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REINFORCEMENT AND MEASUREMENT METHOD FOR EARTHQUAKE DAMAGED MASONRY BUILDINGS TESTED ON A SHAKING TABLE

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Abstract: *Experimental investigations about the behavior of Unreinforced Masonry (URM) structures in comparison with masonry structures reinforced with Fibre Reinforced Cement (FRC) is carried out on the large shaking table at the EU Centre in Pavia. The tests were part of the EU project Polyfunctional Technical Textiles against natural Hazards POLYTECT and POLYMAST. Intention of both projects within the 6th and 7th EU Framework Program is the development of multifunctional textiles with embedded sensors.*

For the purpose of the project a 5.8 m tall 2-storey test structure was built. Archetype of the structure was a typical historical building made of natural stones from the earthquake region "Abruzzo" in Central Italy. A 6.3 magnitude earthquake struck this region in 2009 (L'Aquila earthquake) and caused 260 losses, 1,000 injured and 28,000 homeless.

In an optimization process different new developed textile and special mortar combinations were tested with small in-plane shear walls under cyclic horizontal displacements to find the optimal strengthening solution for masonry structures.

In the first test, the unreinforced structure (URM) was analyzed under seismic impact. The ground acceleration was increased till nearly before collapse of the building. This damaged building was the basis for further investigation. For the second test the specimen was repaired and reinforced with a new developed FRC in a full covering solution on the surface outside the structure. The used fabric is a woven glass/polypropylene fibre combination in four directions.

1 INTRODUCTION

Masonry is a material with a high compression strength compared with his low tensile strength. Under horizontal load cases like wind or earthquake seven decisive failure modes are observable in the bricks and the mortar joints caused by low shear and/or tensile strength. In figure 1 these modes are presented. The idea to upgrade the mechanical material properties is in the first instance to add thin fibre materials with a high tensile strength like carbon fibers, glass fibers or others. To design and manufacture technical textiles in an optimal way for seismic retrofit, the real fracture mechanism in masonry structures is very important. Generally there are:

By applying fibre reinforcement on the wall surface one can observe a failure in the fibers, in the fibre matrix, the brick surface or in the interaction areas. Due to the fact that masonry has high compressive strength, but low tensile strength, diagonal cracks form due to a compression strut under lateral gas pass [5]. Not often the cracks are crossing the bricks. The reason for failure [6] and [7] is the different material behavior from bricks and mortar. The soft mortar has a low Young's modulus, but in comparison the bricks are very stiff. As a result the mortar carries more lateral strain than the brick and with the interconnection, the adverse three dimensional load case compression-tension-tension and the low tension strength occurs vertical or diagonal cracks [6], [7]. In most cases gaping cracks are developed if the tension forces are higher than the adhesive tensile strength between mortar and brick.

If fibers are oriented in such a way that they cross existing or potential crack locations, they provide resistance against tensile forces which can prevent or stop crack growth. Especially in sliding joints [2] diagonal fibers prevent the decrement of shear resistance in the wall. This is the main factor for in-plane loading and for the bracing system of a building in earthquake areas. The shear failure occurs by exceeding the adhesive shear strength of the mortar or uncommonly in the stones. Similar to the function of rebar in reinforced concrete the fibers more "bridge over" the cracks by providing tensile strength. However, the fibers do not improve the compressive strength. Different to reinforced concrete is the size of the crack width. Instead of millimeters the fiber reinforcement has to work in the centimeter region. Due to this reason the ductility of the fiber system has a high impact.

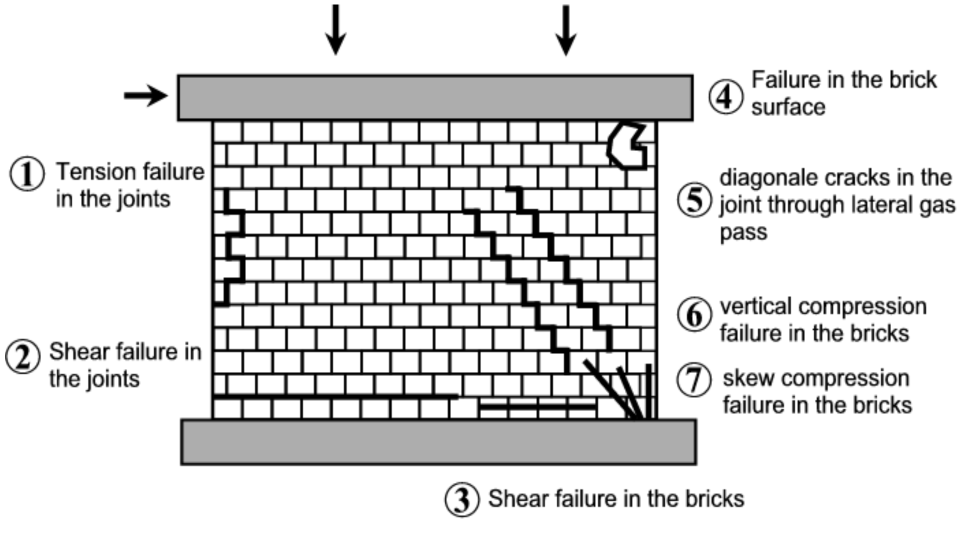

Figure 1: Common failure modes in masonry structures

2 THE TEXTILE

With four main characteristics it is possible to construct a special textile for masonry: (a) Amount of fibre directions, (b) respective inclination angle between the fibers, (c) single or different material types and (d) amount of fibers. For the last point the common way is to calculate with the (fibre-)weight per m² the required tensile strength. Fiber selection is a design problem with polymer, glass, and carbon fibers being the primary material types. Generally, strip reinforcement calls for uniaxial stiff fibers with epoxy adhesive, in opposite to wide area coverage systems calling for more ductile fibers in a multiaxial weave or warp knit pattern. A matrix compound adhesive in combination with carbon fibers with its low strain capacity is an unfavorable option, while the high tensile strength is advantageous. A better solution is a combination with polypropylene fibers (PPF) and AR-glass fibers (ARGF). The PPF performs a high strain rate capacity till the full force is activated. The AR-glass fibers with high stiffness and tensile strength can overtake the first load until the strains reach the ultimate strain value and break. After breaking the PPF will be activated. Through the weight ratio of PPF and ARGF the ductility from the masonry and the textile is adjustable.

The special weaving technique enables the production of multiaxial textiles with different fibre directions with user defined orientation angles. For different small shear and wall tests 2-axial, 3-axial and 4-axial textiles with integrated optical fibers sensors were produced and tested. The range of the weights per square meter was between 290 g/m² and 590 g/m². The weight from the optimized textile was around 425 g/m² and had 4 fibre directions. Especially for failure mode [2] fibers in 45° angel over the cracks can stabilize the shear resistance and this effect is very important for the ductile behavior of the structure.

The textile-stone-mortar composite acts like a laminar ductile tensile reinforcement. The optimal functionality is affected through the high adhesive tensile strength between the mortar brick interface, a lot of small cracks in the matrix without bonding decline, the stiff ARGF at the beginning and the ductile PPF after greater cracks in the masonry.

3 THE MORTAR

The mortar is the link between textile and the structure. The fabric is embedded in two 4 mm thick mortar layers not only to get the best possible bonding but also for the protection of the fragile fibers. The different components of the matrix and the textile fibers are the main elements of this reinforcement method. Both have to be designed to ensure maximum ductility. High adhesive tension strength on the stone surface and a high bonding with the fibers are required for any potential matrix. Different matrixes with different properties were tested at the Institute of Reinforced Concrete Structures (KIT-IMB) to determine their performance characteristics when used for the textile masonry composite system. The matrixes tested were: a) one “soft” mortar with high ductility from BG Polymers, b) a high “stiff” epoxy resin system (“Sika 331 W”) and c) an epoxy surfacer with 3 components (“Sikagard 720 Epo-Cem”). The first two compounds are an epoxy-dispersion and the last is a hard mineral granulation. The compression strength is approximately 40 N/mm² and the adhesive tensile strength is around 3-4 N/mm².

Small shear tests in size 363 mm x 240 mm x 175 mm with three sand lime bricks and between 2 mortar joints were produced to simulate the shear failure [2] in masonry walls. The two outer stones were hold and loaded with a compression force in the horizontal direction in such a way that the mortar bed joints are under normal compressive stresses. The mid brick was pushed using a displacement controlled piston. The force and the corresponding vertical displacement were measured. These tests indicated that the best material solution is between the extreme cases high stiffness (epoxy system) and the high strain rate (BG Polymers). The reason why the cement based epoxy surfacer ("Sikagard 720EpoCem") represented the best solution was a micro cracking and sliding crack direct over the bed joint. For a ductile behavior very stiff or a soft material is able to reach the same deformation for this effect like a "singularity line". While the Sikagard has a consistent load decline the BGP is on a lower strength level more volatile. Further developments will prefer cement based mortars like Sikagard 720 EpoCem, because they are working not like epoxy or other glues as an air barrier for the building which causes fungi and other water based damages.

4 EXPERIMENTS

4.1 Scaled wall tests

Scaled wall tests were conducted with different test specimens to select the best materials for the matrix-fibre-system. Small initial shear test specimens with three stones (363 mm x 240 mm x 175 mm) first simulated the failure mode [2] for walls with textile. Maintain tense consistency scaled wall test (1.25 m x 1.25 m) and full-size wall tests (2.5 m x 2.5 m) were conducted. In these tests the different parameters were the mortar matrix, the textiles and the vertical load value. The shear loading in-plane was in the strong inertia force direction with a vertical load between 0.2 and 1.0 MN/m². For the horizontal cyclic displaced head beam the displacement and the horizontal force were measured. Integrated optical sensors were fixed on the edges of the walls and measured continuously the strains in the mortar and textile (see figure 2).

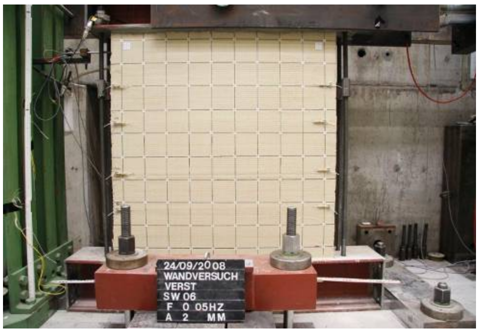

Figure 2: Wall 1.25 m x 1.25 m

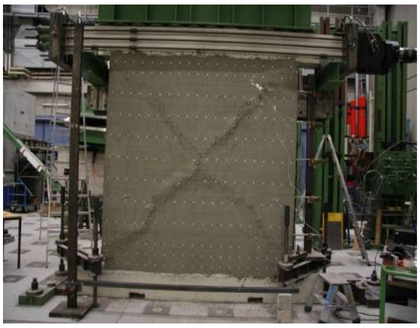

Figure 3: Wall 2.5 m x 2.5 m

Representative results of unreinforced masonry (URM) and reinforced masonry (RM) tests (1.25 m x 1.25 m) are shown below in figure 4 and 5. For the RM wall an optimized hybrid multiaxial textile and Sikagard 720 EpoCem was used. The maximum resistance force of the URM wall was 98 kN and the maximum load of the RM structure was 232 kN. This is an increase of 136%. But the more important effect is the increase of ductility of more than 200%.

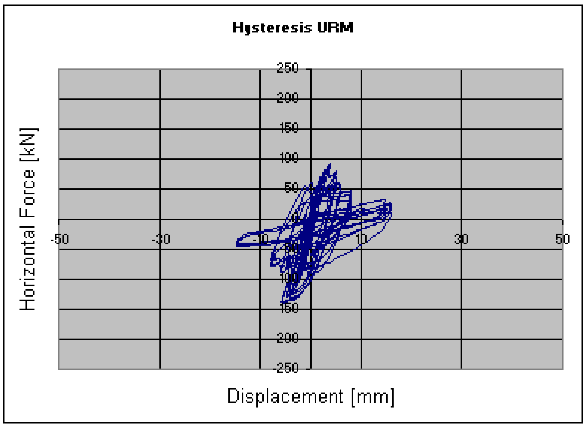

Figure 4: Hysteresis for the URM wall

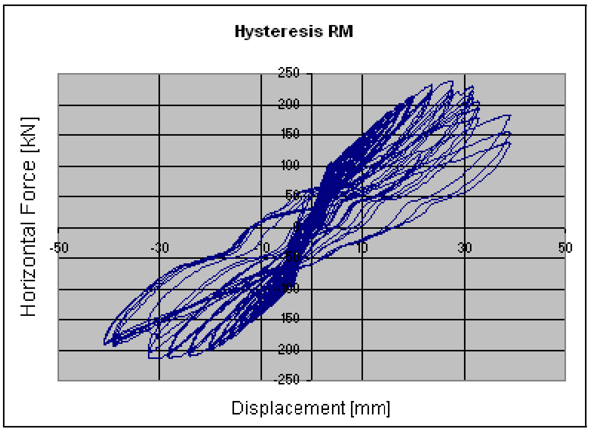

Figure 5: Hysteresis for the RM wall

4.2 Shaking table test with an full-scaled unreinforced masonry building

Motivated by like buildings damaged in the L'Aquila earthquake (2009) the EUCENTRE located in Pavia (Italy) emulated a building with the typical archetype with natural stones and a size from 5.8 m high, 5.8 m long and 4.4 m width. A uniaxial shaking table simulated the L'Aquila earthquake with different increasing amplification factors. After 0.4 g PGA the building was nearby destroyed.

Test number	Peak ground acceleration (PGA)
1	0.05 g
2	0.1 g
3	0.2 g
4	0.3 g
5	0.4 g
6	0.4 g with additional steel anchors

Table 1: Test program

The test of the URM structure exhibited common failure modes. The very soft wooden slab at the ground level led to out of plane bending failures in the front side (failure [1] and [2] in figure 6). Diagonal bending/tension cracks trough the mortar joints [5] over the window parts were the most important failures, due to the fact that the front corner in figure 6 was shortly before collapse. Only the wooden beam held this part together with friction and the roof load. A joint sliding [3], for the "in-plane" walls occurred in the cross between windows and doors and on the bottom between the doors [6]. After the shear cracks in the "beam"-parts [5] the front corner was the most moving part in the building and was the reason for the high deformation in this corner. An existing eccentricity though the asymmetrical arrangement of the wall stiffness led to an additional torsion moment which was increased after cracks in the front side and shear point shift toward the walls without openings (figure 7). This led to very high accelerations in the point A (figure 6). High local deformations in this area caused different orientated cracks in this corner region [4] (see figure 8).

Six tests were conducted until the building was damaged that a collapse was imminent. In the last step the peak ground acceleration was the same, but additional installed steel rods (see figure 6) were used to hold the building like a box together.

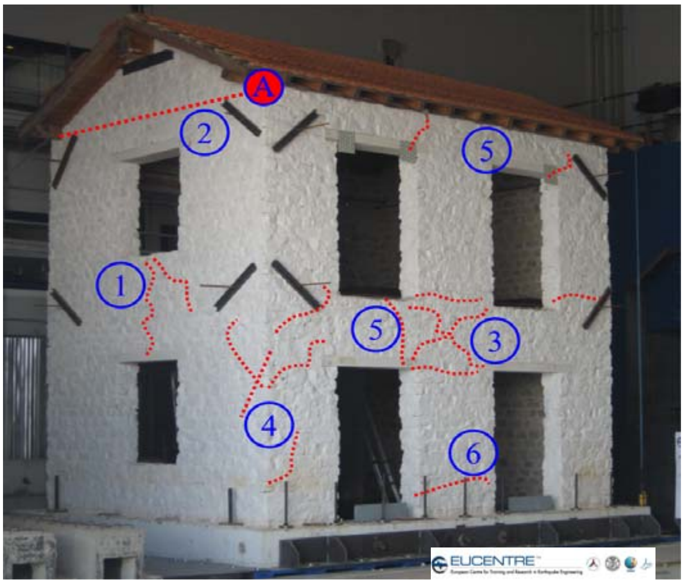

Figure 6: Crack pattern of the URM building

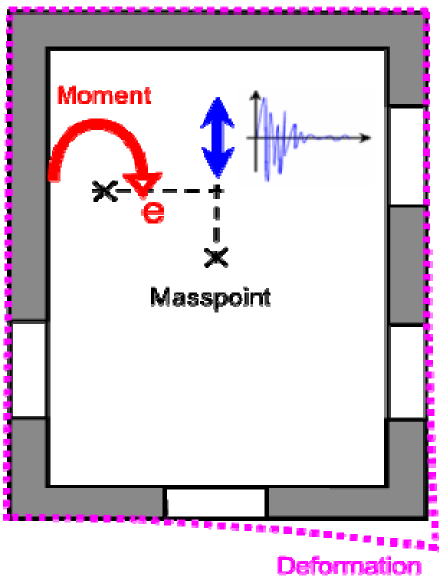

Figure 7: Deformation of the URM building

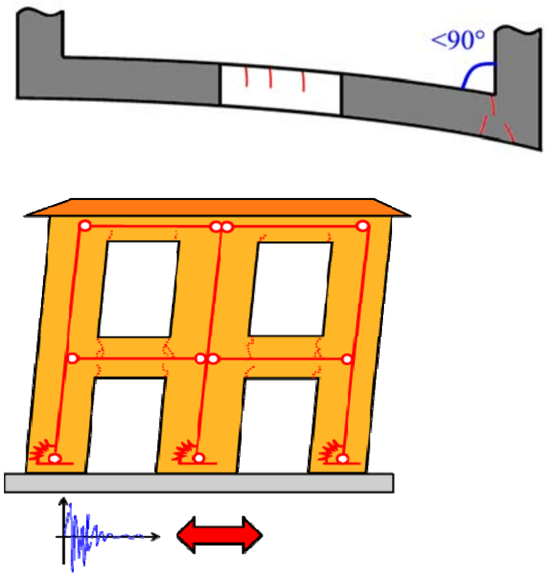

Figure 8: Crack patterns

4.3 Shaking table test with an reinforced masonry building

The idea behind the reinforcement method is to stabilize a building after huge cracks with ductile polypropylene fibers, to add more tensile strength with AR-glass fibers and to increase the global displacement ductility for horizontal force diminishing. The strengthening system is so flexible that it can be used as a repairing tool of nearly damaged masonry structures.

The base for the shaking table test with the reinforced building was the structure described in the chapter before. The pre damage structure was repaired and retrofitted with the mortar-textile system through full coverage application in a sandwich practice mortar - fabric - mortar (figure 9).

Figure 9: Masonry building with textile application

The same earthquake load time history was used. The corresponding response spectrum is shown in figure 11. The applied dynamic load was different between the original and the pre-damage sample due to the damages and cracks. During the test the main frequency of the URM building dropped down from 11.55 Hz (0.107 sec.) to 9.31 Hz (0.086 sec.). This caused a slight increase in the horizontal load.

Figure 10: Crack pattern: a) delamination, b) broken glass fibers

Regardless to the higher accelerations, the building reached with marginal cracks under the window location in the front side (figure 10) a maximum peak ground acceleration of 0.6 g without any tendency of stability failure. This was an increase of 50 % compared the un-strengthened URM structure. After inspection of the applied textile only the projected cracks in the stiff glass fibers were visible while the soft polypropylene fibers hold the crack together and worked like a damping spring in the system. Further frequency and system analysis will be presented in the presentation in the workshop.

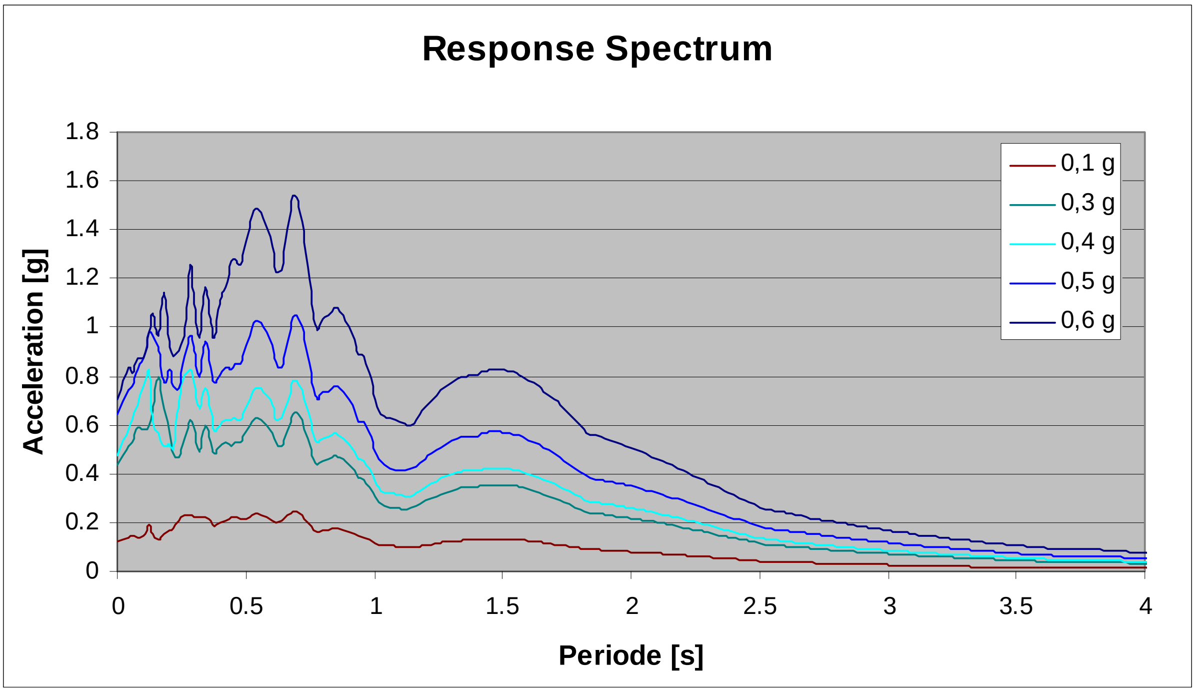

Figure 11: Response Spectrum of the Montenegro earthquake (1979)

5 CONCLUSIONS

Multi axial fiber reinforcing provides the engineer with a new tool for the seismic retrofit of unreinforced masonry structures. This special mortar/textile system adds strength, improves ductility and provides the opportunity to conduct structural health monitoring. Special optical fibers were used to measure strains online within the textile. The design, manufacturing, and testing of these textiles have occurred and are underway in the EU research project POLYTECT. The testing at the EUCENTRE showed the possibilities of such a system.

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