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PERFORMANCES IN SEISMIC STRENGTHENING OF MASONRY

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SUMMARY

The paper refers to masonry strengthened with polymer grids. The need of seismic protection is justified by the increase of losses and fatalities caused by earthquakes. In order to assess the performances of the new strengthening technique, the status of original masonry based on burned clay-bricks and lime mortars was first clarified. That is bygone history: indeed, with modernity masonry was “concretized” and it differs so much from the original that deserves a specific denomination: “mascrete”. Both of these artificial stones, ancient and modern, are too brittle for seismic areas and, if reinforced concrete can provide protection for mascrete, polymer grids proved to be appropriate for masonry. Not all synthetic reinforcements are suitable for such purpose but only grids with solid-integrated joints. When inserted in bed layers the grids are reinforcing the masonry, and when embedded in plaster masonry is coated or confined. The system was named RichterGard and uses the strength resources of plain masonry to increase its bearing capacity under seismic actions. The performances of reinforced and confined masonry come out from the principle to avoid stress concentrations and uniformly distribute the masses. The tests carried out show that X-shaped cracks no longer appear and dislocations are avoided activating a fail-safe mechanism. With the aid of polymer grids the qualities of masonry can be achieved with modern units at convenient costs.

INTRODUCTION

Statistical data show that during the last decades the losses and fatalities caused by earthquakes increased dramatically. Not the Geology of Earth is changing, but the concentration of population in seismic zones together with technological wealth of modern society. To the existing natural hazard of some sites the vulnerability of new buildings is adding progressively. The lessons of History are ruthless. In seismic zones construction rules are different from those applied where earthquakes do not occur. They are severe and precise. If those golden rules are not obeyed sooner or later Nature is revenging. Nowadays these lessons were understood in California and Japan where seismic protection is almost solved. Earthquakes are no longer frightening and produce limited damages. With sustainable scientific and financial efforts seismic movements were accepted as current facts of life. Unfortunately, this is not the case for many areas subjected to recurring disasters. For instance, in 1999 Adapazari, Turkey was almost completely destroyed (Coburn [1]). Only the old mosque with its slender minaret in original masonry remained standing. Many buildings recently built with modern materials and with the aid of advanced technologies were severely damaged. Even in San Giuliano di Puglia, Italy, during recent earthquakes in 2002, some new buildings were damaged,

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with mascrete-walls dislocated and horizontally hollow-bricks crushed. By no means can such damages in masonry be repaired. Dislocated masonry should be removed and replaced with a new one.

The use of cored bricks in seismic zones without any protection against their brittleness proved to be adventurous. Most of the damages caused by earthquakes to masonry buildings are due to the wrong association of brittle cored bricks with brittle cement mortars. The price paid for the ergonomic advantages of those bricks is too high. The Romans who worked much in masonry never have shown any conceptual interest for coring the bricks. It is expected that Eurocode 8 will be more specific with regard of using cored bricks.

Combinations between different construction materials, in so-called composite structures, can become also dangerous in seismic zones. This is why the method of seismic protection of masonry with polymer grids was devised. The system was patented in 1995 and carefully checked before being used. Extensive programs of static, pseudo-dynamic and seismic tests were carried out in prestigious European Laboratories of Earthquake Engineering. It was definitely proved that masonry as brittle artificial stone finds excellent cooperation with this synthetic reinforcement under gravitational and seismic actions.

Beginning with 1999 the method of seismic protection has been applied to old masonry buildings that during their working life faced several strong earthquakes. It is easy to be applied because it does not require highly qualified labour and no special equipment. Since most of works take place on the exterior the building does not need evacuation and may continue in its service. The structural performances obtained in the most severe conditions of testing were confirmed by numerical analyses.

The seismic protection of masonry buildings with polymer grids proved to be very effective. The method, including the manufacturing process together with design-guidelines and installation procedure, was given the acronym “RichterGard”, standing for defence against measurable earthquakes. In 2003 the system won recognition by Eurocode 8. The paper presents the performances obtained in seismic strengthening of masonry and some of its application prospects.

ORIGINAL MASONRY

Historical records suggest that brick-masonry was invented in a region of Palestine scarce in stone but rich in clay. Later, burned-clay bricks bonded with lime-mortar were used in Mesopotamia for city walls and ziggurats, Babel Tower being one. According to Herodotus who visited the area (≅450 B.C.E.) the same masonry was used for the Hanging Gardens. All over the Plain of Shinar, where civilization began, masonry was regarded with confidence and used with art.

The art of masonry consists of dealing with bricks in the gravitational field. Masonry is the only construction material produced manually with the aid of gravity and depending during its service by gravity. Masonry is a free but not casual association between bricks and lime mortars. Bricks of burned clay are solid and never caved. For ergonomic reasons straw is currently inserted in clay before burning. The resulting porous bricks are easily handled, and the labour-efficiency is much increased. Lime mortars are plastic and, according to the law of binding, have lower strengths than bricks. Since both bricks and lime are produced by fire and, after the hardening of mortar, neither contains water there is no any antagonism between them. In the resulting artificial stone the elastic proprieties of bricks and plastic proprieties of mortars are complementary. This is an outstanding quality of masonry and a source of performances when the two masonry components are accordingly bond and well proportioned. For instance, as a consequence of the running bond of bricks, the masonry is discharging its loads not directly by the vertical lines of gravitational field, but through the so-called “vault effect.”

In addition, in the occurrence of stress concentrations generated by long-standing loads around geometrical faults, like vertical brick-joints, the plastic strains of mortar allow a re-distribution of such stresses throughout the cross-section of all surrounding joints, which minimizes the danger of dislocations. This adaptation phenomenon was named "sandwich effect." This is why cuttings, carvings and perforations should be avoided in masonry, not to undermine such self-protective property provided by the gravitational field. As for masonry-stiffness, it is to be noted that bricks and mortars have different modules of elasticity and when loaded they deform differently. Due to this geometric discontinuity of strains, masonry cannot be classified as a composite material. In addition, its thermal coefficient of expansion, $\alpha = 5x10^{-6}\ {}^{0}C^{-1}$, is 2.5 times lower than that of concrete and this is why the two materials cannot be properly associated into mutual cooperation. This type of masonry is still found in many buildings, especially in those of cultural heritage: for these structures the only appropriate seismic reinforcement is based on polymer grids.

CONCRETISED MASONRY OR "MASCRETE"

First the industrial revolution and recently the technological one have changed essentially the original masonry. In order to increase its bearing capacity and enhance labour efficiency, the solid and porous bricks were replaced with ceramic ones, whilst cement replaced lime in mortars. The association of the two materials is made manually in the gravitational field. Since the bricks are produced by fire while cement mortars contain water of constitution even after hardening, the two materials are antagonist. The resulting artificial stone is brittle and, like concrete, does not depend any longer on gravity. That is explaining the new definition of "mas-crete". The loads are discharged in the direction of gravity field and the vault effect does not exist. The strength of cement mortars is higher than the strength of bricks, which is against the rule of binding. Moreover, bricks and mortars have almost the same modules of elasticity. Consequently, when loaded there is a geometric continuity of strains and, according to Saint Venant Principle, mascrete can be classified as a composite material. The lack of ductility under long-standing loads excludes any "sandwich effect."

Like for concrete, there are no restrictions to cut, carve or perforate mascrete. Its coefficient of thermal expansion, $\alpha = 10x10^{-6}\ {}^{0}C^{-1}$, is equal with that of concrete and therefore the two materials are safely associated. Mascrete is usually reinforced and pre-stressed with steel. Fibbers could be also used if appropriate binding materials become available. Since cement mortars contain water, mascrete is a wet artificial stone with rather high coefficients of thermal transfer. Nowadays mascrete is currently used in all types of buildings, even in seismic prone zones.

For the sake of accuracy, at least in Earthquake Engineering, the distinction between the two materials of the same colour seems necessary. It is not any discrimination but rather recognition of their different structural performances. If such distinction is not done in due time, surely the earthquakes are doing it, but then might be too late. Historically, the two materials belong to different époques with specific technologies and levels of knowledge. That does not mean masonry and mascrete are bound to conflict: they do not exclude each other. On the contrary, they can coexist, even if neither of them was created for seismic actions but only for gravitational ones. Nowadays seismic protection of mascrete is satisfactorily provided by steel reinforcement (Pauley [2]) while polymer grids can provide the solution for structures where masonry is prevalent.

POLYMER GRIDS

Carefully selected engineering-grades of polypropylene are extruded to form sheets of high density. The sheets are then punched with a precise and regular pattern of circular holes. The punched sheets are heated and stretched in the pulling direction. By monoaxial stretching the original holes become apertures with curvilinear sides. The monoaxial grids so produced have precise determined dimensions and strengths. They are further used to provide feedstock for subsequent transverse stretching into biaxial grids with squared-like apertures. All this process takes place under controlled heat at pre-determined constant forces of stretching. It is a natural self-shaping process. During the stretching the macromolecules are aligned and oriented in the direction of tension. The intermolecular spaces are reduced and the density of molecules increased. At the same time the strength to tension of cross sections becomes variable along the stretched ribs. The strength is strongly increasing by cross section reduction according to the law of bars with constant bearing capacity to axial tension. This is an ideal mechanical performance and was obtained by optimising geometrical and physical proprieties of the grids. Such a remarkable property is yet to be identified in any other metallic or synthetic material used as reinforcement (Fig.1).

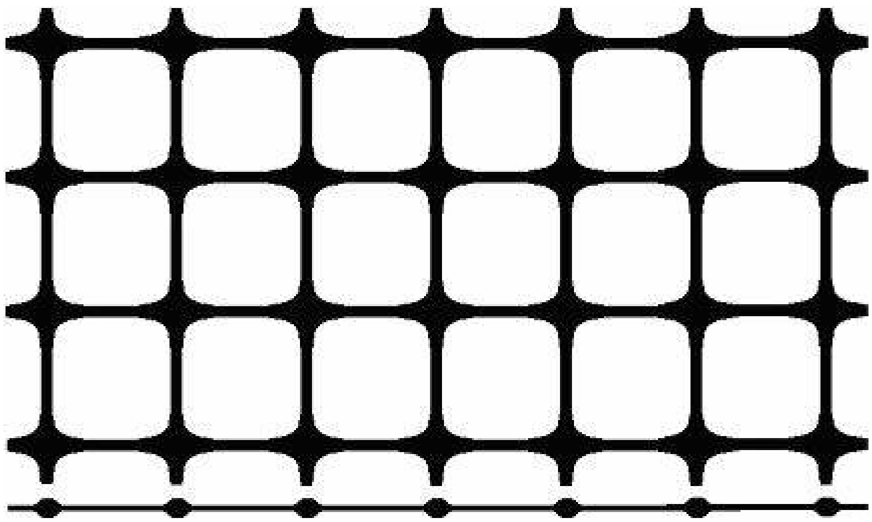

Figure 1: Geometry of the biaxial polymer grids

Polymer grids obtained in this way consist of flexible ribs and rigid joints. The ribs have constant thickness but a variable geometry in their plane. They are narrow at the middle, and progressively increase towards the joints where they become wide. The ribs are connected with joints by continuous curves. The joints are integrated with the ribs but are up to four times thicker. The biaxial grids have four symmetry axes, two in rib directions and two parallel with the diagonals of squared apertures. In their planes the polymer grids are distinguished by two remarkable geometric qualities. Firstly, they appear as multiple connected surfaces. All apertures are limited only by continuous and closed curves. Geometric continuity of aperture-outlines guarantees the fluency of tension-flow in ribs. Firstly, the avoidance of geometric and physic discontinuities excludes any phenomena of local stress-concentration or deviation, known in Mathematics as catastrophic. Secondly, all grid-apertures are only few centimetres small and rigorously equal to each other. Thanks to this geometric quality the grids are able to uniformly distribute, balance and keep under control the stresses which concentrate around the integrated joints. It is a practical way to fulfil Bernoulli's assumption of uniform stress-distribution and reducing the frequency of local concentrations. However, when the values of stresses are exceeding a certain limit, they are redistributed to surrounding joints by the mentioned self-protection mechanism of adaptation. Mechanically, this is a practical way of transferring the vector-actions of forces into tensor-effects of stresses. Therefore polymer grids have variable geometrical and physical proprieties, which are both described by the same nonlinear function. As a consequence of this nonlinearity the analysis of masonry members reinforced or/and confined with polymer grids differs from the methods traditionally used in Civil Engineering. Actually, linearity or nonlinearity is not an intrinsic property of polymer grids, but a mode of expressing some phenomena with the aid of available mathematical tools. Not always a nonlinear analysis is better than a linear one, but sometimes it is the only method to describe a phenomenon. In the case of polymer grids, since Bernoulli's hypothesis of plane cross-sections does not subsists any longer, and Young module of elasticity vary along grid ribs, the available diagram is that of load-strain, instead of stress-strain. The index strength/specific weight is for steel $f/\gamma = 200MPa / 80kN/m^3 = 2.5$ km while for polymer grids RG20 $f/\gamma = 20kN/m^2 / 0.2\ daN/m^2 = 10$ km, i.e. four times higher (Fig. 2).

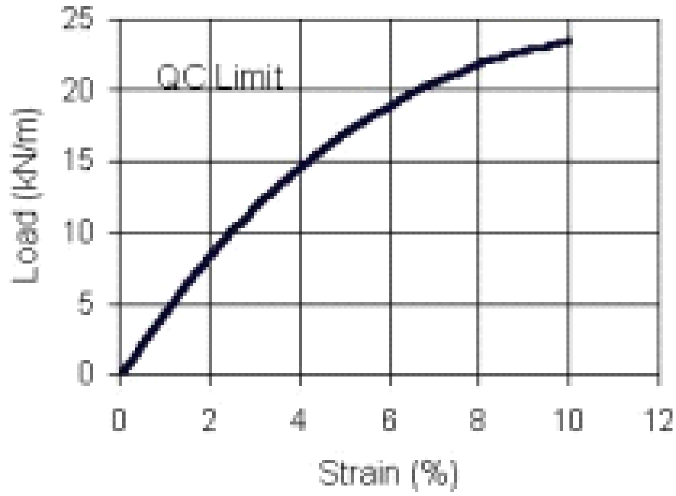

Figure 2: Load-strain diagram of RG20

In addition the biaxial effect of polymer grids should be considered even if they are mainly submitted to forces of monoaxial direction. For instance, when a 3D building model of cored-bricks masonry was tested on the shaking table up to the limit-state of cracking, the bricks behind synthetic reinforcement where crushed while the grids remained integer (Fig.3 left). The response of a similar model made of masonry with solid bricks, tested in the same conditions on the shaking table, was opposite: the grids were torn-out while the bricks remained integer (Fig.3 right). The pattern of cracks in ribs clearly shows the biaxial effect

Figure 3: Crushed cored bricks - left and torn grids - right

of stretching when each tensioned rib behaved like having a negative Poisson ratio, but without loosing its bearing capacity. This outstanding quality of polymer grids is in full accordance with the principle of fail-safe. In practice the torn reinforcement is easily replaced with new grids, able to restore the required seismic protection. In the case of crushed masonry, instead, this is being completely removed for replacement with new one what means long time and high costs.

Due to their biaxial behaviour polymer grids have a high capacity of dissipating earthquake-induced energy. Confined masonry as a composite material is more efficient than masonry reinforced in bed layers only (Fig. 4). This is done not only by plastic deformations but mainly through internal friction.

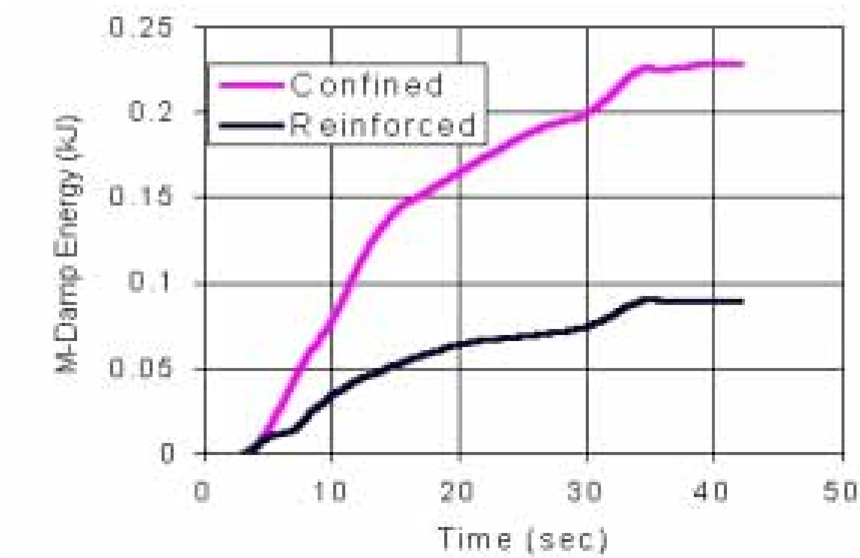

Figure 4: Time history of dissipating energy in reinforced and confined masonry

That is important because friction is not limited like ductility. All codes are praising the ductile qualities of materials without mentioning that plastic deformations are irreversible. When a material consumes its reserves of ductility, it becomes brittle and suddenly fails without any warning. Polymer grids used for confining masonry as seismic protection can be replaced easily at any time. They are acting as passive dampers and with appropriate maintenance of buildings their reliability can be kept at requested level. No other reinforcement used nowadays has this quality of reversibility.

CONCEPTUAL PERFORMANCES

The basic approach of RG System consists in using the resources of strength existing in masonry and avoiding local concentration of stresses. The system applies both to new and existing masonry buildings and involves three specific techniques: 1) reinforcing new masonry by inserting the polymer grids in the horizontal bed-layers of mortar between bricks; 2) coating the outer surfaces of new or existing masonry with reinforced plaster; and 3) confining the structural members with the same reinforced plaster. In all cases, synthetic reinforcement compensates for masonry's lack of ductility and enhances its natural strength capacity.

The first technique improves load-transfer capacity between the masonry units, since the reinforcement prevents horizontal expansion of mortar. It is not necessary to lay the grids in all mortar beds, but only in some, at vertical distances between 20 cm and 40 cm. The joints are obtained by superposition of polymer grids without any joining devices. Coating the masonry with reinforced plaster improves the shear resistance of the masonry wall, whether or not the horizontal reinforcement is present. This technique is efficient only when the reinforced plaster adheres well to the masonry surface. The effect of this type of reinforcement is bi-directional, in the plane of the wall. Finally, confinement with reinforced plaster by wrapping-around of building bodies, or their structural members, improves both compression and shear-resistance and is most efficient when combined with the reinforcement in horizontal layers. Its conceptual performance consists in changing the behaviour of masonry into one typical for composite materials. Indeed, by confining the masonry its strains become continuous, and the state of compression-stresses becomes almost three-axial as it was experimentally proved. In addition, with confinement, the effects of masonry anisotropy and non-homogeneity on stress distribution are much improved comparing with plain masonry.

Due to the ductility of polymer grids and lime in mortars under permanent actions, as the gravitational ones, the confined masonry has both elastic and plastic behaviour. On the other hand under dynamic instant or short time actions the response of confined masonry is elastic but with an enhanced capacity of dissipating the induced energy in comparison with plain masonry. In all three techniques the mechanism of stress-transfer from masonry to grids produces through normal stresses σ by the "anchoring effect", which essentially differs by the "clamping effect", developed in reinforced concrete.

Confinements, as just described, are fully integrated to masonry without ever appearing as additional structural components of columns and walls. The enhancements of strength are due to the high strength of polymer grids as well as extending in space masonry state-of-stresses while the increase of stiffness comes from the geometry of structural members whose continuity and integrity were restored with confinement. RG System preserves the integrity of the original masonry, which is neither cut nor perforated, and due to its reversibility can be removed, if necessary, without spoiling or ruining the structure.

In most of the practical cases, masonry confined with RichterGard System acquires adequate seismic protection without needing either reinforced concrete or metallic structural members. Buildings with confined masonry become more homogeneous than those of plain masonry, there are no unbalanced masses and concentrators of local stresses, which are in accordance with the "Basic principles of conceptual design" provided by Eurocode 8. In addition, the polymer grids ensure continuous connections between building bodies and their foundations contributing to diminish "the snap of whip" effects developed by earthquakes.

FIELDS OF APPLICATION

The most fascinating application of RG System is seismic shaping of the new masonry buildings according to its conceptual performances. That means to combine geometrical and structural performances of buildings potential in order to provide the required seismic protection for the specific hazard of given sites at the minimum costs. By an appropriate shaping become possible to avoid all types of irregularities and especially to balance the building structures by uniform distributions of masses. It is the only opportunity to apply some of the valuable provisions contained in EC8 and ISO 2394:1998. RG is a holistic concept of seismic protection of masonry in buildings and structures located in seismic prone areas. Its concept of analysis and design is based on the relative positions of the two intrinsic centres, gravity centre CG and stiffness or rotation centre CR, both allowing global analysis of the building bodies and detailed analysis of each structural member. For the new buildings the concept also allows a seismic shaping while for the existing buildings only the putting into value of all real reserves of strength and stiffness.

RG system is able to fulfil all three objectives for the assessment of an existing structure in terms of its required structural performance. According to ISO 13822:2001 the level of performance should be specified after consultation with the client, who could be the owner, the authority or the insurance company, as follows:1) Safety performance level, which provides appropriate safety for the users of the structure; 2) Continued function performance level, which provides continued function for special structures such as hospitals, communication buildings or key bridges, in the event of an earthquake, impact, or other foreseen hazard; 3) Special performance requirements of the client related to property-protection against economic loss or serviceability. The level of this performance is generally based on life-cycle cost and special functional requirements. The three objectives just mentioned can be fulfilled through retrofitting, concept that includes repair, strengthening and re-modelling. Therefore it becomes possible the reconstruction or renewal of any part of a damaged structure, to restore or improve the strength and/or ductility which the structure had prior to the damage.

RG system is applicable to the following types of buildings and their structural parts: 1) Residence, social, cultural and patrimonial buildings; 2) Structural and functional components of masonry in mixed structures with wooden, metallic or reinforced concrete members. As for material conditions: 1) Bricks to be either solid or caved of porous, pressed or ceramic burned clay; 2) Stone units to have at least horizontal faces and constant heights; 3) Mortars to be of lime, lime-clay, lime-cement or cement-lime.

RG System does not apply in the following cases: 1) Structural or functional members without strength like those made of earth, wooden rubble, gypsum, or textiles; 2) Brick or stone masonry with mortars of cement without lime; 3) Masonry of bricks horizontally hollowed; 4) Masonry in multiple-withe walls, consisting of combinations brick-block walls or cavity walls, in so called "American style"; 5) Structural members of concrete or reinforced concrete, either pre-cast or cast in-situ; 6) Due to the content of lime in mortars the System is restricted in zones exposed to aggressive agents of calcium compounds and where the protection measures are not effective or too expensive.

EXPERIMENTAL RESULTS

Strong earthquakes are dangerous for masonry buildings because the occurrence of jerks may crush the ceramic bricks or even cause dislocations of some structural members. Jerks are due to sudden variations of accelerations and were first used by Karl Gustav Jacobi in his doctoral thesis in Mathematics presented on August 13, 1825. For humans the lower threshold is 30 m/s^3, and for an earthquake of IX degree on Mercalli scale the jerk reaches 496 m/s^3. Masonry reinforced with polymer grids, under jerk actions behaves elastically. Between two consecutive changes of acceleration there is no time for grids to develop plastic deformations and therefore their ductile qualities are not fully used. Earthquake-induced energy is dissipated mainly by friction forces.

The tests on models of masonry buildings seismically strengthened with polymer grids have been already presented in previous publications (Sofronie [3, 4, 5]). The static tests were carried out in Romania on 12 short columns and 18 panel walls. The pseudo-dynamic program at JRC Ispra, Italy consisted of 4 full scale masonry infills tested on the reaction wall. Finally, the seismic program includes 10 full scale models with one and two storey tested on the shaking table of Enel.Hydro ISMES in Seriate, Italy.

In other recent tests the models submitted to shocks, according to ISO 7892:1998, have shown a rapid amortisation of the induced oscillations by distributing them evenly, in all directions. The tests also followed the requirement of the clause 2.9.6 of Eurocode 8 regarding the out of plane protection of masonry walls. Masonry reinforced and confined with polymer grids proved to be appropriate for such purposes.

The aim of first testing program was to evaluate the capacity of polymer grids inserted in plaster to dissipate the energy induced by shock. For test purpose it was used the model with cored brick masonry. Two points have been chosen for experiment: point 1 on the belt of reinforced plaster under the opening for window and point 2 on the wall free of cracks near the same opening. The pendulum of a steel cylinder weighting 34daN was successively launched in each point five times from increasing heights: 0.1m, 0.2m, 0.3m, 0.4m and 0.5m. The impact-effects in both principal directions, horizontal and vertical, were recorded electronically. No micro-cracks appeared on the surfaces of impact. In point 1 the mortar was detached after each impact on depth from 0.8mm to 1.8mm, while in point 2 from 4.1mm to 5.9mm. The positive and negative displacements, with respect to the initial position of rest in the plan of wall, were in general smaller than 0.1mm and did not increased linearly with impact values (Fig.5).

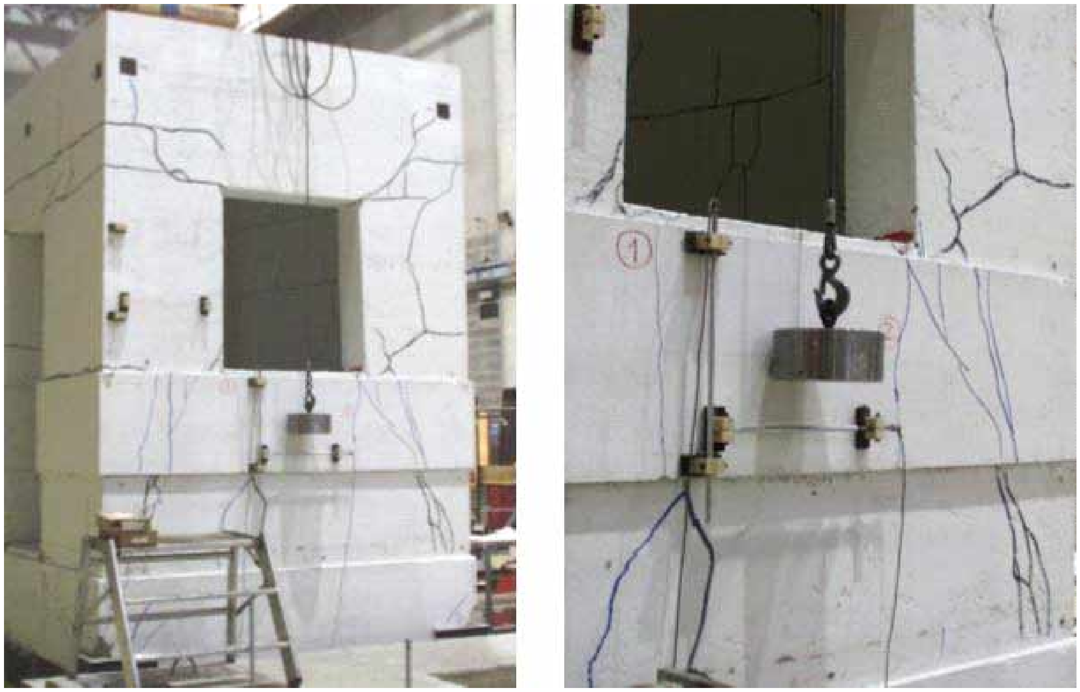

Figure 5: Point 1 on the belt of reinforced plaster

The displacements in the direction of impact were also small and quickly damped. In point 1 on the belt some permanent displacements were recorded in both directions, while the amplitude of oscillations was extremely reduced. On the contrary, in point 2, directly on the wall with higher density, the dislocations were small while the amplitudes of oscillations much larger (Fig.6).

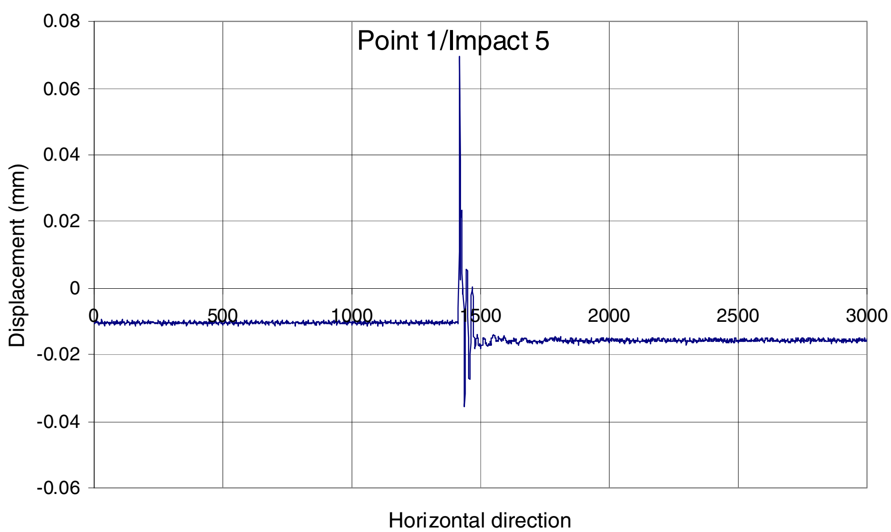

Figure 6: Displacement in point 1under impact 5 in horizontal direction

For the second testing program three wall panels of 1115x2700mm were considered: one of plain masonry, the second of masonry confined with RG40 and the third confined with a steel grid. The three panels were comparatively tested to impact with a conical bag weighting 50daN, according to ISO 7892:1998. The weight was successively launched from increasing heights with pendulum inclination: α=10º, 15º, 22º, 30º, 35º, 44º, 55º, 60º and 66º. It is to be mentioned that all panels were arranged as simply supported beams and responded to shocks by bending (Fig.7).

Figure 7: Fixing the reinforcement RG40 on masonry panel and the standard weight

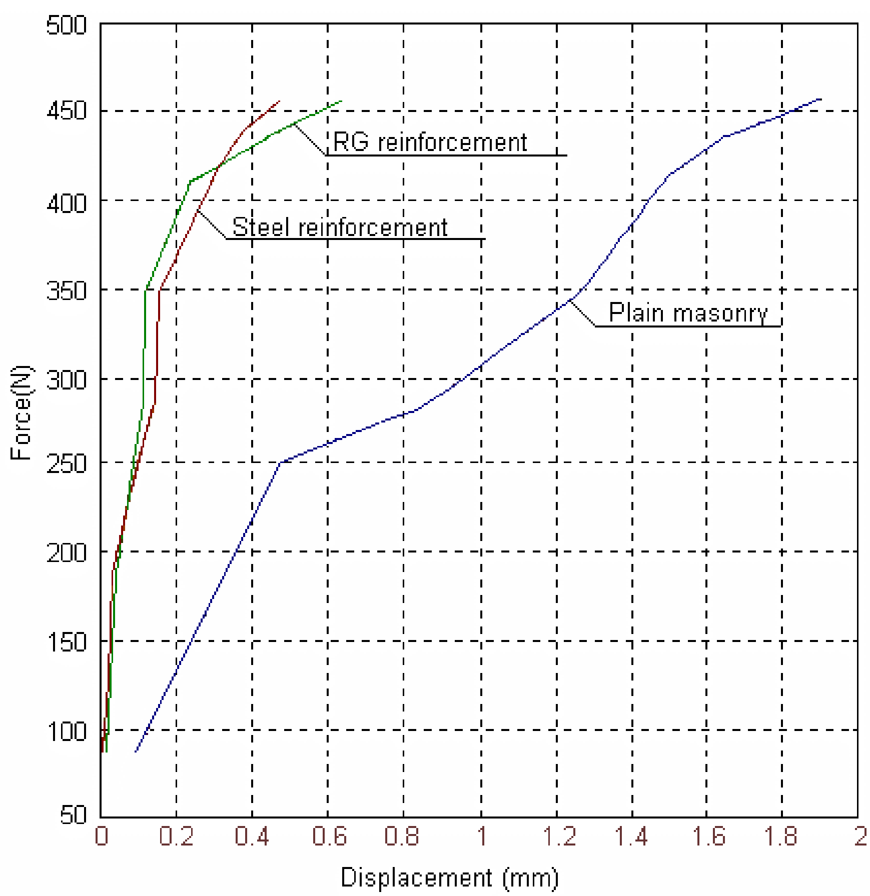

Figure 8: Diagram of force-displacement in the three panels

The reinforcement strongly influenced the response to shock of the three panels. The plain-masonry panel developed plastic deformations from the very beginning, while the other two presented an almost elastic response. The difference between steel and synthetic reinforcement occurred only near the ultimate limit state, when in the panel with polymer grids was recorded a ductile behaviour (Fig.8).

The aim of the third testing program was to evaluate the behaviour of a masonry building protected with reinforced plaster against the following impact-cases: 1) Underground explosion near the building; 2) Overground explosion in front of wall (Fig.9); 3) Internal explosion; 4) Distant but strong underground explosion. The reinforcement behaved perfectly (Fig.10), even under the severe underground excitation (Fig. 11).

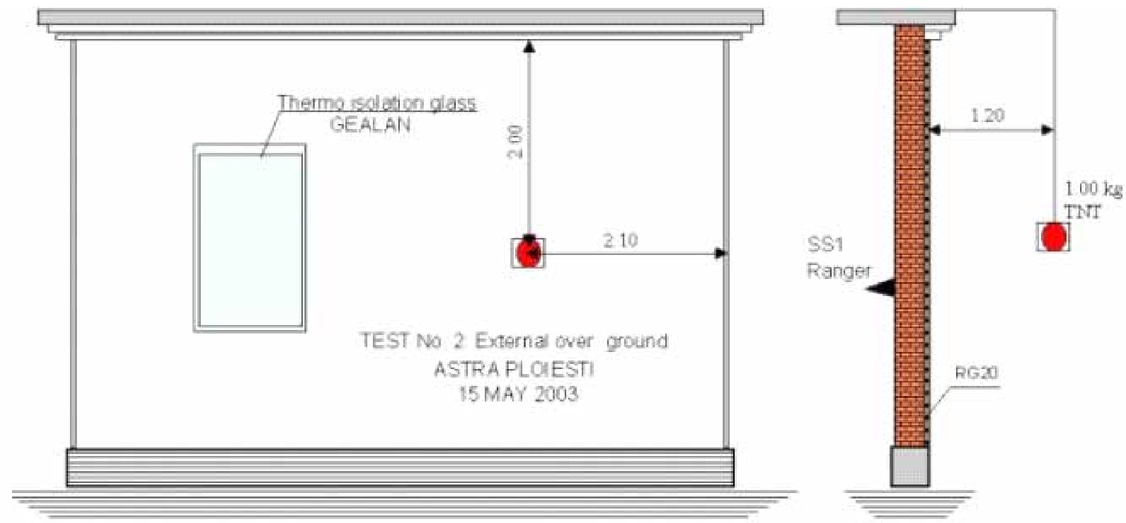

Figure 9: Scheme of the test overground

Figure 10: Synthetic reinforcement and masonry after explosion

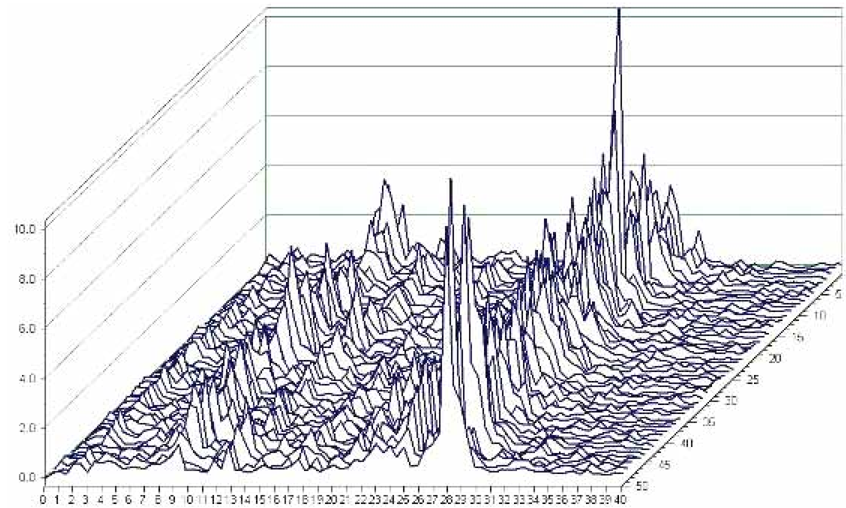

Figure 11: Initial micro seismic Fourier spectra for velocity

CONCLUSION

There are strong proofs that RichterGard System provides real performances in seismic strengthening of masonry. Polymer grids are as suitable for masonry as steel reinforcements are for mascrete. Ductility is indeed the ability of buildings to survive accidental loads like earthquakes, but it is based on plastic, hence irreversible strains. Once a building has lost its ductility it becomes brittle and either fails or has to be demolished. RichterGard System provides a reversible seismic protection that can be easily removed and renewed. Due to their special shape, polymer grids have the ability to distribute unidirectional actions by the two principal directions. The performances in seismic strengthening of masonry with polymer grids are obtained in convenient conditions of time and money.

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