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OVERVIEW OF DIFFERENT STRENGTHENING TECHNIQUES APPLIED ON WALLS USED IN HISTORICAL STRUCTURES

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ABSTRACT

Different types of vertical elements, such as masonry, massive walls and timber frame elements, exhibit a different response exposed to the same loading scenario, in particular when it concerns dynamic loading. It is therefore paramount to investigate the principal response of different types of construction with different materials under a variety of loading scenarios. From there, the design of strengthening techniques against earthquakes can be performed. This paper presents the results from experiments, where various retrofitting techniques were tested. The goals were to define and improve laboratory procedures for evaluating the intervention technologies and specifications for laboratory specimens. From this base tests to characterise the experimental behaviour of original and strengthened masonry walls were performed, in order to obtain information on the system performance and the main constitutive laws relevant for modelling. The test campaigns were focused on static tests as well as cyclic tests of unreinforced and reinforced vertical building elements. The study is part of our work in the framework of the ongoing project NIKER funded by the European Commission dealing with improving immovable Cultural Heritage assets against the risk of earthquakes.

Keywords: *Stone masonry, Brick masonry, Earthen materials, Half timbered walls, Grouting*

1. INTRODUCTION

The choice of different materials and constructions for the tests was mainly ruled by the variety of materials and techniques used for historical constructions. In the scope of the presented paper it was necessary to find the most common construction techniques and materials for historical structures which is representative for a larger number of immovable heritage assets but also reflects the competence and expertise of the partners participating in this work package. The materials used enclose the most common ones utilised for traditional construction: Stone, wood, brick and earth. The construction techniques consisted of masonry, massive walls and timber frame. Intervention methods for vertical elements for the various building techniques were chosen according to their expected performance. The construction techniques for stone masonry consisted essentially in regular and irregular three leaf limestone masonry with natural hydraulic lime (NHL) mortar or hydraulic lime mortar with a natural pozzolan, respectively. Clay brick walls consisted of one leaf masonry specimen with cement or earth mortar. Adobe wall specimens were constructed as one leaf masonry with earthen

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mortar. Earth blocks consisted of mechanically molded adobe. Rammed earth specimens were prepared in the traditional way by mostly by hand with formwork. Cob specimens consisted of a mixture of raw earth and straw and were cut from a larger block. The timber frame panels consisted of timber and clay brick masonry with cement mortar. The static and cyclic tests in the laboratory were each performed on wall element specimens with and without retrofitting. One focus was laid in providing a compatible solution in form of a minimum intervention method.

2. THREE-LEAF STONE MASONRY WALLS STRENGHTENED WITH GROUTING

2.1. Monotonic and cyclic compression tests by University of Padua

The experimental research aimed at studying the mechanical behaviour under compressive load of the single- and three-leaf stone masonry panels unstrengthened and strengthened with grout injection. Furthermore, the tests were designed to evaluate capacity to increase the in-plane compressive strength of a single panel due to the injection with NHL grout – FEN-X/B, [1], and, as so, obtain a better understanding on the effectiveness of the investigated strengthening technique as well as its influence on the failure modes and transversal deformations of this wall typology. In this experimental campaign, 6 panels in scale 1:1 (wall B) and 6 panels in scale 2:3 (wall D), half in original conditions and half consolidated with hydraulic lime-based grout, were tested under monotonic and cyclic compression. Four single-leaf panels (wall F) were also tested for a good insight into the structural behaviour of each one of the leaves that compose the studied typology of wall. The specimens were instrumented with linear potentiometric displacement transducers in all sides as shown in Figure 1.

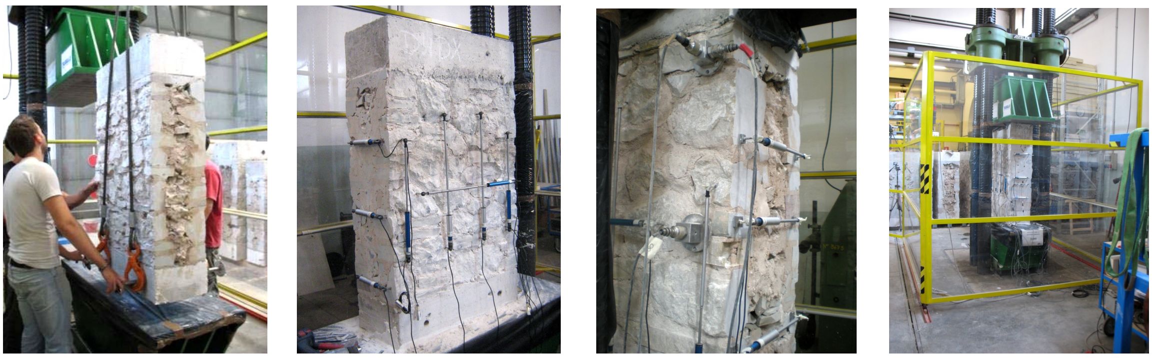


Fig. 1 Setup and instrumentation of the specimens

2.2. Evaluation and interpretation of results

The experimental results obtained from the performed monotonic and cyclic compression tests were used for a comparison of the overall behaviour of all specimens. The resumed results of these tests are presented in Table 1 and Figure 2, namely the maximum compressive strength of the specimens (σ_{max}), the stress level corresponding to the first crack appearance ($\sigma_{1,cr}$), the mean values of the elastic modulus computed considering the intervals between 30% and 60%σ_{max}, ($E_{30\%-60\%}$) as well as 10% to 40%σ_{max} ($E_{10\%-40\%}$) and the Poisson ratio in both longitudinal (ν_L) and transversal direction (ν_T) of the panels.

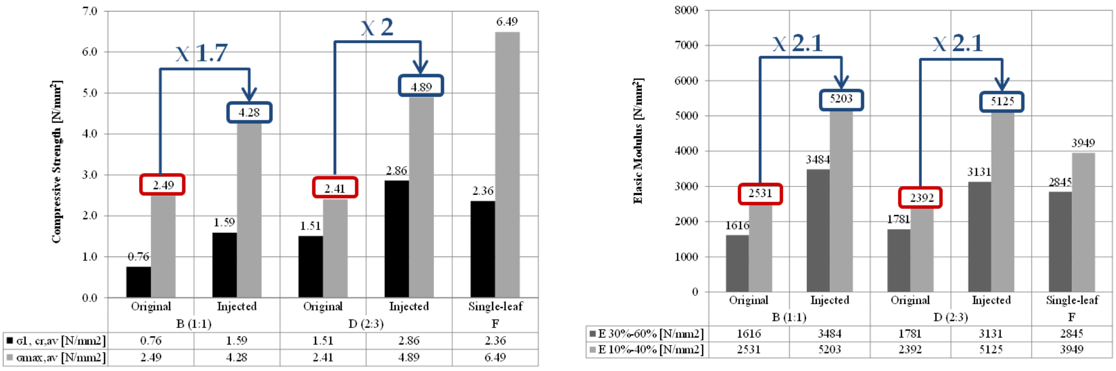


Fig. 2 On the left: average σ_{max} and $\sigma_{1,cr}$ for all specimens. On the right: elastic modulus values obtained for all the tested panels under monotonic and cyclic compression at 10%-40% and 30%-60% σ_{max} for all specimens

Table 1 Mechanical properties of the panels subjected to compression (monotonic and cyclic). **Not reliable*

MONOTONIC TESTS									
Panel	**Scale**	**Condition**	σ_{max} [N/mm^2]	$\sigma_{1,cr}$ [N/mm^2]	$\sigma_{1,cr}$ [%]	$E_{30\%-60\%}$ [N/mm^2]	$E_{10\%-40\%}$ [N/mm^2]	ν_L [–]	ν_T [–]
B3	**1:1**	**UR**	2.1	0.4	21.0	1770	2885	0.044	0.030
B6		**R**	4.2	0.7	16.3	4421	4103	0.060	0.042
D2	**2:3**	**UR**	2.8	1.6	57.5	1364	2813	0.028	0.122
D4		**R**	5.4	4.4	81.0	3197	5030	0.013	0.020
F4	**Single-leaf (1:1)**	**UR**	6.5	1.2	18.9	1789	1691	*	–
CYCLIC TESTS									
Panel	**Scale**	**Condition**	σ_{max} [N/mm^2]	$\sigma_{1,cr}$ [N/mm^2]	$\sigma_{1,cr}$ [%]	$E_{30\%-60\%}$ [N/mm^2]	$E_{10\%-40\%}$ [N/mm^2]	ν_L [–]	ν_T [–]
B1	**1:1**	**UR**	2.9	0.7	24	1487	2415	0.025	0.042
B2			2.5	1.1	46	1591	2294	0.069	0.061
B4		**R**	3.7	2.0	54	2404	4725	0.089	0.867
B5			4.9	2.1	43	3628	6781	0.003	0.288
D1	**2:3**	**UR**	2.2	1.4	64	3427	3427	0.010	0.122
D3			2.2	1.5	68	2033	2636	0.669	*
D5		**R**	4.0	2.7	66	3385	5708	0.012	0.123
D6			5.3	1.6	30	2810	4637	0.091	0.515
F1	**Single-leaf (1:1)**	**UR**	5.8	2.8	48	2536	3418	0.005	–
F2			6.7	2.6	39	2319	3486	0.008	–
F3			7.0	2.9	41	3681	4944	0.188	–

From this experimental study the following main conclusions were drawn: After consolidation an increase of approximately 2 times of the compressive strength was observed in all specimens, the average elastic modulus of the panels (unstrengthened and strengthened) is approximately the same with an increase of approximately 2 times after the consolidation procedure. Although the injected panels exhibited higher deformability at σ_{max}, the increase started for higher levels of stress, compared to the non-injected panels which exhibited their maximum strain gradually. This is very important as it proves that the injection intervention is mechanically compatible with the original panels and, at the same time, it increases its performance by delaying the opening of the leaves.

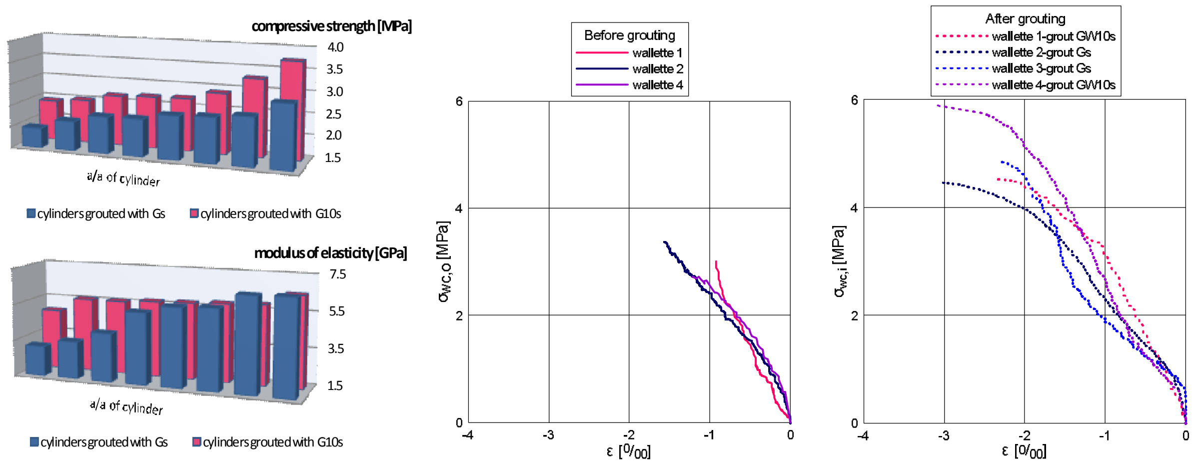
2.3. Compression tests by National Technical University of Athens

The purpose of the series of tests carried out was to (a) check the efficiency of a natural hydraulic based grout made with St Astier NHL 5 and superfine natural pozzolan (for details see [2]), (b) to enrich the database on the behaviour of three leaf masonry in compression and (c) to obtain more data on the behaviour of grouted filling material. Thus, four wallettes (scale 2:3) made of three leaf rubble stone masonry were constructed, as well as 16 cylinders made of filling material [2]. For the construction of the stone walls, a strong limestone was used (compressive strength equal to 100 MPa), whereas the mortar was a lime-pozzolan one. The wallettes were tested in compression before and after grouting. For each wallette, vertical stresses, vertical strains, horizontal deformations and transverse deformations were measured. The cylindrical specimens were tested only after grouting. Curves of vertical stress vs. deformation measurements were drawn for each cylinder. The mixes used for grouting of wallettes and cylinders were a) pure NHL5 grout (Gs) and b) NHL5 plus 10% superfine natural pozzolan, commercially available as μ-silica W type (GW10s).

2.4. Evaluation and interpretation of results

The experimental results on cylinders showed that for the grout mixes that were used, comparable mechanical properties of the grouted infill material were achieved (see Fig. 3a). Moreover, significantly higher values of the modulus of elasticity were obtained within this study as compared to those available in the literature. This was attributed to the high compressive strength of the stones.

As far as the wallettes are concerned, the typical behaviour of three leaf masonry [3], before and after grouting, was fully confirmed. The failure mode of wallettes implied vertical cracks on the faces of the wallettes, as well as vertical cracks within the thickness of masonry. Failure was due to the separation between exterior leaves and infill material and to the subsequent out-of-plane bending of the exterior leaves (Fig. 3). With the exeption of one wallette, in which an extensive cracking on the faces of the wallette was occurred (wallette 4 after grouting, Fig. 3), the failure mode of the remaining three wallettes was similar to that observed in the same wallettes before grouting. However, the opening of transverse cracks was significantly delayed. In terms of mechanical properties, it was clear that both grout mixes were efficient in enhancing the compressive strength of three leaf masonry (Fig. 3b, 3c). Actually, independently of the grout mixed used, grouting led to a significant improvement of the compressive strength of masonry (by 32 to 115%).



(a) (b) (c)

Fig. 3 (a) Compressive strength and modulus of elasticity (measured at 30% of the compressive strength) of grouted cylinders at the age of 180 days; Vertical stress vs. vertical strain curves for wallettes 1 to 4 (b) before grouting and (c) after grouting

FRONT FAÇADE C SIDE FAÇADE D FRONT FAÇADE C SIDE FAÇADE D

Fig. 4 Failure mode in compression before (red line) and after (blue line) grouting of a) W. 2 and b) W. 4

By the interpertation of the obtained curves, the latter was explained [2] by the enhancement of the properties of the infill material, as well as by the improvement of the bond properties between the exterior and interior leaves. Moreover, higher values of compressive strength were exhibited by wallettes grouted with mix GW10s thanks to the better bond properties achieved in the interfaces between this type of mixes and in-situ materials. Another positive result was that the strain of grouted masonry at failure was significantly larger than that of the ungrouted masonry (see Fig. 4b, 4c). Finally, it is important to note that the use of hydraulic lime based grouts did not lead to an increase of the stiffness of masonry. In some cases, reduced modulus of elasticity were obtained due to the fact that masonry was grouted after the occurrence of damages. The experimental results confirm that for this type of masonry, the main failure mechanism is the separation of the three leaves and to the consequent out-of-plane deformation of the external leaves. Moreover, in general, it was observed that grouting did not lead to the modification of the failure mode of the wallettes. In terms of mechanical properties, it was observed that both grouts were efficient in improving significantly the compressive strength of the wallettes, as well as its deformability, without modifying the stiffness of masonry elements. Thus, it was confirmed that the use grouts with low compressive strength (hydraulic lime based grouts) for strengthening of historic masonries, ensures both a mechanically efficient and durable intervention.

3. EARTH BLOCK MASONRY, RAMMED EARTH AND COB WALLS STRENGHTENED WITH TEXTILE BELTS AND GROUTING

3.1. Diagonal compression tests by Federal Institute for Material Research and Testing

Strengthening techniques were investigated on different types of earthen wall elements in form of static loading experiments. The types of wall segments considered in the experiments consisted of one leaf masonry of adobe (earth block masonry) in combination with earth mortar and monolithic walls in form of rammed earth and cob specimens. The grouting mortar consisted of a lime based material with pozzolanic additions. The original idea for the belts was to introduce a vertical element for walls in order to take up horizontal loads which result in a shear response of the building element. Therefore, the reinforced specimens were tested in diagonal compression. For fixing the belts into the specimen three adhesives were tested on cob specimen: Polyurethane foam, epoxy resin and commercially available hydraulic repair mortar. From these tests, the hydraulic repair mortar proved to be the material with the best performance and the least intrusiveness. This material was therefore used for rammed earth and earth block masonry retrofitting. It has to be considered, that vertical cuts into the samples for fixing the belts are points of weakness and have to be mitigated by the adhesive. Two retrofitted earth block panels were tested, which were prepared with wetted earth blocks. One retrofitted sample showed an above average shear strength of 0.42 MPa. However, with this panel the set of displacement transducers did not work properly to the end of the deformation.

(a) (b) (c) (d)

Fig. 5 Failure modes of the retrofitted rammed earth specimen. (a) Polyurethane foam adhesive (b) epoxy resin adhesive (c) hydraulic repair mortar adhesive (d) grouting

The other panel exhibited average shear strength of ca. 0.37 MPa but showed a much higher strain. Both panels showed strain values which were much higher than with the unretrofitted panels. This was due to the action of the belts, which went into action enabling a better stress distribution over larger deformations and mitigating the brittle behaviour of the earth block panels. Even after total failure of the panel the belts hold most of the building blocks in place. The cuts for the belts had no effect on the crack development during loading. Most of the shear cracks of both specimens went perpendicular to the belts. A better performance with higher shear values might be reached by modifying the placement of the belts in the panels. For both panels the cuts were made in the earth blocks and not in the joints (except for the horizontal joints). If the belts would be placed in the vertical joints an increase in shear strength could be expected. In case of rammed earth panels the belts were inserted perpendicular to the compaction layers of the panels. Both panels had lower shear strength values as the average unretrofitted samples. However, maximum strain of both samples was increased compared to the panels without belts. The failure in the retrofitted rammed earth specimen occurred partially at the cuts were the belts were inserted (Fig. 5). Certainly the cuts were weakening the specimen and this was not entirely compensated by the adhesive in form of the repair mortar. The failure mode was also enhanced by the diagonal loading which was not correctly perpendicular to the belt system but rather supported the course of the cracks in the cuts. A rammed earth panel from a previous diagonal compression test, which was cracked but still in one piece was subjected to grouting with the hydraulic mortar. The crack width was not more than 1 mm. Before injection, holes were drilled into the crack system for improving grout penetration and for the packers. The panel was then subjected to another diagonal compression test. The comparison of the test results before and after groutingshows clearly that theoriginal shear strength could not be regained by grouting. However, around 20% of the original value was reached in the shear test. Earth based materials are fairly difficult to structurally repair by grouting. Usually, the elastic modulus has to be limited in order to not introduce a stiff element. But by this restriction it is also difficult to introduce a grout which fulfils all the requirements concerning adhesion and tensile strength.

3.2. Evaluation and interpretation of results

Results from the diagonal compression tests of the retrofitted samples in comparison to the not retrofitted specimen are listed in Table 2. The results indicated that the type of retrofitting technique by belts has a lesser impact on the shear strength but more on the strain capacity. In almost all retrofitted samples with repair mortar as an adhesive (R-RM in Table 2) the shear modulus was reduced and the strain after failure was usually extended. This was in particular evident with earth block masonry, where unretrofitted specimen were suddenly collapsing but retrofitted samples showed a distinctive post failure displacement. The repair mortar as an adhesive performed best in the experiments. The bond towards the polyester belt and earth was satisfying but could certainly be improved by fine adjusting the mortar. From the mechanical point of view, the retrofitting method seems not to increase stiffness of the structure at all but enlarges the strain capacity.

Table 2 Comparison of the diagonal compression test data for not retrofitted and retrofitted panels (R-RM = retrofitted with belt and repair mortar; R-PU = retrofitted with belt and polyurethane foam; R-ER = retrofitted with belt and epoxy resin; G = repaired by grouting)

	Shear strength τ_u [MPa]		**Shear modulus $G_{1/3}$ [MPa]**		**Shear strain $\gamma_{1/3}$ [%]**	
	Mean	**STD**	**Mean**	**STD**	**Mean**	**STD**
Earth block masonry	0.34	0.06	660	246	0.020	0.011
Earth block masonry (R-RM)	0.36	0.08	120	124	0.192	0.170
Rammed earth	0.71	0.11	2326	710	0.011	0.003
Rammed earth (G)	0.16	–	52	–	0.105	–
Rammed earth (R-RM)	0.58	0.00	1211	347	0.017	0.005
Cob	0.50	0.10	420	137	0.041	0.006
Cob (R-PU)	0.36	–	301	–	0.040	–
Cob (R-ER)	0.79	–	608	–	0.043	–
Cob (R-RM)	0.51	0.06	306	99	0.058	0.012

In case of earthquakes, this means that an earthen building might still be damaged but it can hold together a longer time and increase the escape period for their inhabitants. The approach for retrofitting the earthen elements by polyester textile belts, which were glued vertically into the walls, showed in general a good performance. They acted by increasing the strain capacity of the samples under shear stress. However, more tests on this retrofitting technique are needed in order to investigate the bond behaviour between belt, adhesive and substrate. Furthermore important are the ratio of width of belt and wall as well as the frequency of vertical belts per meter of wall length to be inserted to get an optimal performance.

4. ADOBE MASONRY WALLS STRENGHTENED WITH WIRE ROPES AND GEONETS

4.1. In plane cyclic tests by Institute of Theoretical and Applied Mechanics

The experimental tests consisted of in-plane shear tests on masonry walls strengthened with different techniques and subjected to a combination of compression and cyclic shear loading.

Table 3 Wire steel ropes and geo-nets specifications

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 × 45
Geo-nets – polyester (PET) Miragrid GX 35/35(TENCATE)	–	–	35 kN/m (both directions)	25 × 25

Masonry specimens were made with bricks of different materials. In particular, adobe, burned clay bricks and dried lay bricks were used. Two examples using adobe material are given in this section for illustration and for the sake of brevity. The reinforcing systems was realized using steel wire ropes mechanically fastened to the wall and disposed according to an X shape see Fig. 6 and using geonets fastened to the walls and Table 3 for material details. The reinforcement was done on both surfaces of the wall. Also the retrofitted technique by means of used reinforcement method has been on the applied on previously damaged walls.

4.2. Evaluation and interpretation of results

The tests carried out and the graphs show several important results. It has been shown that steel wire ropes on an adobe wall surface increase significantly the load-carrying capacity of the wall under horizontal load. It was observed that the strengthening system leads to an increment of strength by 60%, see Figure 6. The effectiveness of the system is evident also in terms of increment of the displacement capacity of the wall. This type of reinforcement is relatively cheap with respect both to material and work and it is the most efficient from the point of view of the load bearing capacity from all the used method. Almost the same improvement can be achieved using geo-nets, even with lower costs. In Figure 6, the force-displacement curves for the unreinforced wall and for the wall reinforced with geo-net are plotted in the same graph. It is observed that the application of the reinforced mortar layers onto the wall's surfaces allows the specimen to reach a higher value of strength, with an increment of about 20%. Moreover, an increment in terms of ductility is also registered. Geo-nets have also good ratio of strength to the strength of the bricks and, therefore, they are favourable to be applied. Moreover, u nlike in the case of steel wire ropes, there is not such a danger of pulling out the reinforcement in the out-of plane. The geo-nets have been used also for the retrofitting on the damaged specimens applying them on the damaged (control) wall. The results from one example are shown in Figure 6. Comparing the force-displacement curve of the retrofitted wall by means of geo-nets (PET) with the unreinforced adobe brick wall, it has been observed that the strengthening allows the specimen to reach the original wall strength in almost 70%. Naturally, the stiffness of the retrofitted wall is lower than the stiffness of the control wall after the intervention. The reinforcement of the adobe wall using Poly-Propylene nets significantly increased load capacity of the wall similarly to the case of Poly-Eethylene nets. The comparison of results of both types of geo-nets showed almost the same behaviour and capacity of the walls. Nevertheless, the reinforcement using PP geo-net gave higher resistance of the wall on cyclic loading for partially damaged specimens. The reinforcements using wire ropes and geo-nets were very effective for all types of tested walls. Used reinforcements significantly increased the strength and load-carrying capacity on cyclic horizontal loading. From this point of view steel ropes are a bit more effective than geo-nets. On the other hand the geo-nets provide compactness of the material of the wall even after the partial damage. All tested types of reinforcement could improve the resistance of the wall as a part of the historical structure to earthquake and extend the general lifetime of the whole structure.

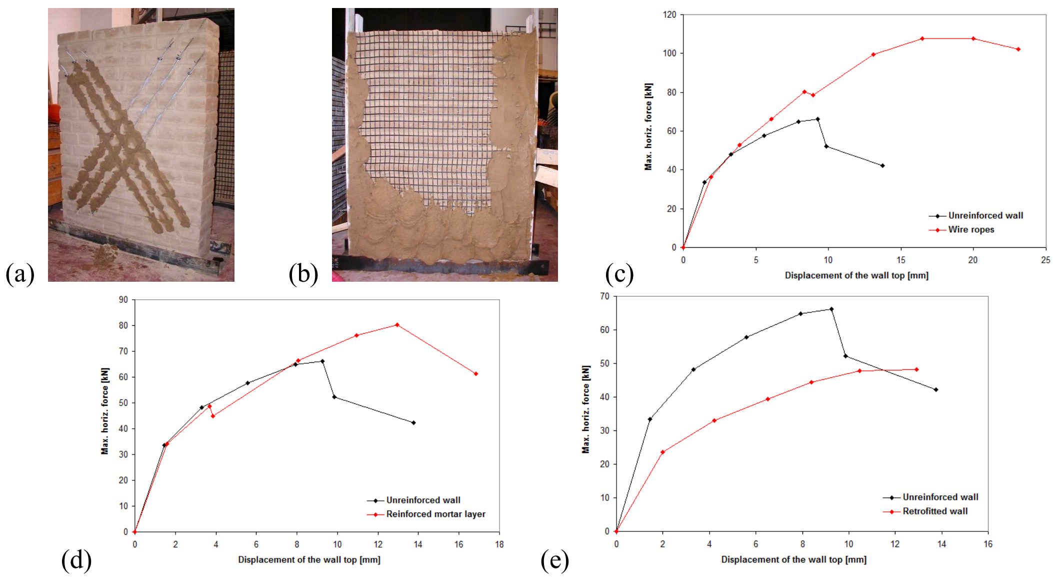


Fig. 6 (a) Reinforced adobe wall with steel ropes. (b) Reinforced adobe wall with geonets. (c) Behaviour of the wall strengthened with steel wire ropes compared to the unreinforced wall (d) Behaviour of the wall strengthened with geonets. (e) Behaviour of the retrofitted adobe wall by geonets to the unreinforced wall

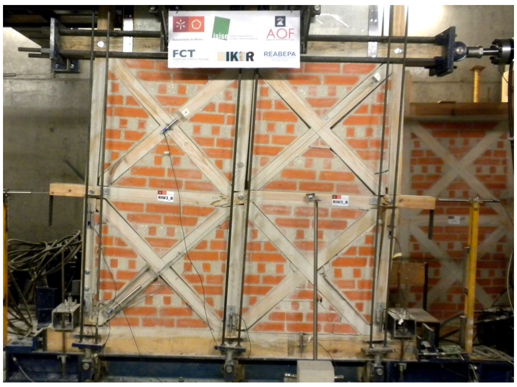
5. HALF TIMBERED WALLS STRENGHTNED WITH STEEL PLATES AND BOLTS

5.1. Cyclic tests on strengthened walls by University of Minho

Half-timbered structures represent an important historical heritage that has to be preserved. Examples of this structural typology are present in many countries around the world. In Portugal, timber frame walls infilled with brick or rubble masonry are typical constructive elements dated from the reconstruction of Lisbon city after the earthquake of 1755. The idea of using these timber frame walls was to improve the seismic behavior of masonry structures by providing high dissipative shear walls, which act also as a connecting elements to the masonry façades, aiming at improving the out-of-plane of the overvall structure. Given the reduced results available in the literature and in the scope of the NIKER project, an experimental programme was defined in order to evaluate the cyclic performance of timber frame walls. The experimental programme encompasses static cyclic tests on unreinforced and retroffited specimens. The lateral behavior of these walls is higly dependent on the behavior of the connections and thus the lateral resisting properties can be enhanced by strengthening the traditional connections. Different types of reinforcement were considered for the walls, namely steel bolts and stell plates The retrofitting techniques were applied directly on unreinforced walls previously tested under cyclic loadings. It was decided to test full scale timber frame walls and reproduce typical traditional connections, see Figure 7a. The walls were tested as cantiliver walls. The vertical loads, compatible with real values possibly transfered by the pavements were applied directly on the vertical posts by three hydraulic actuators. The horizontal load was measured by an horizontal servo-controlled actuator connected to a reaction wall by an hinge and to the top of the walls by a steel plate and four steel bars as can be seen in Figure 7b. The static cyclic tests was carried out under displacement control. The displacement time history used for retrofitted walls was the same as that applied on the unreinforced walls.

5.2. Evaluation and interpretation of results

A distinctively different behaviour can be noticed with a varying vertical pre-compression. The typical S-shape curve of a flexural response with a rocking mechanism at the bottom of the wall was evident for the walls subjected to a lower vertical load level whilst a predominant shear behaviour was encountered in walls under a higher vertical load level. The walls exhibited, for low vertical load levels, a highly predominant flexural behaviour. They reached the maximum load level at a horizontal displacement of approximately 50 mm and the subsequent loss of capacity was 20% of the maximum load or less. Due to the connection type, the vertical posts uplift during the test and the wall rocks back and forth. When a higher vertical pre-compression level was applied, the prevailing mechanism was shear, but the flexural mechanisms was still present, as can be seen from the amount of vertical uplift of the lateral posts, which was lower (42%) if compared to the wall subjected to a lower vertical load.

(a) 

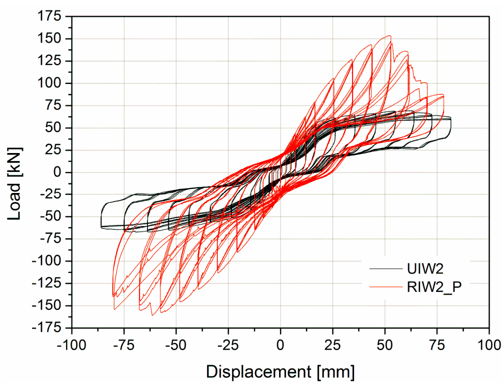
(b) 

Fig. 7 Details of the experimental testing; (a) experimental setup; (b) force-displacement diagrams for the wall retrofitted with plates (lower vertical load level)

The walls tested under a higher vertical load level reached their maximum capacity at approximately the same horizontal displacement, but the post peak loss of capacity was higher. In the hysteretic curves of the walls, the change in stiffness that can be observed in the unloading path, occurred when the vertical uplift of the bottom connections returned to be zero, thus increasing the stiffness of the wall, as more resistance was given by the posts [3]. For the lower vertical load, the walls did not present significant damage, but became significant for the walls tested under higher load. While the walls subjected to the lower level failed due to the opening of the bottom connections, with the vertical posts uplifting at the bottom the higher loaded walls failed due to shear in the central connection with wood crushing. The bottom connections tended to open and uplift in this case too, but they did not control the general wall failure. In the case of strengthening done with bolts, the improvement in terms of load capacity, energy dissipation and ductility was not overly significant. For the lower vertical load level, the retrofitted wall experienced a gain in terms of load capacity of 24%, while for the wall subjected to a higher vertical level there was no gain but the wall regained its initial capacity and improved in terms of energy dissipation. The insertion of bolts did not influence the overall behaviour of the walls. The response of the wall was characterized by a combination of flexural and shear mechanisms, the posts continued to uplift, though the vertical uplift decreased of 40% when compared to the unreinforced condition. The main advantage was that the connections were now unable to open out-of-plane, thus allowing them to function until the ultimate displacement, whereas in the unreinforced specimen, the opening of the connection effectively caused that connection to cease working properly. Analysing the behaviour of the walls strengthened with steel plates, it was observed how this type of strengthening highly stiffened the wall, see Figure 7b. The gain in load capacity for the wall subjected to the lower vertical load level was of 121% when compared to the unreinforced condition. The plates did not show great deformations, but the holes of the bolts generally became oval, especially the ones corresponding to the diagonal elements of the central connection, which were the elements that worked more as they pushed and pulled the central connection, and those of the bottom connections, since those were the ones which normally tended to uplift more.

6. CONCLUSIONS

The strengthening of walls in existing buildings needs to be focused on two main aspects: use of effective technological solutions and the preservation of the original characteristics of the historical substrate. Strengthening interventions adopting traditional materials with traditional techniques and the use of innovative materials need to be used taking into account their mechanical and chemical compatibility with existing materials, easy application and limited costs. Moreover durability and removability aspects can not be neglected. The techniques presented in this paper, mainly focused on the use of composite material and grouting, showed an improving of both load and displacement capacity. In general, it was observed that strengthening techniques adopted did not lead to the modification of the failure mode of structural elements tested. In most of cases, in terms of mechanical properties, they were efficient in improving significantly the compressive strength, as well as the deformability, without modifying the stiffness of structural elements.

REFERENCES

[1] Tassullo S.p.A. (2011). Tassullo Trento, Italy – Available at: http://www.tassullo.it.

[2] Adami C.-E., Vintzileou E., Mouzakis Ch., Badogiannis E., Kalagri A. (2012) The effect of hydraulic lime pozzolanic grouts on the mechanical properties of three-leaf stone masonry in compression, *8th International Conference on Structural Analysis of Historical Constructions*, October 15-17, Wroclaw, Poland, 2012.

[3] Poletti E, Vasconcelos G. (2012) Seismic behaviour of traditional half timbered walls: cyclic tests and strengthening solutions, *8th International Conference on Structural Analysis of Historical Constructions*, October 15-17, Wroclaw, Poland, 2012.