Seismic Strengthening of Stone Masonry Walls with Polymer Coating

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SUMMARY:
The efficiency of strengthening traditional three-leaf stone masonry walls with different types of polymer coating has been investigated. Glass fibre grid or fabric and single component fibre reinforced mortar or epoxy resin were used as coating materials, with coating anchored or not anchored to the masonry at the corners of the walls. Two walls in the original state have been tested as control specimens. All walls failed in shear. Significant increase in lateral resistance with regard to control walls has been observed in all cases, amounting to 4.0-times the resistance of the control walls. As the test results indicated, the coating of the walls improved also the displacement and energy dissipation capacity, but increased the rigidity of the original walls. The degree of improvement did not depend on the type of coating but on the technology of application.

Keywords: stone masonry, strengthening, glass fibre grid, coating, cyclic in-plane shear, testing

1. INTRODUCTION

Locally available stone is traditional construction material in many earthquake-prone countries, including Slovenia. Depending on local resources and tradition of construction, a great variety of types of stone masonry exist, worldwide. In Slovenia, stone masonry walls are typically made of rubble or river-bed stone, lime-stone or slate, built in two outer layers of irregularly sized bigger stones, with an inner infill of smaller pieces of stone, in poor mud mortar with a little lime. In the city centers and towns, the walls are made of relatively compact mix of stone, brick and mortar, with no distinct separation between the individual layers of the walls. Regularly cut, or partly cut stone is rarely used. Connecting stones are also rare.

Typically, stone-masonry houses are 3–4 stories high in the cities and towns, whereas their height is limited to 2 stories in rural areas. Structural layout is usually adequate. The distribution of walls is uniform in both orthogonal directions, and, because of the thickness of load bearing and cross-walls and relatively small rooms, the wall/floor area ratio is very large, in many cases exceeding 10 %. Floor structures and lintels are traditionally wooden, without any wall-ties provided to connect the walls. Wooden floors are sometimes replaced by brick vaults above cellars, staircases and corridors. Roof structures are wooden and covered with ceramic tiles, sometimes laid in mortar. As a rule, the buildings are built without any foundation, whereas foundation walls are of poorer quality than the walls of the structure above the ground level. As the earthquakes in the past indicated, seismic resistance of such buildings is not adequate. Since significant damage can be expected even in the case of moderate seismic events, stone masonry buildings which in most cases represent buildings of historic importance, need to be strengthened.

Among different methods of strengthening of stone masonry walls, injecting the walls with cementitious grouts proved to be most efficient. Although repointing and coating of such walls with reinforced cement coating have been also used, in many cases these methods did not prove to be as successful. The methods of both types are being constantly improved. Whereas in the case of injections, masonry friendly grouts have been developed where cement is replaced by lime or inert materials, attempts have been also made to replace traditional coating materials, such as steel and concrete, with synthetic ones, such as fiber reinforce mortars reinforced with carbon (CFRP) or glass fiber reinforced polymers (GFRP) grid or mesh. The efficiency of various techniques of strengthening brick masonry walls with polymer coatings has been already tested (e.g. Schwegler 1994, Triantafillou 1997, ElGawady 2006, Konthesingha 2010, Tomaževič 2011). However, not much experimental work has been carried out to investigate the efficiency of such kind of strengthening applied to the stone masonry walls. Since the interest of using such methods of strengthening, which are time-effective and relatively clean, is growing with the decreased costs of polymers, especially GFRP, an experimental campaign to investigate the efficiency of some recently developed methods and prepare recommendations for their practical use, has been launched also at Slovenian National Building and Civil Engineering Institute in Ljubljana, Slovenia. Some test results will be presented and discussed in this paper.

2. PROGRAM OF TESTING, TYPES OF STRENGTHENING AND MATERIALS USED

To investigate the efficiency of different strengthening types, a total of 12 stone masonry walls with dimensions 1500/1000/500 mm (height/length/thickness), representing typical rural three-wythe stone masonry in Slovenia, have been built in the laboratory. Coarse lime stone (compressive strength about 220 MPa), delivered from a demolished stone-masonry house in the region of Posočje, has been used for the construction of 10 wall specimens. The stones, up to 30 cm in size, have been laid in lime mortar with small amount of cement added to accelerate hardening. The compressive strength of mortar, consisting of river bed sand (maximum aggregate size 4 mm), hydrated lime and cement in volumetric proportion 8:1:0.5, was 3.3 MPa (c.o.v. = 0.35. The specimens have been built on reinforced concrete foundation blocks, and had reinforced concrete bond-beams on the top. The dimensions of the walls are shown in Figure 1.

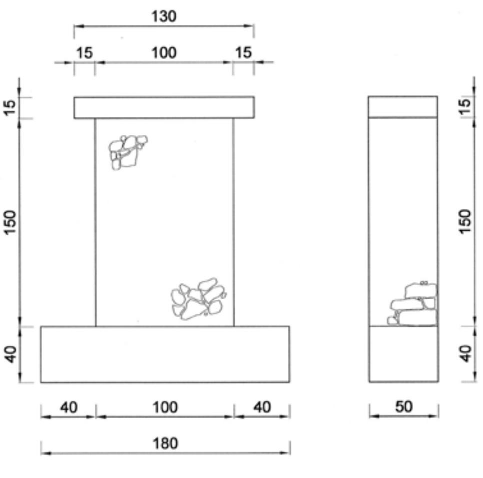


Figure 1. Dimensions of the tested walls (in cm)

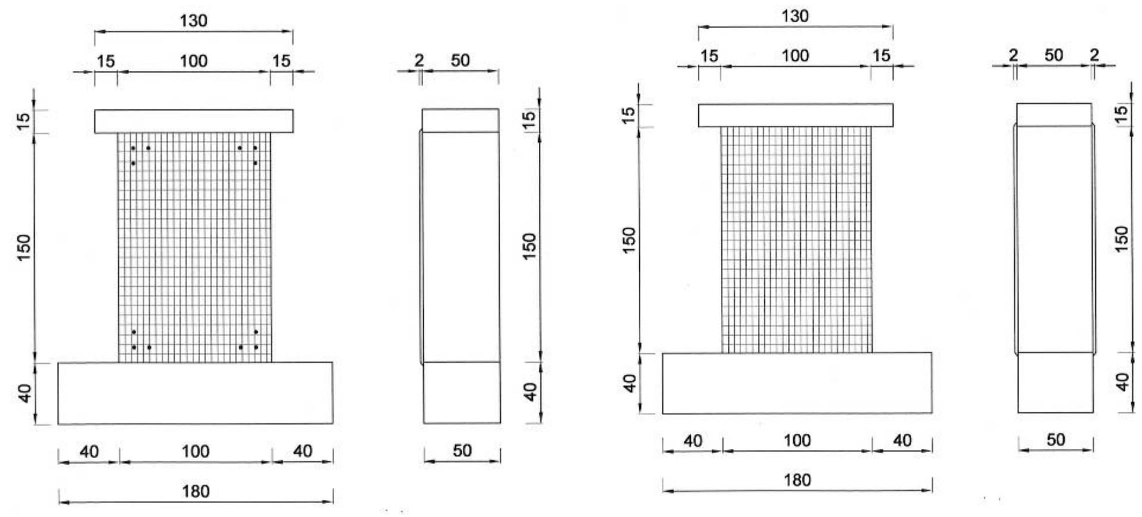
To determine the compressive strength, f_c (f_c = 1.26 MPa) and modulus of elasticity of masonry, E (E = 470 MPa), two walls have been tested by compression in accordance with European standard EN 1052-1. Others were tested as vertical cantilevers, subjected to constant pre-loading, simulating the gravity loads which induced compressive stresses in the horizontal section of the walls, σ, equal to 26 % of the compressive strength of masonry (preloading ratio σ/f_c = 0.26), and programmed cyclic displacements, simulating the horizontal seismic loading, acting at the level of the bond-beams in the plane of the walls. For reference, two control walls (i.e. the walls in the original state) have been tested up to collapse. The remaining 8 walls have been strengthened by applying 4 different types of strengthening solutions. In the case of strengthening solutions Type 1 and 2, the coating has been applied on previously damaged walls, whereas in the case of application of strengthening solutions

Type 3 and 4, the walls in the original, not damaged state have been strengthened (see Table 1). No specific measures to repair the cracks before the application of strengthening solutions Type 1 and 2 have been carried out.

Table 1. Program of testing

Wall designation	No. of specimens	Type of test	Type of coating	Note
SM-V1, SM-V2	2	Compressive	-	Control walls
SM-1, SM-2	2	Cyclic shear	-	Control walls
SM-4S, SM-6S	2	Cyclic shear	Type 1	Previously damaged
SM-3S, SM-5S	2	Cyclic shear	Type 2	Previously damaged
SM-9S, SM-10S	2	Cyclic shear	Type 3	Undamaged
SM7S, SM-8S	2	Cyclic shear	Type 4	Undamaged

In the case of solution Type 1, the coating consisted of vertical GFRP grid as reinforcement and 15−20 mm thick fiber reinforced cementitious mortar as a matrix. The coating, anchored to the wall in the corners, was placed on one side of the wall only. In the case of solution Type 2, the same coating was placed on both sides, however without being anchored to the wall. In the case of solution Type 3, the grid was placed diagonally on both sides and the coating was anchored to the wall in the corners. In the case of solution Type 4, 30 cm wide GFRP fabric strips have been used as reinforcement, laid in epoxy resin matrix. They were placed vertically and diagonally on both sides of the wall and anchored to the wall in the corners. Before application of coating, the surface of the walls has been leveled with fiber reinforced cementitious mortar. The coating has not been anchored into the r.c. foundation blocks or r.c. bond beams on the top of the walls. Strengthening solution types are schematically presented in Figures 2 and 3.



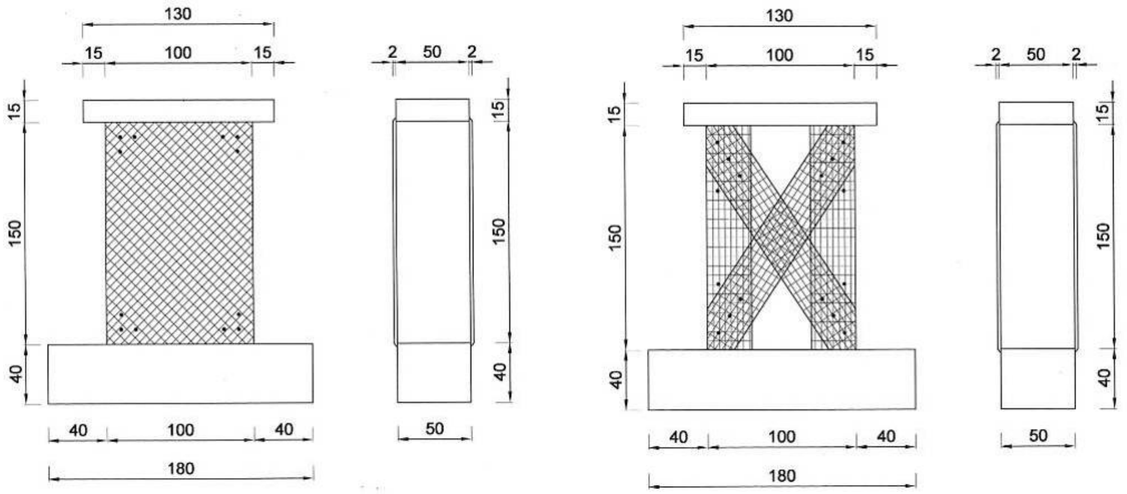
Strengthening Type 1: vertical GFRP grid placed on one side of the wall, anchored in corners

Strengthening Type 2: vertical GFRP grid placed on both sides of the wall, no anchors

Figure 2. Schematic presentation of strengthening Types 1 and 2 (dimensions in cm)

Commercially available materials have been used to strengthen the walls. Bi-directional glass fiber grid, SikaWrap®-350G grid and Sika® MonoTop®-722 Mur mortar have been used in the case of strengthening Types 1, 2, and 3, whereas SikaWrap®-430G fabric and SikaDur-330 epoxy resin matrix have been used in the case of strengthening Type 4.

SikaWrap®-350G grid with approximately 17/15 mm windows (nominal 15.7/10.1 mm) is a glass fiber grid with an alkali resistant coating. The tensile strength, measured on virgin filament, is 3.4 GPa. The ultimate load in longitudinal direction is 77 kN/m; in transverse direction, 76 kN/m. Tensile stiffness, expressed as the load at 1 % elongation, is 20 kN/m and 25 kN/m in the longitudinal and transverse direction, respectively. Elongation at rupture is 3 %. SikaWrap®-430G, is uni-directional woven glass fiber fabric, 0.17 mm thick. The tensile strength of fibers is 2.3 GPa, whereas the tensile modulus of elasticity of fabric is 76 GPa with 2.8 % strain at rupture..



Strengthening Type 3: diagonal GFRP grid placed on both sides of the wall, anchored in corners

Strengthening Type 4: diagonal and vertical GFRP fabric strips on both sides of the wall, anchored

Figure 3. Schematic presentation of strengthening Types 3 and 4 (dimensions in cm)

Sika® MonoTop®-722 Mur is a fiber reinforced mortar with reactive pozzolanic components, selected aggregates and special additives. The compressive strength at 28 days, tested in accordance with EN 196-1, is 22 MPa. Bending strength is 7 MPa, and modulus of elasticity, tested in accordance with EN 13412, is 8 GPa. Sikadur®-330 is a 2-component epoxy impregnation resin used for application of glass or carbon fabric reinforcement to the masonry. Its properties, measured according to DIN 53455 at 7 days are: tensile strength 30 MPa, elastic modulus in bending 3.8 GPa, elastic modulus in tension 4.5 GPa and elongation at rupture is 0.9 %.

The anchors, SikaWrap® Anchor C, are carbon fiber strings, contained in elastic gauze wrapping, 10 mm in diameter. Before being placed into the holes drilled into the wall, the strings are cut into the pieces, about 200 mm longer than the holes, the wrapping is removed and the fibers are soaked in epoxy resin. The anchor is inserted into the hole, filled with epoxy resin, by means of a simple tool. At the protruding end, the fibers are spread in the form of a circular fan and glued on the prepared surface of the wall with epoxy resin.

3. TESTING PROCEDURE AND TEST RESULTS

3.1. Testing procedure and instrumentation

To study the efficiency of the proposed strengthening solutions, the walls have been tested as vertical cantilevers, subjected to constant vertical and cyclic in-plane lateral loading, induced by hydraulic actuators acting on the bond beam on the top of the walls. Reinforced concrete foundation blocks on which the walls were constructed, were fixed to the strong floor by means of bolts. Test set-up consisted of a steel testing frame and hydraulic actuators, fixed to the frame in order to simulate constant gravity loads and cyclic lateral in-plane seismic loads. Compressive stresses in the walls' horizontal section, equal to 26 % of the compressive strength of masonry, were kept constant during the tests. In-plane lateral loads were simulated in the form of cyclic horizontal displacements, imposed by means of a programmable hydraulic actuator acting at the midheight level of the bond-beam. The displacement amplitudes were step-wise increased up until the collapse of the walls. At each displacement amplitude, the loading was repeated three times to study the resistance and stiffness degradation. All walls were instrumented with load cells and displacement transducers (LVDT-s) to measure relevant forces and displacements. Testing arrangement and instrumentation can be seen in Figure 4.

Figure 4. Testing arrangement and instrumentation

Figure 5. Control wall: damage at ultimate state

3.2. Behavior and failure mechanisms

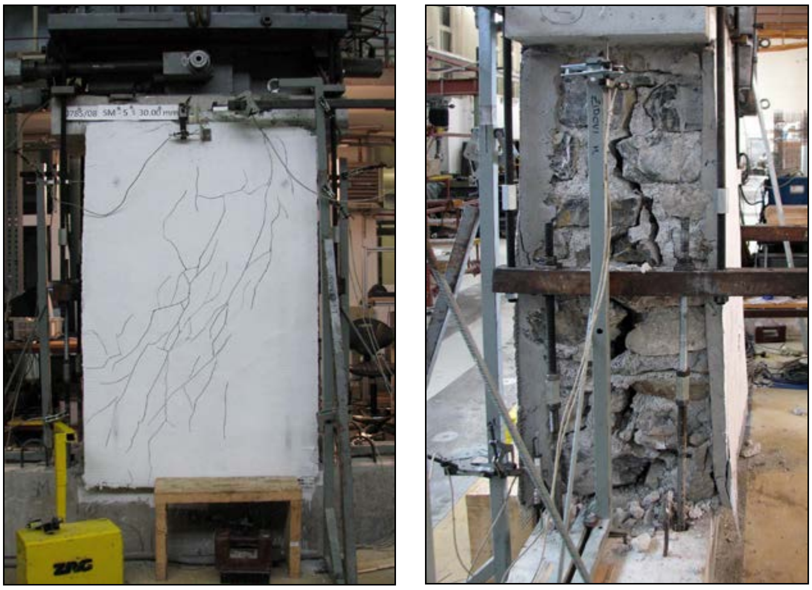
Shear governed the behavior of all, control and strengthened walls. In the case of control walls, diagonally oriented cracks occurred in mortar joints in the central part of the walls. By increasing the amplitudes of imposed lateral displacements, the width of the cracks increased as they propagated over the entire surface of the walls (Figure 5). Ultimately, delamination of the walls' wythes took place and individual stones started falling out.

a.) b.) c.)

Figure 6. Strengthening Type 1: a.) damage on the uncoated side of the wall at ultimate state; b.) cracks in the coating; c.) delamination of the wall's wythes

Generally speaking, the failure mechanism of the strengthened walls was similar in all cases. The mechanism was characterized by diagonally oriented and uniformly distributed cracks in the coating as well as delamination of individual wythes of stone masonry at ultimate state. However, some differences, typical for each particular strengthening type, have been observed.

In the case of the single-side coated walls (strengthening Type 1 – Figure 6), similar distribution of cracks as in the case of control walls has been observed on the uncoated side of the wall. Cracks which developed in the coating, anchored in the corners, followed more or less the same pattern. Ultimately, the unstrengthened wythe delaminated and partly collapsed, whereas the coated wythe remained monolithic.



a.) b.)

Figure 7. Strengthening Type 2: a.) cracks in the coating at ultimate state; b.) delamination of the wall’s wythes

a.) b.)

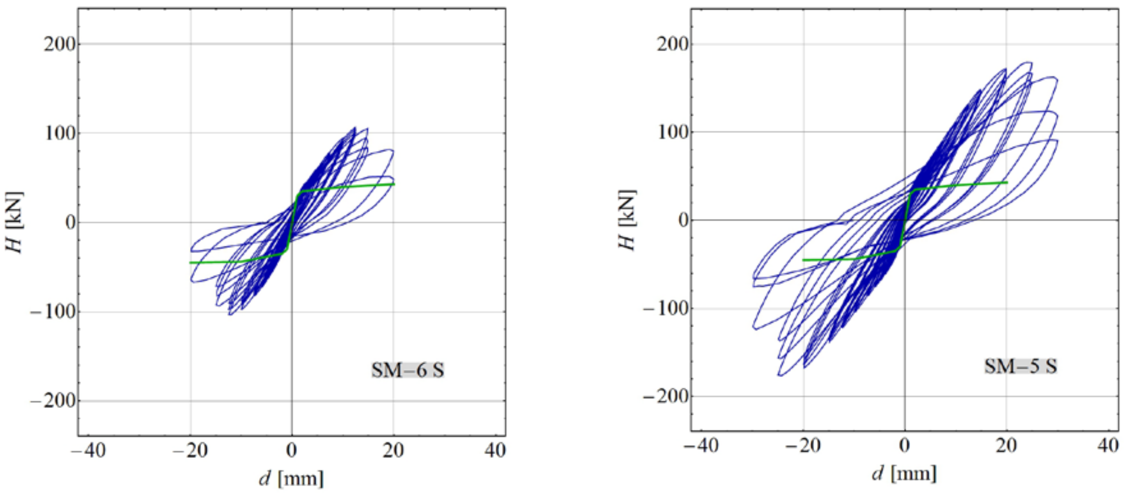
Figure 8. Strengthening Type 3: a.) cracks in the coating at ultimate state; b.) buckling of coating and delamination of the wall’s wythes

Although final delamination of coated stone-masonry wythes was the reason of collapse in all cases of specimens where coating has been applied on both sides (Figures 7b, 8b, and 9b), the crack pattern depended on the type of strengthening. In the case of strengthening Type 2 (vertical grid without anchors), diagonally oriented cracks developed, distributed over the entire surface of the wall (Figure 7a), whereas in the case of strengthening Type 3 (diagonal grid, anchored in the corners), the area with diagonally oriented cracks was concentrated in the central part of the wall (Figure 8a). In the case of diagonally and vertically placed fabric strips, anchored in the corners (strengthening Type 4), visible cracks occurred only on the part of masonry, not covered by coating (Figure 9a).

a.) b.)

Figure 9. Strengthening Type 4: a.) cracks in the uncoated part masonry at ultimate state; b.) delamination of the wall's wythes

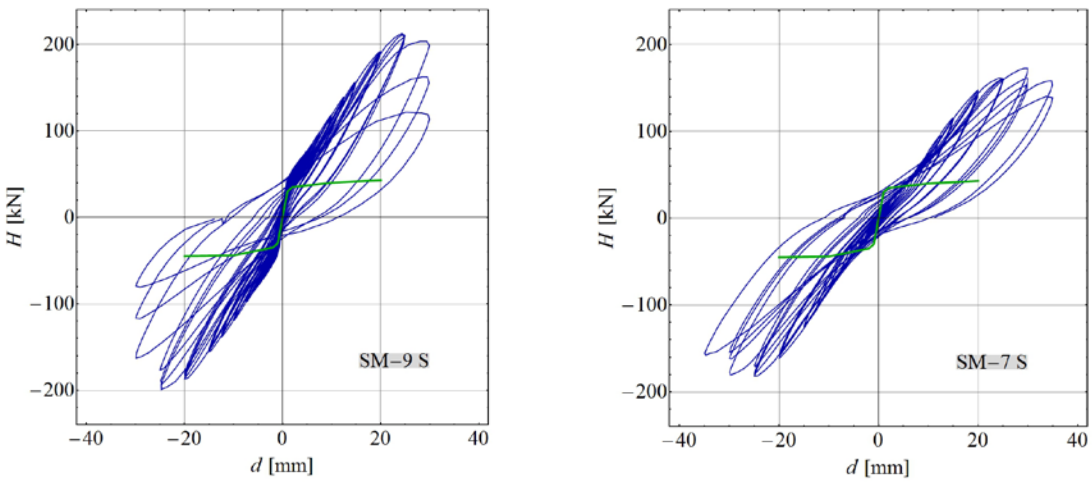
3.3 Lateral resistance and displacement capacity



a.) b.)

Figure 10. Lateral load−displacement hysteresis loops, obtained by testing the strengthened walls. a.) Strengthening Type 1, b.) Strengthening Type 2

Typical lateral load−displacement hysteretic relationships, measured during the testing of walls, strengthened by different strengthening methods, are shown in Figures 10 and 11. For comparison, lateral load−displacement envelopes, obtained by testing the unstrengthened, control walls, are also plotted in the figures (green line).



a.) b.)

Figure 11. Lateral load−displacement hysteresis loops, obtained by testing the strengthened walls. a.) Strengthening Type 3, b.) Strengthening Type 4

To assess the efficiency of strengthening, the resistance and displacement capacity of the walls at three limit states have been compared:

a. Crack (damage) limit state, where the first cracks occur in the walls, causing evident changes in stiffness of the wall;
b. Maximum resistance;
c. Ultimate limit state of collapse, defined by severe degradation of resistance at repeated lateral load reversals or collapse of the wall.

Test results are summarized in Table 2, where the values of lateral load, *H*, displacement, *d*, and rotation angle, $\Phi = d/h$ (in % of *h*; *h* = height of the wall), at characteristic limit states are given as the average values obtained by testing two specimens, strengthened in the same way. The values measured at the first amplitude peaks in positive and negative direction of loading at each particular limit state are considered. For comparison, the relevant values obtained by testing the control walls, are also given in Table 2.

Table 2. Test results: lateral resistance, *H*, and displacement, *d*, and rotation, Φ, at characteristic limit states

Strength. type	Damage limit			Maximum resistance			Ultimate state		
	H_{cr} [kN]	d_{cr} [mm]	Φ_{cr}	H_{max} [kN]	d_{Hmax} [mm]	Φ_{Hmax}	H_u [kN]	d_u [mm]	Φ_u
Control	27.5	1.5	0.05	45.2	11.13	0.75	26.6	20.0	1.35
Type 1	32.3	1.5	0.10	123.6	14.8	1.00	45.6	22.5	1.52
Type 2	35.1	1.3	0.08	169.8	22.2	1.50	64.7	27.5	1.86
Type 3	39.0	1.1	0.08	191.5	23.5	1.60	79.9	30.3	2.06
Type 4	40.3	1.0	0.07	188.6	24.3	1.84	93.2	32.5	2.20

Test results are analyzed in Table 3, where the resistance and displacement capacity of the strengthened walls are compared with the average values, obtained by testing the unstrengthened, control walls. In addition, the values of effective stiffnesses, defined as the ratio between the lateral load and displacement at the damage limit state, $K_e = H_{cr}/d_{cr}$, are also compared. As can be seen, by application of polymer coating the lateral rigidity of the walls is increased substantially.

Table 3. Efficiency of strengthening methods

Strengthening type	Stiffness		Resistance capacity		Displacement capacity	
	K_e [kN/mm]	Strengthened/ control	H_{max} [kN]	Strengthened/ control	d_u [mm]	Strengthened/ control
Control	18.33	-	45.2	-	20.0	-
Type 1	21.53	1.17	123.6	2.73	22.5	1.13
Type 2	27.00	1.47	169.8	3.76	27.5	1.38
Type 3	35.45	1.93	191.5	4.24	30.3	1.51
Type 4	40.30	2.20	188.6	4.17	32.5	1.63

As shown in Table 3, the strengthening of traditional three-leaf stone masonry by application of polymer coating significantly improved lateral resistance and displacement capacity of the tested walls. The efficiency did not depend much on the type of coating (vertically or diagonally placed polymer grid in fiber reinforced mortar; polymer fabric in epoxy resin matrix), but depended mainly on the method of application. Analyzing the test results, no indication can be obtained regarding the influence of damage state of the wall at the time of application of coating (previously damaged, undamaged) on lateral resistance and displacement capacity. On the basis of the observed mechanism, the difference in resistance of walls where strengthening Types 1 and 2 have been applied, can not be attributed to the previous damage state, but to the method of application:

The application of coating on only one side of the wall, although anchored in the corners, improved the resistance to a lesser degree than the application of coating on both sides of the wall. Moreover, the application of coating on only one side did not improve the displacement capacity. The analysis of test results has shown the importance of anchoring the coating at least in the corners of walls. As can be seen, the improvement in both, resistance and displacement capacity was greater in the case of strengthening Types 3 and 4 where the coating was anchored in the corners than in the case of strengthening Type 2 without any anchors. The difference in resistance and displacement capacity between the strengthening Types 3 and 4 (grid versus fabric) can not be considered significant.

The types and direction of placing of the coating (grid−fabric; vertical−diagonal), influence the position and distribution of cracks. The coating, however, did not prevent the delamination of the wall wythes at ultimate state. Because of delamination, falling out of stones and compression of masonry which resulted in consequent sudden buckling of coating, severe resistance degradation takes place during the ultimate phase of behavior (Figures 10 and 11).

To study the influence of different types of coating on the energy dissipation capacity of the walls when subjected to cyclic loading, the ratio between the dissipated hysteretic, E_{hys}, and input energy, E_{inp}, at characteristic limit states has been calculated. In the analysis, the dissipated hysteretic energy has been calculated as the sum of areas of hysteresis loops, from the beginning of tests to the first displacement amplitude at the particular limit state. The input energy, however, has been calculated as the actuator work from the beginning of test to the same point. The results are summarized in Table 4. As can be seen, the ratio does not depend significantly on the strengthening type. It can be also seen that the ratio does not change until significant damage to the walls occurs at ultimate state.

Table 4. Energy dissipation capacity as the ratio between the dissipated hysteretic, E_{hys}, and input energy, E_{inp}

Strengthening type	Crack limit E_{hys}/E_{inp}	Maximum resistance E_{hys}/E_{inp}	Ultimate state E_{hys}/E_{inp}
Type 1	0.30	0.30	0.43
Type 2	0.30	0.32	0.41
Type 3	0.29	0.29	0.37
Type 4	0.31	0.30	0.37

4. CONCLUSIONS

A series of three-leaf stone masonry walls, constructed in the laboratory in the traditional way, and strengthened by application of different types of polymer coating, have been tested by subjecting them to constant vertical load and cyclic shear, simulating seismic loads. The coating consisted of either GFRP grid as reinforcement and 15−20 mm thick fiber reinforced cementitious mortar as a matrix, or 30 cm wide GFRP fabric strips as reinforcement, laid in epoxy resin matrix. The methods of application of coating also varied (one side, both sides, anchored, not anchored).

The tests have confirmed the efficiency of composite coatings. The in-plane lateral resistance can be improved by more than four times and the displacement capacity by up to 50 %, depending on the type of strengthening. No significant difference in the efficiency of various types of coating has been observed if the coating was applied on both sides of the walls and anchored to the wall in the corners. The application of coating increased also the rigidity of the walls.

Although the composite-based coatings proved to be efficient as regards the resistance of traditional three-leaf stone masonry, further efforts should be made to develop techniques which will prevent delamination of masonry and prevent large resistance and stiffness degradation at ultimate state.

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