-
Geo-nets – polypropylene (PP) (TENAX)	-	-	9,3/17 kN/m	30 x 45
Geo-nets – polyester (PET) Miragrid GX 35/35(TENCATE)	-	-	35 kN/m (both directions)	25 x 25

For the experimental program was prepared an adobe specimen severely damaged in a previous test, which has been repaired using the same system of geo-nets and tested again. The cracks have been only plastered with a thin cement mortar in order to smooth the surface for fixation of geo-nets.

In Figures 2 – 3 the tested walls are showed onto which the reinforcement nets were applied. Figure 4 shows a detail of the anchoring (reinforcement with wire ropes).

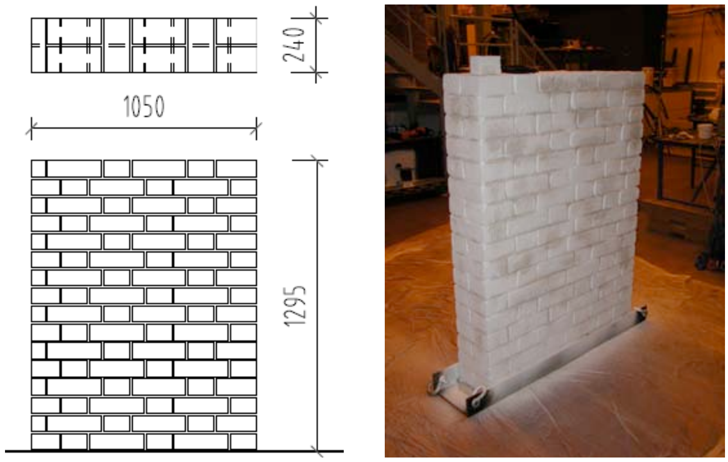

Fig. 1: Test sample

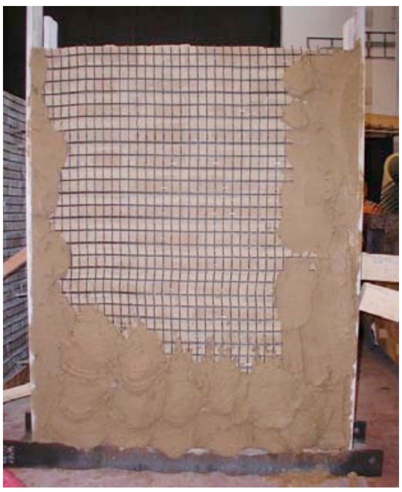

Fig. 2: Adobe brick wall with geo-nets (ABW_3)

Fig. 3: Adobe brick wall with a steel wire ropes (ABW_2)

Fig. 4: Connection detail (ABW_2)

The test specimens were mounted into a special testing rig that enabled simultaneous uniform compression and cyclic horizontal loading on the top of the tested specimen. The outline of the experimental equipment is illustrated in Figure 5 including the location of the sample into the test facility.

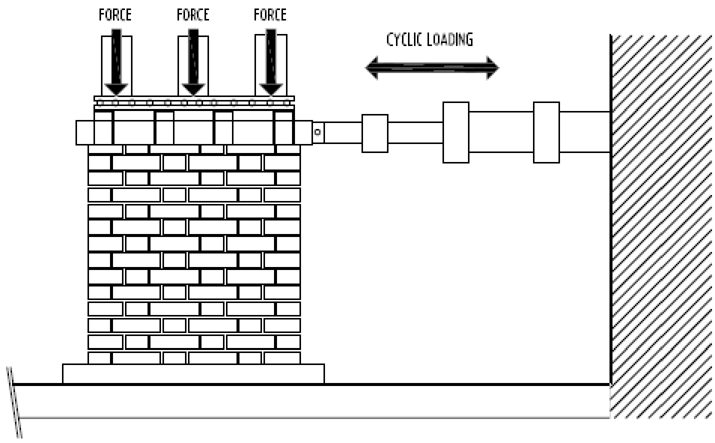

Fig. 5: Scheme of the testing system

Three hydraulic jacks generated the vertical load, which was transmitted to the wall by a steel 'hat' on the top of the wall. A horizontal displacement (force) on the top of the wall was introduced using a servo-hydraulic MTS actuator of 250 kN capacity. During the first loading combination, with static vertical loading only, the deformation characteristics of the wall were obtained. The horizontal displacement on the top of the wall and the deformations perpendicular to the shear diagonals of the panels were measured during combined vertical and horizontal loading. In the experimental testing the following loading condition has been considered. First, the above-mentioned compressive loading only was applied, and was increased continually up to a value of 80 kN, evenly distributed across the cross-section. Then, the vertical compressive pre-stress was combined with cyclic horizontal loading mode with a stepwise increase in the maximum cycling limits. The application of the horizontal load follows the pattern illustrated in Figure 6. In particular, for each step of loading defined by a maximum value of the amplitude (step = 2,5mm) of the displacement imposed by the actuator, three cycles were performed. For each step of loading, the frequency of application of the horizontal force was kept constant and equal to 0.1 Hz.

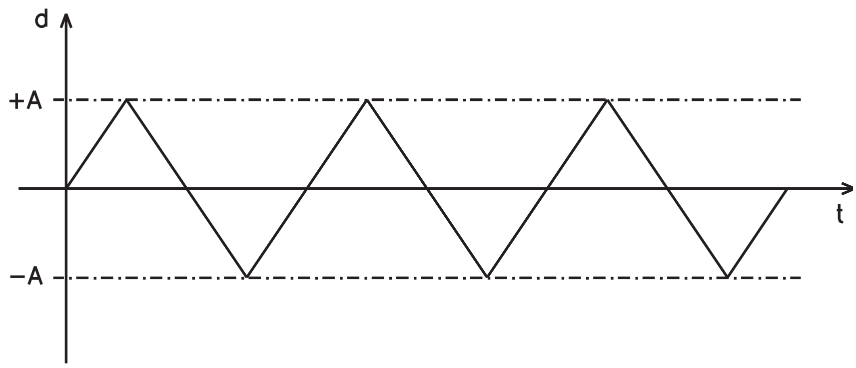

Fig. 6: Loading pattern for each step of application of the horizontal force.

During the test the forces on the vertical hydraulic jacks as well as on the horizontal actuator were recorded. Further, horizontal displacements at the bottom and top of the wall and diagonal deformations of four lines on both surfaces were measured. The sequence of initiation and development of cracks on both surfaces were recorded in all loading steps. Loading was terminated in a moment when the force started to decrease at the controlled deformation.

2. Results on wall segments

2.1. ABW_1 Adobe brick wall - unreinforced

The tests on all walls have been carried out considering fixed the frequency of the load and equal to 0,1 Hz, and incrementing the maximum displacement imposed in the actuator, starting from 2,5 mm and with increment of 2,5 mm.

Typical failure cracking of a plain masonry wall without plaster loaded by combined uniformly distributed vertical static stress and a horizontal cyclic load is shown in Figure 7. The development is highlighted by means of colouring of the cracks.

The envelope curve of the maximum horizontal force and the correspondent displacement obtained from the cyclic curves for each step of loading are plotted in Figure 8. In particular both the tension and the compression side of the cyclic curves are presented.

Fig. 7: Crack pattern at failure of the plain masonry control wall under a combination of vertical compression and cyclic shear.

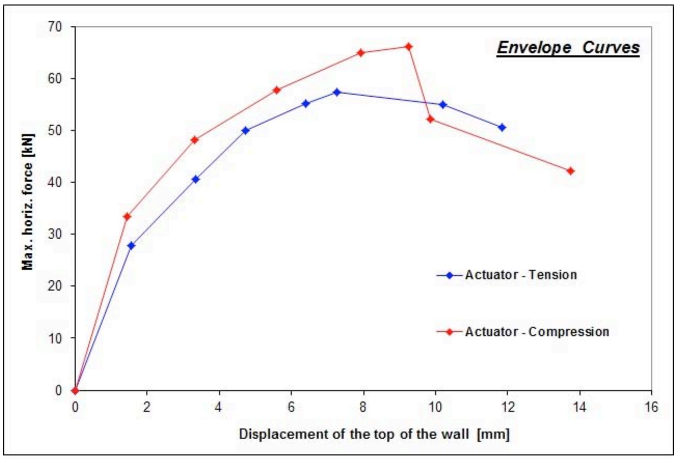

Fig. 8 - Envelope curves for unreinforced adobe wall (ABW_1).

2.2. ABW_2 – Adobe brick wall with reinforced by the wire ropes

The adobe brick wall reinforced by means of steel wire ropes also has been tested. In Figure 9 the crack pattern upon failure of the specimen is shown. In case this kind of reinforcement is adopted an important improvement in terms of resistance can be attained. The wall reinforced by means of this technique behaves in a quite compact manner since the wire ropes play a very effective role in sewing up the cracks and keeping the masonry blocks together. Some cracks can appear along the mortar joints in the surroundings of the reinforcement and, in general, there is a good redistribution of the stresses and a more widespread crack pattern compared to the unreinforced wall.

Fig. 9: Crack pattern at failure of the plain masonry control wall under a combination of vertical compression and cyclic shear.

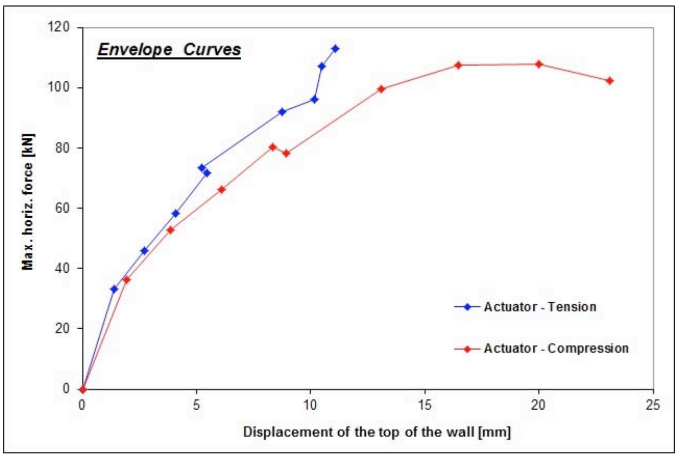

Fig. 10: Envelope curves for reinforced adobe wall by wire ropes (ABW_2).

Another important aspect brought to light by the experiments is related to the damage due to the possible out-of-plane of the reinforcement. In particular, the wire ropes are places quite superficially in grooves made on the wall faces and just plastered with mortar. Since during the application of cyclic horizontal loading both direction of reinforcement can be subjected alternatively to compression, causing the tendency to the ropes to go out of the grooves. However, since the reinforcement is made by steel wire, during tension phase they can easily be able to continue to be effective, involving only superficial damage of the wall. The envelope curves for the wall reinforced by the wire ropes is depicted obtained from the cyclic curves are plotted in Figure 10.

2.3. ABW_3 – Adobe brick wall reinforced by the geo-nets (PET)

The tested reinforcement of adobe walls was the reinforcement by PET geo-nets. The nets were attached to the both surface of the wall by means of steel staples shooted by pneumatic pistol.

It is, thus, evidenced the typical behaviour of walls reinforced by means of this technique. It is noticed that the cracks visible on the surface represent a combination of two sets of damages: masonry cracks and cracks which occur in the plaster only and originate from the differential movement of the geo-nets mesh. It is observed that compared to the typical crack pattern usually found in plane masonry walls, the case of the wall strengthened with reinforced mortar layer present a more widespread and diffused crack pattern. In fact, when unreinforced masonry wall is subjected to a combination of vertical pre-stress and horizontal cyclic load cracks are localized in the two diagonal lines of the walls evidencing the typical X-shaped pattern. The application of the reinforced mortar with geo-nets to the surfaces of the wall has also the effect to redistribute the stresses originated upon loading along the two diagonal lines of the wall and, thus, to spread the pattern over a wider area of the wall surface. An important aspect to be taken into account in the evaluation of the effectiveness of this kind of reinforcement is the interface behaviour between the external reinforcement and the masonry substrate to which it is applied represented by the wall. Since the reinforced mortar layer applied on the wall surfaces is slightly thin (1.5 ÷ 2.0 cm), and due to the different stiffness compared to the substrate, the out-of-plane forces can detach it. The experimental evidence of the detachment of this layer is much more evident when the difference in stiffness is larger. This happens particularly in the cases of application to this kind of reinforcement to clay bricks walls, while in case of adobe walls it is not so evident since the plaster has been made of the same material of the bricks. In Figure 11 it is shown a detail of the detachment of the plaster from the surface of the masonry wall.

Fig. 11 - Evidence of the detachment of the plaster from the wall surface.

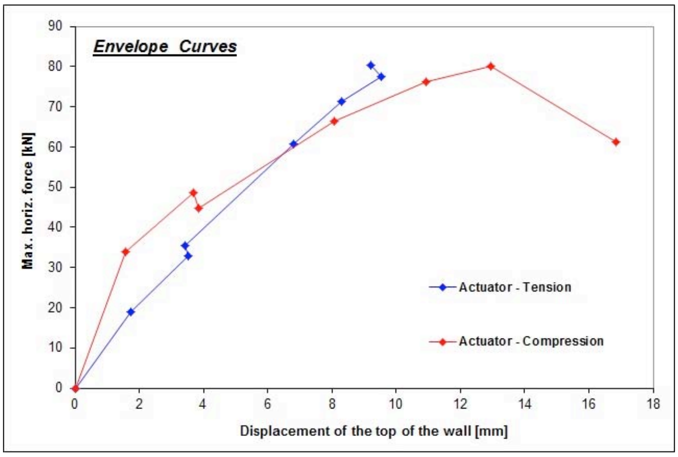

Fig. 12 - Envelope curves for reinforced adobe wall by the geo-nets PET (ABW_3).

2.4. ABW_4 - Reinforced adobe brick wall by the geo-nets PET (retrofitted ABW_1)

The experimental campaign carried out also a test on a retrofitted wall. It is the case of an adobe brick wall (ABW_1) severely damaged under cyclic loading conditions in a test carried out in a previous study at the ITAM. The damaged specimen has been repaired employing the same strengthening technique of the other walls, using geo-nets and plastering the surface with about 2 cm thick layer of mortar. The retrofitted wall has been, thus, tested again under combination of vertical pre-stressing load and cyclic horizontal load. During the loading steps the development of cracking in the central area of the panel with detachment of mortar plaster and a concentration of damage at the base corners of the specimen were observed. Also in this case, as already observed in the case of the undamaged wall strengthened with reinforced mortar layers, the wall experienced the detachment of the mortar. However, in this case the major detachment is in the central area of the specimen. For higher values of the driven displacement, the out-of-plane detachment of the plaster in the lower part of the wall close to the corners was also observed. Moreover, due to a very high stress concentration in that area, a significant crack appeared and spread in the wall thickness, as reported in Figure 13.

In the Figure 14 the global envelope curve of the maximum force and corresponding displacement at the top of the wall cyclic for particular loading are showed.

Fig. 13: Vertical crack in the wall thickness

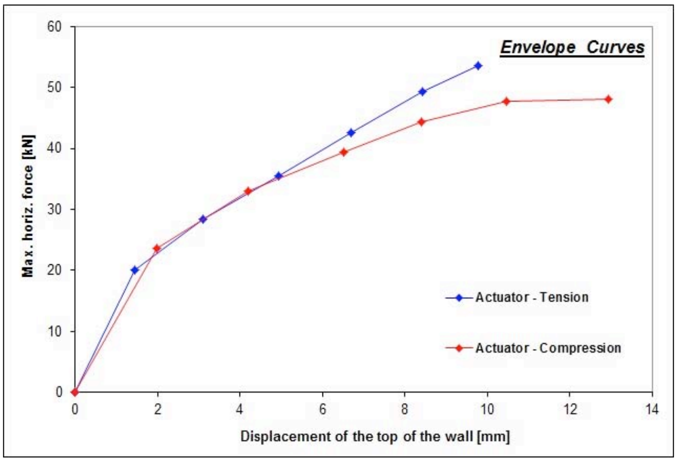

Fig. 14: Envelope curves for retrofitted adobe wall by the geo-nets PET (ABW_4).

2.5. ABW_5 – Adobe brick wall reinforced by the geo-nets (PP)

The further tested reinforcement of adobe walls was the reinforcement by PP geo-nets. The nets were attached to the both surface of the wall by means of steel staples shooted by pneumatic pistol. Figure 15 presents the crack pattern at failure registered for the wall with reinforced plaster by PP geo-nets after test. The behaviour of this reinforced wall is the same as the behaviour of the wall ABW_3. It is, thus, evidenced the typical behaviour of walls strengthened by means of this technique. Also in this case the wall experienced the detachment of the mortar. However, in this case the major detachment is in the central area of the specimen. For higher values of the driven displacement, the out-of-plane detachment of the plaster in the lower part of the wall close to the corners was also observed. Moreover, due to a very high stress concentration in that area, a significant crack appeared and spread in the wall thickness. The cracks in the case ABW_3 and ABW_5 are similar. The envelope curve of the maximum horizontal force and the correspondent displacement obtained from the cyclic curves for each step of loading are plotted in Figure 16.

Fig. 15: Vertical crack in the wall thickness

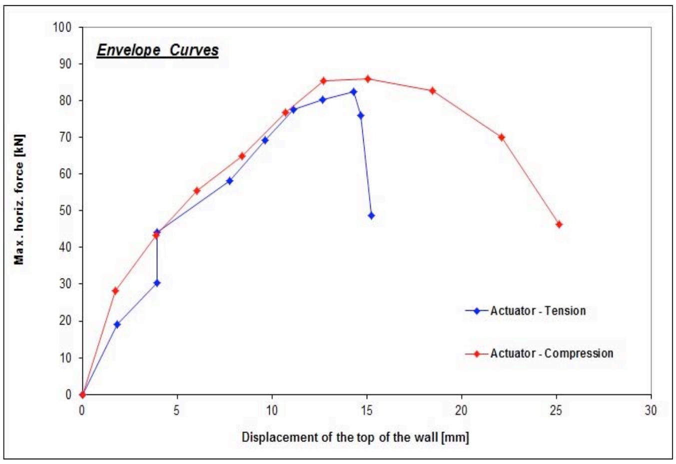

Fig. 16: Envelope curves for retrofitted adobe wall with geo-nets PP (ABW_5).

3. Evaluation and interpretation of results

In the following paragraphs, the results and the interpretation of the experimental tests on adobe brick walls are presented in terms of deformation capacity. In particular, attention is paid to the resulting ductility ratio μ_u (equal to ratio between ultimate displacement δ_u and elastic displacement δ_e). Clearly, the results in terms of deformation capacity are influenced by several factors such as the geometry of the specimen, the level of compression and the boundary conditions. Still, it is difficult from the results analyzed herein to find a clear trend regarding the influence of the vertical stress on deformation capacity. Another issue that seem to affect the results is represented by the dimensions of the specimens which are in turn determined by the available experimental facilities. The confinement provided by the top and bottom restrains in these small specimens can affect the results especially as regards the cracking initiation and propagation with respect to specimens having larger dimensions.

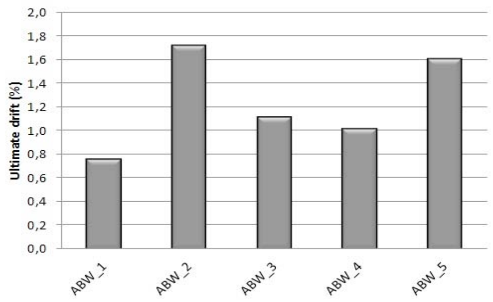

Fig. 17: Ultimate drift

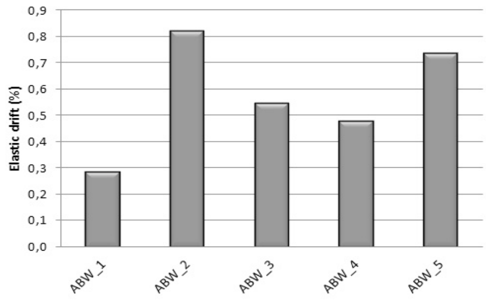

Fig. 18: Elastic drift

In conclusion, the values of ultimate drift are extremely dispersed. The minimum value is related to the specimen ABW_1 and it is equal to 0,76%. The mean value of the ultimate drift of all the tests is equal to 1,24%, see Figure 17. The elastic drift is depends on the reinforcement technique. The greatest value have the specimens ABW_2 and ABW_5, see Figure 18. The values of ultimate displacement ductility of the specimens are very low but quite homogenous, see Figure 19.

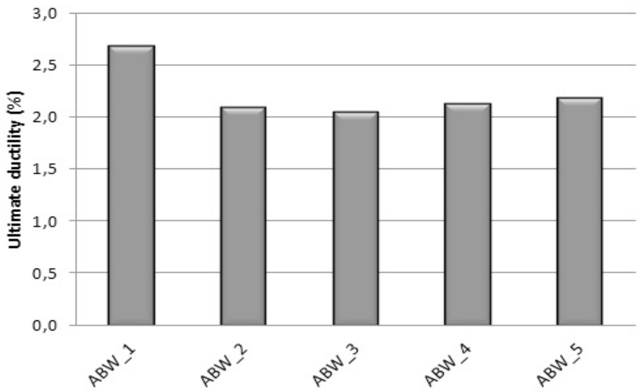

Fig. 19: Ductility

The next comparison is by the energy dissipation. Energy dissipation was calculated from the area of a hysteresis loop. The area was determined from one cycle in a given step. The tests carried out here provide several important results for adobe brick walls. It has been shown that steel wire ropes on an adobe wall surface increase significantly the energy dissipation of the wall. The effectiveness of the system is evident also in terms of increment of the displacement capacity of the wall. This type of reinforcement is very cheap in costs and the most efficient from the point of view of the strengthening from the all used method. It was observed that the application of the reinforced mortar layers onto the wall's surfaces allows the specimen to reach a higher value of energy dissipation. Moreover, an increment in terms of ductility is also registered. Geo-nets have also a better ratio of strength to the strength of brick and, therefore, it is favourable to apply them. Unlike in the case of steel wire ropes, there is not such a danger of pulling out the reinforcement in the out-of plane. Comparing the energy dissipation of the retrofitted wall by means of geo-nets (PET) with the unreinforced adobe brick wall it can be observed that the stiffness of the retrofitted wall is lower than the stiffness of the control wall, even after the intervention. Comparing the energy dissipation of the retrofitted wall by means of geo-nets (PET) with the unreinforced adobe brick wall it can be observed that the stiffness of the retrofitted wall is lower than the stiffness of the control wall, even after the intervention. Comparing the force-displacement curve of the reinforced wall by means of geo-nets (PET) with the reinforced wall by means of geo-nets (PP) it can be observed that the strengthening with mortar reinforced with both geo-net is similar. However, energy dissipation is greater in the use of geo-nets (PP), see Figure 20.

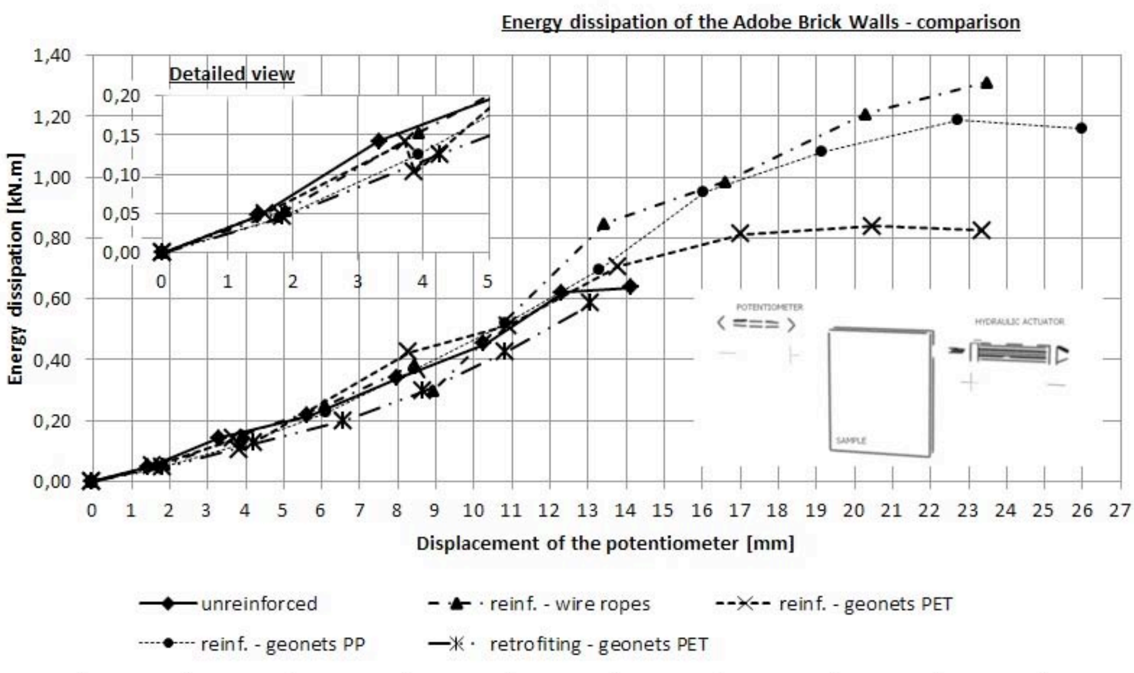

Fig. 20: Comparison of the energy dissipation

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