THE USE OF POLYMERIC GRIDS FOR THE SEISMIC ENHANCEMENT OF BRICK MASONRY BUILDINGS

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SUMMARY

The performance of masonry walls reinforced using polymeric grid embedded into plaster layers as a tools for the seismic enhancement of brick masonry buildings has been investigated by experimental tests. The results of the experimental campaigns are presented and discussed.
Based on the experimental data and on the results of detailed numerical simulations, simplified models to be used as tools for the design of the retrofitting intervention are proposed. The models properly consider the so called "first mode" and "second mode" collapse mechanisms as well as the grid effect in the evolution of the above mentioned mechanisms.
Restoration and conservation issues relevant to the application of the proposed methodology to historical building and cultural heritage are also presented and discussed.

1. INTRODUCTION

The insertion of steel reinforcement into the plaster layers for the seismic rehabilitation of masonry structures is a technique that has been widely used in the last decades, although often criticised because of some intrinsic contradictions and limitations mainly related to its actual retrofitting efficiency and durability. Recently, other plaster reinforcements have been proposed in literature and are available on the market, like those using light carbon grids included into thin cement plaster layers. Polymeric reinforcements could also be employed as retrofitting tool in the seismic upgrading of masonry buildings and could represent an alternative retrofitting system able of overcoming some deficiencies of the other reinforcements (e.g. steel corrosion) and being more effective in terms of cost-benefit. The basic underlying idea in the use of polymeric grids is that they could improve the performance of the masonry by increasing its strength and its ductility.

2. SEISMIC BEHAVIOUR OF MASONRY BUILDINGS

Notwithstanding masonry buildings usually represent the simplest constructions configuration and require a very poor constructive technology, their seismic behaviour show elements of complexity greater than those typical of new structural configurations associated to the modern materials, like steel and reinforced concrete frames.
In masonry constructions, the ordinary structural configuration consists of a three-dimensional assembly of mass-distributed plane elements that are characterised by a twofold behaviour when horizontal inertia forces are induced by earthquake attacks. The forces in the plane of the panels, combined with those exerted by vertical loads, induce a membrane behaviour with in-plane normal and shear stresses, while the actions orthogonal to the panel induce a plate behaviour with out-of-plane bending and shear. The stress status in the members is complex and strongly influenced by the in-plane deformation of the element and by its interaction with the neighbouring elements. Masonry is indeed a composite material whose behaviour depends on the macroscopic mechanical characteristics: tensile and compressive strength, elastic and shear modulus. The tensile strength is practically

null; this can easily induce cracks on the surfaces subjected to tension, causing a subdivision of the panels into separate portions that can transform sections of the building in kinematisms, so that each rigid portion can move with respect to the other till the structure's collapse. Such mechanisms can develop in the plane of the panels as well orthogonally, giving rise, respectively, to the so called first and second mode collapse mechanisms [1], as shown in Figure 1.

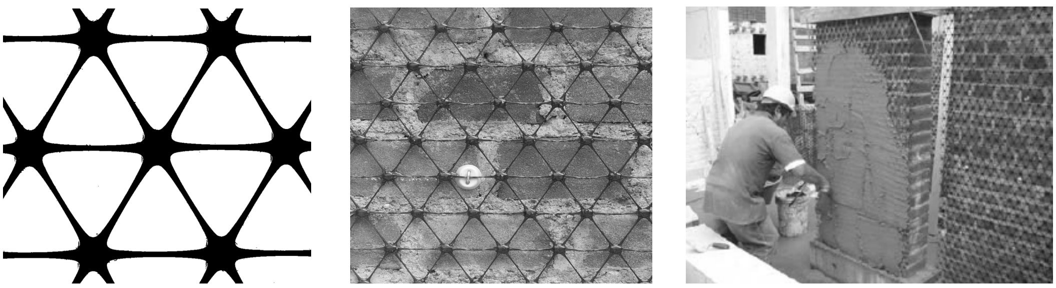
Figure 1. Failure modalities of masonry elements (left: 1st mode mechanism, right: 2nd mode mechanism)

The first mode mechanisms are priorities, being characterised by a limited, or even absent, ductile behaviour and because they can be activated as a consequence of the lack of continuity in panels cracked by second mode failures. They are typical in the large and continuous building complexes of the historic centre. Moreover, the texture of the masonry, associated with the dimensions and the organization of the blocks, can induce other behaviours characterised by the loss of integrity of the structural elements that can collapse for the breaking of the internal links among the blocks.
The seismic behaviour of a masonry building depends on three fundamental performance issues to be guaranteed:

- the preservation of the global integrity, with no separation into macro-elements, thus allowing for a box-like behaviour with a redistribution of the horizontal forces among all the resisting elements;
- the capability of all the members to resist the forces induced by the seismic actions, i.e. the capability of sustaining the induced forces without reaching the ultimate displacement;
- the capability of the panels not to develop collapse mechanisms associated to the evolution of the kinematisms and the loss of integrity.

3. SYSTEM DESCRIPTION

The retrofitting system presented in this paper consists in the insertion of a polymer grid embedded into a thin lime based mortar plaster. The grid is the "RichterGard RG TX" one, a stiff monolithic polymer grid with integral junctions, characterised by an isometric geometry resulting in apertures of equilateral triangles. Figure 2 shows the grid and its installation.



(a) grid (b) installation of the grid (c) plastering

Figure 2. Characteristics of grid and its installation

4. EXPERIMENTAL ACTIVITIES

A pre-requisite for the use of the proposed retrofitting technique is the assessment of the effectiveness of plaster reinforcement strengthening tool. A series of tests, mainly aimed at evaluating the actual influence of the grid in the mechanical behaviour of the reinforced element, with particular attention to its response to the horizontal actions, were carried out. A detailed description of the tests is given in [2], [3] and [4]. Four testing campaigns, each one including one or more series of tests, have been planned and executed; they consisted of:

- diagonal compression tests on brick masonry squared panels;
- shear compression tests on brick masonry rectangular panels;
- out-of-plane tests on brick masonry large panels;
- shear and flexural tests on complex 3D elements.

4.1. Diagonal compression tests

Six groups of 3 panels, for a total number of 18 panels, were manufactured and tested, according to the ASTM standard [5]. Panels were made of solid bricks coming from current industrial production. The mortar used for the layers was a mix of cement, lime and coarse sand in a 1:2:9 volume proportions, with an average strength of 8.0 MPa. The nominal thickness of the plaster layers was 20 mm; its actual thickness turned out to be varying between 20 and 25 mm. The plaster mortar was a mix of cement, lime and coarse sand, with a volume proportion of 1:1:5 and an average compressive strength of 9 MPa. Panels' dimensions were 1200 x 1200 x 260 mm. Particular attention has been paid to the grid installation in order to obtain its correct positioning within the plaster. To enhance plaster bonding, joint mortar have been scarified before applying the plaster. Table 1 reports the details of the tested panels.

Table 1 – Characteristics of panels for diagonal compression tests

Group	Number of panels	Panel's ID	Plaster	Grid
1	3	#1, #2, #3	No	No
2	3	#4, #5, #6	Yes	No
3	3	#7, #8, #9	Yes	One side
4	3	#10, #11, #12	Yes	Both sides
5	3	#13, #14, #15	Yes	Both sides (*)
6	3	#16, #17, #18	Yes	Both sides (*)

(*) a different grid type has been installed

Each panel has been subjected to cyclic loading in subsequent runs of increasing amplitudes (namely 30%, 60%, 80% of the nominal ultimate load) and then up to collapse.
For each tested panel, a diagram of shear stress vs. shear distortion has been produced. The diagram of panel #3 (bare panel) is reported in Figure 3 as a reference.

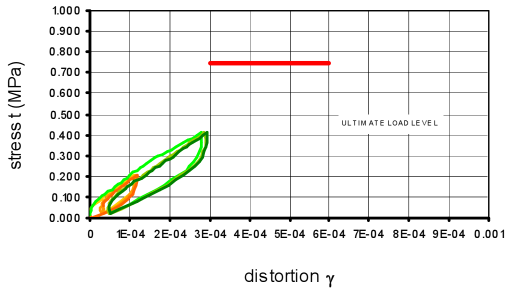


Figure 3. Diagram of shear stress vs. distortion for panel #3

The plastered unreinforced panels (Group 2) showed a significant increase of the ultimate shear strength with respect to the bare panels; this result has been mainly attributed to the contribution of the plaster to the global strength. The reinforced panels (Group 4) showed ultimate shear stresses practically equal to the plastered unreinforced ones, with only a slight increase given by the presence of grid that positively contributed to the panel strength. The main grid role was played on the ultimate deformations of the panels, that turned out to be strongly influenced by the presence of the reinforcement, as it clearly appears from the diagram reported in Figure 4-left.

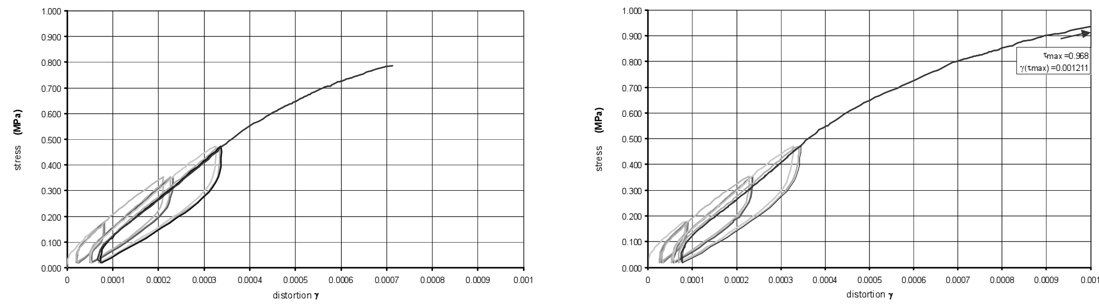


Figure 4. Diagrams of shear stress vs. distortion of panels #6 (plastered unreinforced) and #12 (double reinforcement)

The ultimate deformation was actually increased by a factor of 2 to 3, thanks to the grid presence. It can therefore be conclude that the grid added a positive contribution the global ductility of the wall.
Considering the cyclic characteristic of the seismic response, an important factor for the protection of structural elements is their ability of dissipating energy. The absolute value of the energy dissipated in a single cycle does not constitute a representative parameter for comparisons among different specimens; a more representative parameter is given by the so called "Cycle Dissipating Efficiency", CDE = A_c/A_r, computed as the ratio of the area of the cycle, A_c, to the area of the rectangle external to the cycle, A_r (Figure 5).

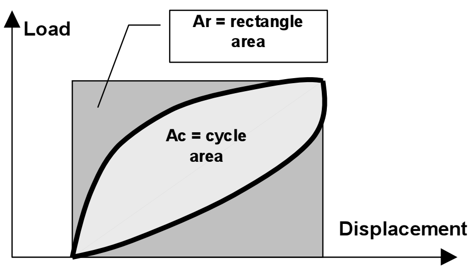


Figure 5. Graphic representation of the CDE factor

From the data analysis it was found that the grid does not increase the energy dissipation capability of the panels for load cycles lower than the 60% of the actual panel's ultimate load: in the testing conditions the grid is still performing in the elastic range and the cracks are quite closed.
Looking at the load-displacement paths of the instruments on the two faces of the Group 3 panels, i.e. those reinforced on a single side, it was noted a significant difference on the response of the instruments on the two faces that can be attributed to the different stiffness of the two plaster layer. The reinforced layer is probably stiffer because of the presence of the grid and the increment of the plaster thickness due to the grid inclusion. The ultimate load decreases, due to the load eccentricity causing a non uniform stress status within the panel.

4.2. Shear-compression tests

Three groups of 4 panels, for a total number of 12 panels, have been manufactured and tested. For each group, two panels were subjected to 0.50 MPa axial load and two panels to 0.75 MPa. Table 2 reports the characteristics of the experimented specimens. The dimensions of panels were 1200 x 1200 x 220 mm. Panels were made of solid bricks having dimensions 110x220x70 mm. Different mortars have been evaluated for masonry joints and plasters in order to simulate a hypothetical retrofitting situation where the plaster mortar is stronger than the joints one. The mortar for the layers was a mix of cement, lime and coarse sand in a 1:2:7 volume proportions, with an average strength of 4.21 MPa. The nominal thickness of the plaster layers was set to 20 mm. The mortar for the plaster was a mix of cement, lime and coarse sand, with a volume proportion of 1:1:5 and an average compressive strength of 7.12 MPa. Figure 6 shows the scheme and setup of the test.

Table 2 - Characteristics of panels for shear-compression tests

Group	Number of panels	Panel's ID	Plaster	Grid	Compression stress [MPa]
1	2	#1, #2	No	No	0.50
	2	#3, #4	No	No	0.75
2	2	#5, #6	Yes	No	0.50
	2	#7, #8	Yes	No	0.75
3	2	#9, #10	Yes	Both sides	0.50
	2	#11, #12	Yes	Both sides	0.75

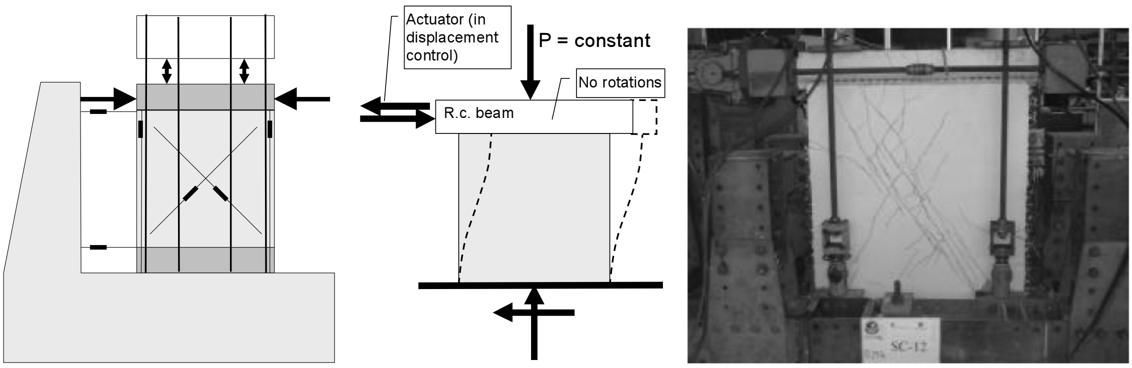


Figure 6. Test set up of the shear-compression tests

Panels were subjected to horizontal cyclic loads, applied under displacement control, constant vertical load and top rotations constrained. The first run consisted of 3 cycles up to 50% of the estimated ultimate load. The cycle amplitude was increased by 30% for each subsequent triplet of cycles. After the third triplet, the load was increased up to panel's failure.

The results from shear-compression tests basically confirmed those from the previous diagonal-compression tests. An important consideration can be derived by looking at the reinforced panels' conditions at failure with respect to the bare and unreinforced ones. Even if the failure modalities are similar, bare and unreinforced panels show very "clean" cracks approximately along two diagonals of the panel, while the reinforced panel is characterised by a widespread net of cracks (Figure 7). This effect suggests that the panel's collapse requires the formation of a large number of failure surfaces and, therefore, an higher value of the ultimate strength.

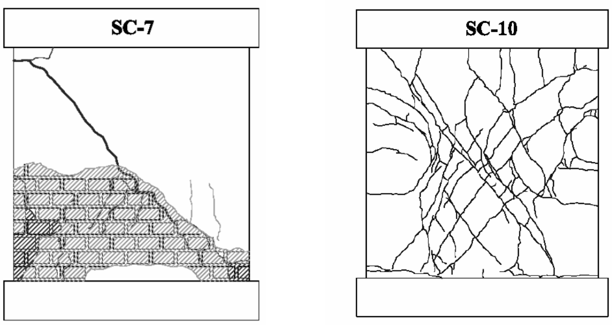


Figure 7. Crack pattern in panel SC-7 (unreinforced) and in panel SC-10 (reinforced)

The shear-compression tests also confirmed the positive effect of the grid on the ductility of panels; the analyses of the shear-displacement curves of the reinforced panels showed a good ductile behaviour of the panels as well as a significant energy dissipation capacity.

4.3. Stability tests

Six groups of 2 panels, for a total number of 12 panels, have been manufactured and tested. Table 3 reports the details of the samples. The panels are 800 mm wide, 1600 mm high and 220 mm thick. The materials and construction techniques are similar to those of the shear-compression tests. Figure 8 shows the scheme, with the LVDT instrumentations, and the actual setup of the test. The tests aimed at reproducing the out-of-plane collapse mechanisms.

Table 3 - Characteristics of panels for stability tests

Panel's ID	Plaster	Grid	Panel's ID	Plaster	Grid
F1	Both sides	No	F7	No	Tension side
F2	Both sides	No	F8	No	Tension side
F3	No	No	F9	No	Tension side
F4	No	No	F10	No	Compression side
F5	Both sides	Tension side	F11	Both sides	Tension side overlap
F6	Both sides	Tension side	F12	Both sides	Tension side overlap

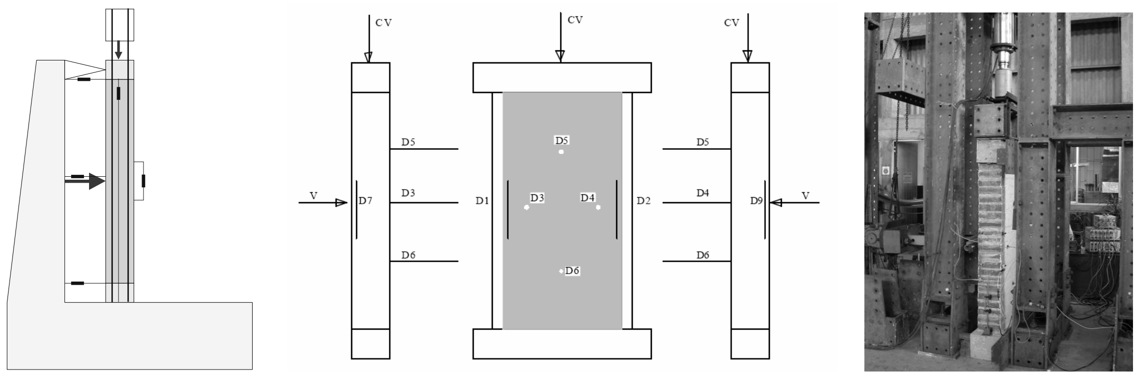


Figure 8. Test set up of the stability tests

The tests carried out clearly demonstrated the positive effects of the grid reinforcement on all the significant mechanical parameters of the panels, i.e. on ultimate load, ultimate displacement and energy dissipation. The spread distribution of the crack patterns, already observed in shear compression tests, put into evidence the beneficial contribution of the grid, related to the mitigation of the damage peak and to the increase in energy dissipation due to the spreading of the damaged areas.
The stability of the post-elastic pattern of the force-displacement curve given by the plastered reinforced panels is shown by the graph reported in Figure 9.

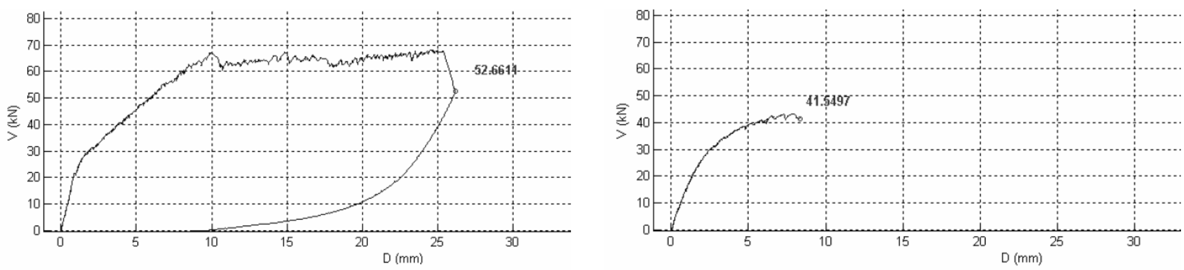


Figure 9. Force vs. displacement curves for the plastered reinforced panel (left) and the bare panel (right)

In the same figure is reported, for comparison, the curve from a bare unreinforced panel. The analysis of the experimental data confirmed the expected beneficial effects of the grid on the out-of-plane behaviour of the panel, allowing for a significant enhancement of the resistance against the collapse mechanisms.
An interesting result, even if relevant to a single test and therefore requiring further investigations, came from the test on panel F-10 where the grid was located only into the plaster layer on the compression side. The graph in Figure 10 shows the good behaviour of the specimen, with a post-elastic pattern exceptionally extended, demonstrating the effectiveness of the grid in restraining the collapse mechanisms also when located on the compressed side.

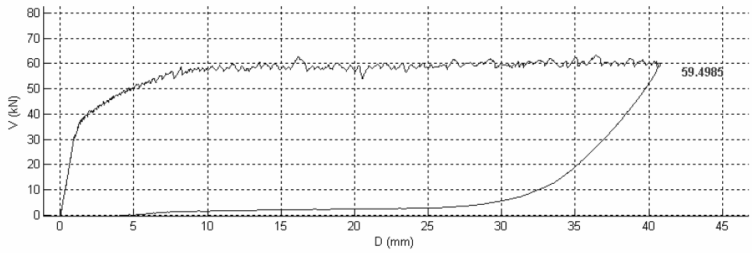


Figure 10. Force vs. displacement curve for the panel with reinforcement on the compressed side

The tests carried out on panels where the reinforcing grid was overlapped for a length of 150 mm showed an increment of the bending resistance of approximately 30%.

5. EFFECTS OF THE GRID REINFORCEMENT

In general terms, the effects of the plaster reinforcement consist in an increase of both strength and ductility.

5.1. Strength increase

Different results on the strength increment have been obtained from the different tests carried out.
The diagonal compression tests didn't showed significant shear strength increase of the panels; experimental results reported in literature confirm this behaviour [6]. On the contrary, the shear-compression tests pointed out some non negligible increment of the maximum resistant shear force, but with peak effects; the ultimate strength values are closer to the those of the elastic limit (beginning of the damage).
A significant difference in the diagonal-compression and shear-compression tests consists, besides the different testing modalities, in the different bricks mechanical characteristics used in the panels manufacturing. The diagonal-compression tests were carried out on masonry panels built with high strength bricks, while in the shear compression tests use of medium strength bricks was made. Taking into account the fact that existing buildings are often made of poor quality masonry, it can be stated that the polymeric grid reinforced plaster gives a shear strength increase. Such an increment can therefore be assumed in the design, with values ranging from 1.0 (no increase) up to 1.5 (maximum experimental finding), based on the designer's judgement. A 1.2 value is prudentially suggested by the authors. The strength increment can be taken into account by selecting an appropriate value of the ratio α_u/α_1, as given in [7] or by [8] for r.c. buildings, that modify the structure factor q, thus reducing the elastic spectrum in linear seismic analysis. The designer could also take into account the strength increment by assuming a "modification coefficient" of the mechanical parameters, also provided in [7], consequent to improvement interventions foreseen on the masonry.

5.2. Ductility increase

The increment in the ductility capacity, given by the presence of polymeric grid, is a constant result of all the tests carried out, therefore the fact that the reinforcement increases significantly the ductility is proven and must be considered in the design of the retrofit interventions. This effect can be directly taken into account when nonlinear static or dynamic analyses are carried out, for which the force-deformation relationship of each structural element is explicitly defined. According to the experimental results, the force-deformation diagrams of

the reinforced panels can be characterised by an ultimate deformation of 0.4% (shear distortion). On the contrary, the maximum distortion of the tested unreinforced panels turned out to be approximately 0.2%.
If a linear analysis with reduced spectrum is carried out, the increase in ductility of the reinforced masonry can be taken into account in the definition of a structure q factor value greater than the minimum defined by the codes. For instance, considering the definition of the q factor as given in the Italian seismic code [7], the designer could consider, at the same time, the ductility and the strength increment by selecting a suitable value of the ratio α_u/α_1, ratio that can reach a value of 2.4 assuming a strength increase of 1.2 and a ductility increase of 2.0. It has to be noted that the values of the ultimate displacements obtained from tests carried out are lower than those found in literature for either new and ancient masonry [9], [10]. The more pronounced plastic behaviour shown in the literature cases could be attributed to the mortar characteristics and to the masonry organization; this aspect will be clarified by further tests, already planned, on masonry panels characterised by low quality mortar.

6. ANALYTICAL MODELS FOR DESIGN

The experimental activities have been supported by theoretical and numerical investigations aimed at interpreting, reproducing the results and defining suitable simplified models to be used as tools for the design of the retrofitting interventions [11].
As previously said, in the existing masonry buildings partial collapses for seismic actions often happen, generally for loss of equilibrium of masonry portions. The verification with reference to these in-plane and out-of-plane mechanisms, is meaningful only if a monolithic behaviour of the masonry wall is guaranteed; under this assumption, the verification can be carried out by resorting to the limit analysis of the equilibrium, according to the kinematic approach. The application of the proposed verification method presupposes therefore the analysis of the local mechanisms, deemed significant for the construction, that can be assumed from the knowledge of the seismic behaviour of similar structures, already damaged from the earthquake, or that can be defined by considering the presence of cracks patterns, even if not directly related to seismic actions. Moreover, the quality of the connections among the walls, the masonry organisation and texture, the presence of tie-bars, the interactions with other elements of the construction or the neighbouring buildings must be considered. The kinematic approach allows for the determination of the evolution of the horizontal action that the structure is progressively able to withstand meanwhile the mechanism evolves. Such an evolution can be represented by a multiplier α, given by the ratio of the horizontal forces applied to the correspondents weights of the structural masses, as a function of the displacement d_k of a reference point in the system. The curve, determined up to the annulment of any capability of sustaining the horizontal actions ($\alpha = 0$), can be transformed into a capacity curve of an equivalent single-degree-of-freedom system, for which the ultimate displacement capacity of the local mechanism can be defined and compared to displacement demand requested by the seismic action.
For any possible local mechanism of interest for the considered building, the method is articulated into the following steps:

- transformation of a part of the construction into a labile system (kinematic chain), through the identification of rigid bodies, defined by fracture planes hypothesised on the basis of the insufficient tensile strength of the masonry, and able to relatively rotate or sliding;
- determination of the horizontal loads multiplier α_0 that involves the activation of the mechanism (damage limit state);
- determination of the evolution of the horizontal loads multiplier α_0 at the increase of the displacement d_k of a reference point within the kinematic chain, usually chosen in proximity to the centre of mass, up to the annulment of the horizontal seismic force;
- transformation of the obtained curve into a capacity curve, e.g. of the spectral acceleration a^* versus the spectral displacement d^*, with the evaluation of the ultimate displacement of the mechanism (ultimate limit state);
- safety checks, through the control of the compatibility of the movements and/or the resistances requested to the structure.

For the application of the analysis method, the following assumptions are generally made:

- the masonry tensile strength is null;
- absence of sliding among the blocks;

- the masonry compressive strength is infinite.

However, for a more realistic simulation, the following parameters shall be considered, even if in a simplified way:

- the sliding between the blocks (taking into account the friction);
- the connections (even if of limited resistance) among the walls;
- the presence of metallic tie-rods;
- the presence of the polymeric grid within the plaster and on the corners;
- the limited compressive strength of the masonry (by considering sets of hinges adequately located);
- the presence of multi-leaves walls.

6.1. Linear kinematic analysis

In order to get an evaluation of the horizontal loads multiplier α_0 that leads to the activation of the local mechanism, it is necessary to apply to the rigid blocks composing the kinematic chain the following forces: the self weights of the blocks (applied on their centres of mass), the dead and live vertical loads acting on the blocks, a system of horizontal forces proportional to vertical loads (if such forces are not transmitted to others walls), other external forces (such as those transmitted by metallic tie-rods), other internal forces (such as the actions related to the connection between blocks and the grid presence). Assigning a virtual rotation θ_k to the generic block k of the kinematic chain, it is possible to determine, as a function of the rotation and geometry of the structure, the displacements components of the various forces applied in the respective directions. The multiplier α_0 is obtained by applying the Principle of the Virtual Work and equating the work done by the internal and external forces applied to the system acting through the virtual displacement:

$$\alpha_0\left(\sum_{i=1}^{n} P_i\delta_{x,i} + \sum_{j=n+1}^{m} P_j\delta_{x,j}\right) - \sum_{i=1}^{n} P_i\delta_{y,i} - \sum_{h=1}^{o} F_h\delta_h = L_{fi} \tag{1}$$

where:
n is the number of all the forces applied to the various blocks of the kinematic chain;
m is the number of forces not directly acting on the blocks, generating horizontal forces on the elements of the kinematic chain;
o is the number of external forces, not associated to masses, applied to the various blocks;
P_i is the vertical force of the generic block;
P_j is the generic vertical force, not directly applied to the blocks;
$\delta_{x,i}$ and $\delta_{x,j}$ are the horizontal virtual displacements of the points of application of the forces P_i and P_j;
$\delta_{y,i}$ is the vertical virtual displacement of the point of application of load P_i;
F_h and δ_h are, respectively, the generic external force applied to a block and the displacement of the application point;
L_{fi} represents the work of the internal forces.

6.2. Nonlinear kinematic analysis

In order to evaluate the displacement capacity of the structure, up to its collapse, in the considered mechanism, the horizontal load multiplier α_0 can be determined not only with reference to the initial configuration, but also to modified kinematic chain configurations, representatives of the evolution of the mechanism and defined by the displacement d_k of a system's reference point.
The analysis must be carried out up to the configuration corresponding to the annulment of the α multiplier, corresponding to a displacement $d_{k,0}$. For any configuration of the kinematism, the value of the α_0 multiplier can be determined from equation (1), properly rewritten by referring to the modified geometry. The analysis can be carried out with the use of graphic methods, by defining the system geometry in the different configurations up to the collapse, or with analytical-numerical methods, by considering a set of virtual displacements and rotations to be progressively updated based on the system geometry evolution.

If the forces involved (weight, external and internal forces) are kept constant during the kinematism evolution, the resulting curve is almost linear; in this case, and in a simplified way, it is possible to evaluate directly the displacement $d_{k,0}$ for which the multiplier assumes a null value. The equation of the curve, then, becomes the following:

$$\alpha = \alpha_0\,(1 - d_k / d_{k,0})$$

The aforesaid configuration can be obtained by expressing the geometry, in a generic modified configuration, as a function of the finite rotation $\theta_{k,0}$, applying the Principle of Virtual Work, and obtaining from the equation, generally nonlinear, the unknown entity $\theta_{k,0}$.
When the progressive variation of the external forces with the kinematism evolution is taken into account (for instance when considering the elongation of the polymeric grid within the plaster), the curve could be linearized by segments, evaluating the curve in correspondence to displacements for which significant variations happen (i.e., yielding of the grid, ultimate deformation of the grid, etc…).

The proposed analysis approach can be applied also to out-of-plane collapse mechanisms. The analysis is based on the following assumptions:

- the collapse mechanism consists of an horizontal crack located at an unknown level of the masonry panel;
- the crack divides the masonry panel into two "rigid" portions;
- if the horizontal floor restraints are absent or ineffective, the whole wall must be considered in the analysis.

The solution procedure is expressed by the equilibrium condition derived from the Principle of Virtual Works by equating the total work done by the external and internal forces that are applied to the considered system along the correspondent virtual act of motion. The forces doing the work along the system's virtual displacement are:

- the weight of the lower and upper portions;
- the lateral seismic forces related to the self weight, given as a function of the α_0 multiplier of the actions that activate the mechanism;
- the vertical reaction at the top of the wall (including the loads originating from the supported walls and floors);
- the resistant moment of the cracked reinforced section, evaluated considering the grid's presence.

The displacements of the forces' application points and the rotations of the moment application axes, can be easily derived from geometric considerations on the kinematism.

Similar approaches can be extended to nonlinear analysis.

7. USE OF POLYMERIC GRID IN REHABILITATION, RESTORATION AND CONSERVATION

Polymeric grid reinforcement can be successfully used for the seismic rehabilitation of common masonry buildings, where plaster is normally considered a protection layer to be removed and changed during maintenance intervention. However, polymeric grid could also constitute a challenging solution for old or even historical buildings where the plaster has to be restored, because absent or historically non relevant, as it can provide for a complete chemical and physical compatibility, thanks to its characteristics and not invasive installation procedures. In case removal of plaster is envisaged, the technique can also be considered fully reversible.
The proposed retrofitting technique has been used for pilot applications on buildings located in different Italian seismic areas: intervention designs have been completed and retrofitting works are currently in progress.
Among the various applications, it is worthwhile mentioning the following examples.
The first one is relevant to the use of the grid in the rehabilitation of a typical northern Italy rural construction made of stone and brick masonry (Figure 12, top left) to be renovated and reused as residence.
In the second application, concerning an ancient tuff building in southern Italy to be restored and destined to host a natural park visitors centre (Figure 12, top right), the grid reinforced plaster was used to easily achieve the required seismic upgrade of the structure. It is worthwhile mentioning that the building is located in an area that

only recently has been included within the earthquake prone areas based on the recent reclassification of the Italian territory. It is therefore representative of a common situation, in which structures conceived without consideration of earthquake forces have to be enhanced to comply with the new standards.
The third example refers to the rehabilitation and restoration of an 19th century construction (Figure 12, bottom), severely deteriorated and located in southern Italy in an area characterised by a significant seismicity (PGA = 0.25 g). The building, made by stone and brick masonry at the lower level, tuff masonry at the upper level with lime mortar joints of significant thickness, requires significant restoration and seismic upgrading, due to its actual conditions and to its final destination as civic and cultural centre. In this case, in addition to its normal application within the plaster, the polymeric grid was also used as reinforcement for the newly constructed masonry, by inserting strips of grid into the bed joints.
In all the aforesaid pilot applications, significant seismic performance enhancements were achieved.

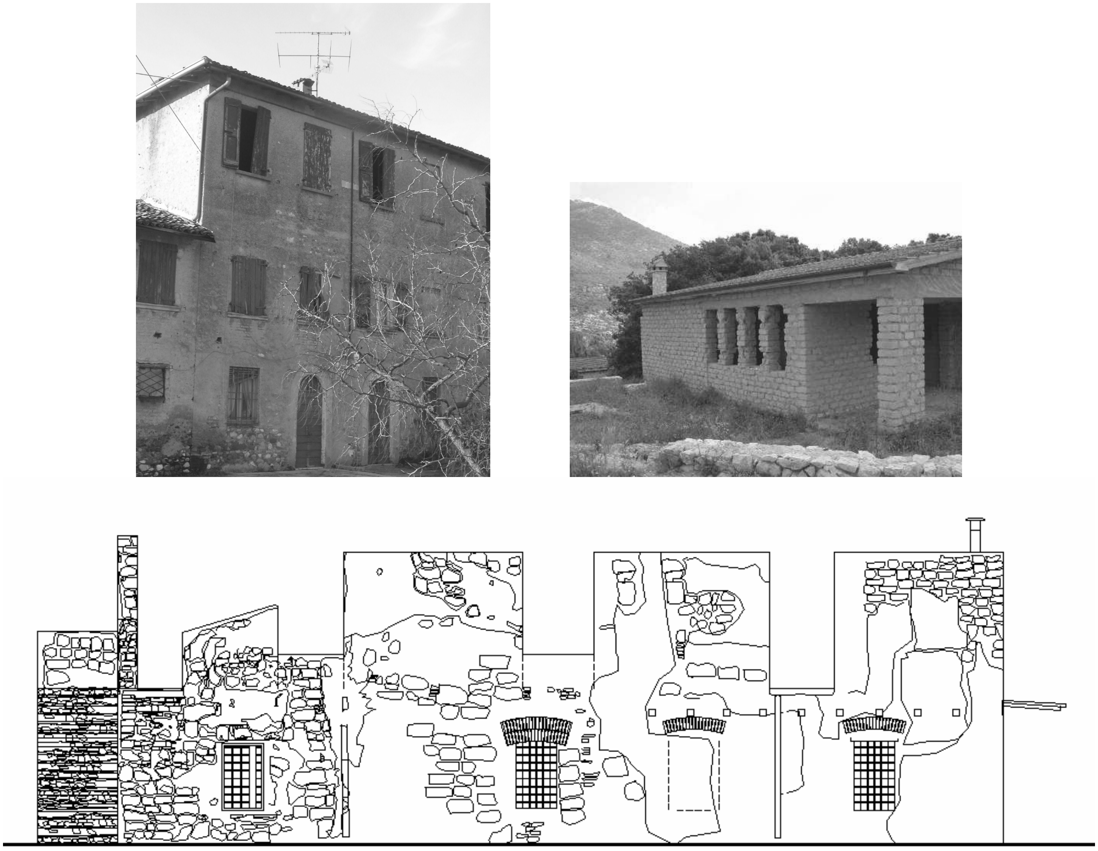


Figure 12. Pilot cases: renovation of rural constructions (top) and restoration of an historical building (bottom)

8. CONCLUSIONS

Plaster reinforced with polymeric grid has been proven to be an effective, simple and a low-cost solution for the seismic performance enhancement of masonry buildings and thus to be able to offer a significant contribution in the restoration and rehabilitation of masonry structures. The tests and the pilot applications made use of the special RichterGard grid characterised by a triangular shape. The grid shows its positive effect after the masonry failure, avoiding the collapse and crumbling of separated portions. The experimental data clearly demonstrated significant increase of ductility and a non negligible increase in strength. Theoretical and numerical investigations aimed at interpreting and reproducing the results have been carried out; based on the experimental evidence, suitable simplified models to be used as practical tools for the design of the retrofitting interventions using the plaster reinforced with RichterGard grid have been developed and validated.

9. REFERENCES

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