Comparison of different earthquake strengthening methods for masonry buildings

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SUMMARY:
In this paper a comparison of different strengthening techniques using various textiles are given. Four shaking table tests with full size masonry buildings were carried out to improve how different strengthening systems are working. Therefore a uniaxial glass fibre stripe solution with epoxy resin (FRP), a full coverage multi axial fibre and cement based mortar system and the unreinforced masonry were compared in three clay brick buildings on a 6-dof shaking table at SERC Chennai/India. The results demonstrated very different efficiencies of each system. Another natural stone building with the archetype like buildings in the region from L'Aquila/Italy was tested to check the performance of the full coverage solution in the case of exiting predamages due to former earthquakes. The presentation includes the repair and the results of the shaking table tests which are carried out on a single-degree-of-freedom shaking table in Pavia/Italy. Pretesting with small 1.25 m x 1.25 m x 0.24 m natural stone walls is also discussed.

Keywords: shaking table test, masonry, strengthening, quadaxial hybrid textile, cement based matrix

1. INTRODUCTION

Fibre materials as reinforcement are one out of several strategies to retrofit or strengthen existing masonry buildings. The benefit is the additional high tensile strength for masonry, while the weight compared to other materials is very low. This is the most important benefit for earthquake loads which are related to the mass of a building. The effects to masonry structures are through the failure mechanisms very different and dependent on the orientation. The load bearing of walls can happen in the out of plane and in plane direction. Therefore all researchers divided the both loading scenarios in their experimental campaigns in two different cases and conducted tests on out of plane specimens and in plane specimens. In this paper the first mentioned failure scenario is considered, which is responsible for the load capacity of a masonry building.

For in plane loading different authors made several static cyclic, pseudo dynamic and dynamic real-time tests on single masonry walls. Schwegler one of the first researchers in this field tested under cyclic loading masonry walls with different fibre materials and different reinforcement strategies in 1994. He found that full covered solutions are less problematic for the bonding failure in the stone surface. Wallner considered the existence of openings in walls with windows in his work. Other fibre reinforced materials were conducted by Hohlberg and Hamilton and Münich in static cyclic tests. Only El Gawady tested his walls under dynamic conditions on a shaking table. He used hollow bricks, carbon stripes, glass and aramid fibre textiles. The possible increase in the load bearing capacity was between 30% and 150%.

Positive studies in the past showed the possibilities of the fibre materials in the field of application for masonry. But there is still missing the knowledge about the real behaviour under dynamic and full building conditions. This work shows a new reinforcement technique which was tested under static cyclic tests, full building conditions and under dynamic shaking table conditions.

2. MATERIALS

In general the fibre material is in all test specimen embedded in a matrix which provide a good bonding to the masonry surface. Different fibre fabrics and matrix materials were used in this experimental campaign and given in the table below.

Table 2.1.

Specimen	Matrix	Textile	Fibre Material
Wall 1 – natural stone	-	-	-
Wall 2 – natural stone	Sikagard 720 EpoCem	hybrid, 4-axial	glass + polypropylene
Natural stone building 1	-	-	-
Natural stone building 1-precracked	Sikagard 720 EpoCem	hybrid, 4-axial	glass + polypropylene
2-Storey building – 1	-	-	-
2-Storey building – 2	epoxy resin	stripes, uniaxial	glass
2-Storey building – 3	Sika MonoTop 722 Mur	hybrid, 4-axial	glass + polypropylene

Three different matrix materials like *Sikagard 720 EpoCem*, Sika MonoTop 722 Mur and a common epoxy resin were used for application. The first mentioned material was applied directly to the stone surface in a special mortar-textile-mortar sandwich configuration. *Sikagard 720 EpoCem* as matrix for the bonding to the natural stone consists on three components: A = cement powder, B = epoxy resign, C = hardener. Especially the fineness of powder grinding plus the epoxy component provide a perfect bonding to the fibre grid with his small openings which are visible in figure 2. Less optimal for the bonding is *Sika MonoTop-722-Mur* because the fineness with particle size of up to 1 mm results in more air pockets around the fibres. But this mortar is for the practical use the more economic material. The last matrix is a high performance epoxy resin with excellent bonding behaviour to the fibre as well as the stone surface. But it implicates the vapour barrier effect and should not be applied in full covering the surface. This reason together with the high price leads in the past to the stripe solution in combination with carbon or glass-fibre materials [Schwegler, El Gawady…]. Here it is used as benchmark for materials which were used in the most works in literature.

Two different fabrics were used in the experimental campaign. The first is a 15 cm wide uniaxial glass-fibre textile for stripe application with epoxy resin and the second is a hybrid multiaxial fabric for full covering the masonry surface. As new system a 425 g / m² heavy glass fibre/ polypropylene fabric was developed that takes into account all possible failure modes of masonry. It is woven in four fibre directions in angels of 0°, 90° and +/- 30° with the two different fibre materials. In a sandwich structure consisting of a layer of high-strength epoxy-cement mortar, a layer fibre fabric and a covering layer of the same mortar, the whole system is applied flat to the outside surface of a building. The system is called “eq-grid” (see figure 1 + 2).

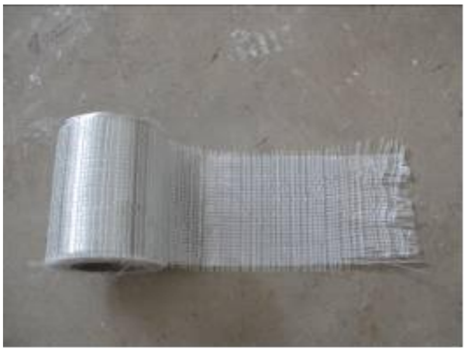

Figure 2.1. Uniaxial fabric for stripes

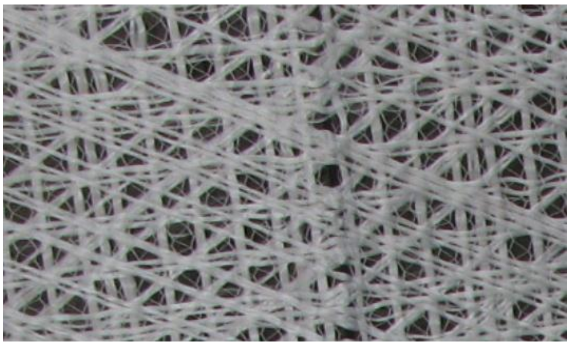

Figure 2.2. Eq-grid fabric with four fibre directions

3. NATURAL STONE MASONRY

3.1. Static Cyclic Wall Tests

Scaled wall tests were conducted with two different test specimens to compare the behaviour of unreinforced and strengthened masonry. The used construction materials for the masonry were an Italian mortar and natural stones with the origin of north Italy. The specific mechanical properties are given in table 3.1.

Table 3.1.

Material	Compression strength [N/mm^2]	Flexural tension [N/mm^2]
Mortar	3.67	0.88
Stones	166.7	-

The shear loading in-plane was in the strong inertia force direction with a vertical stress of 0.4 MPa. For the horizontal cyclic displaced head beam the displacement and the horizontal force were measured.

Representative results of an unreinforced masonry (URM) and a reinforced masonry (RM) wall test (1.25 m x 1.25 m) are shown below in figure 3.1. & 3.2.. The strengthening was conducted on only one side with Sikagard 720 EpoCem and a hybrid quadaxial glass-fibre and polypropylene- fibre fabric. The maximum resistance force of the URM wall was 117 kN and the maximum load of the RM structure was 147 kN. This is an increase in maximum force of 25 %. But the more important effect is the increase in ductility. Both walls failed in diagonal cracking through the mortar joint and the stones. While the crack opening was more than 30 mm after a wall displacement of 16 mm in the case of the unreinforced wall, only 3 mm were measured after 28 mm displacement with fibre reinforcement. Much more small cracks were observed in the last case and the increase in maximum displacement reached in comparison 75 %. Further dynamic studies are presented in the next chapter.

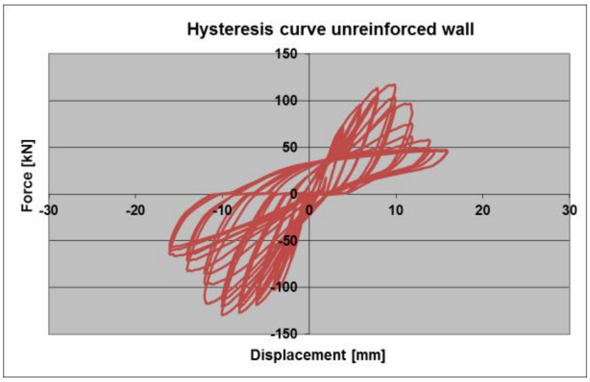

Figure 3.1. Test result on a unreinforced wall

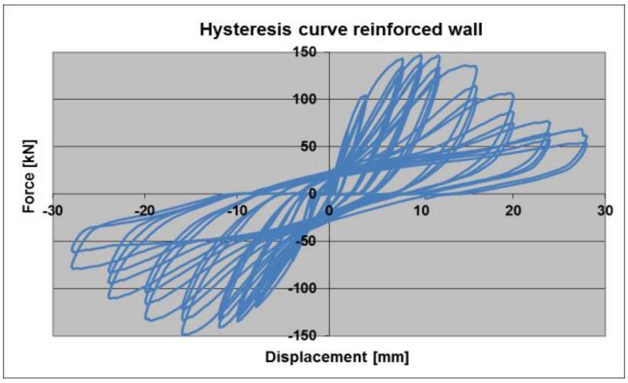

Figure 3.2. Test result on a reinforced wall on one side

3.2. Natural Stone Masonry Building under uniaxial Earthquake Loading

Motivated by buildings damaged in the L'Aquila earthquake (2009) 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 was built on a shaking table in Pavia (Italy) at the EUCENTER. A uniaxial shaking table simulated an earthquake and in five increasing amplification steps from 0.05 g peak ground acceleration (PGA) to 0.4 g. After the last earthquake loading the building was almost destroyed and had several big cracks (see figure 3.3).

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 no. 1 and no. 2 in figure 3.3). Diagonal bending/tension cracks trough the mortar joints (no. 5) over the window locations were the most important failures, due to the fact that the front corner in figure 8 was shortly before collapse. Only the wooden beam held this part together with friction and the roof load. A joint sliding (no. 3), for the “in-plane” walls occurred in the cross between windows and doors and on the bottom between the doors (no. 6). The shear cracks at the “beam”-part (no. 5) resulted in the most moving point at the front and were the reason for the high deformation in this corner area. 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. This led to very high accelerations in the point A of about 0.9 g. High local deformations in this area caused different orientated cracks in this corner region (no. 4)

After repairing the displaced roof and the wooden slab as retrofitting tool the eq-grid system was used to repair all the cracks in the masonry which occurred in the tests before. The tests of the repaired building showed no cracks after 0.4 g PGA, the maximum level of the URM building. Further tests at 0.5 g led to small micro cracks at the window locations. The maximum possible PGA for table was reached after 0.6 g. At this stage cracks in the glass fibres occurred local under both windows at the front side which is seen in figure 3.3. Also delamination between the first layer mortar and textile was observed, but the total building was in good shape. The textile as repairing solution after the damage could retrofit the building at least to the original strength plus 50% more capacity.

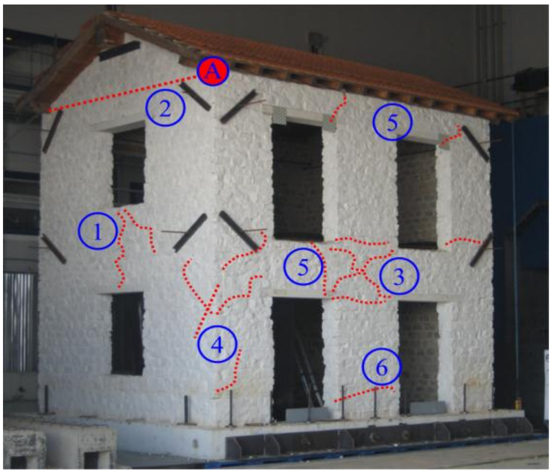

Figure 3.3. Cracked URM building

Figure 3.4. Reinforced building with quadaxial fabric

4. CLAY BRICK MASONRY UNDER TRIAXIAL EARTHQUAKE LOADING

Three identical and for India typical buildings were constructed to observe the different behaviour of two fibre reinforcing methods in comparison to an unreinforced structure. All three buildings were built with full clay bricks (size 220 mm x 110 mm x 70 mm) and a cement based mortar (cement mortar ratio = 1:4). Important to mention is the untypical case of a high mortar stiffness in comparison to a low stiffness of bricks.

Table 4.1.

Material	Compression strength [N/mm^2]	Young’s Modulus [N/mm^2]	Compression strength parallel to the bed joint [N/mm^2]
Mortar	7.1	1540	-
Stones	9.6	808	4.3

The 2- storey building had different window and door configuration in each floor. In the ground level one entrance door (2.11 m x 0.79 m) in front and one window (1.15 m x 0.79 m) on the backside were chosen. In the second level two windows and one balcony door were inserted. One side of the building had no opening which resulted in a very stiff behaviour and load eccentricity through shifting of the shear point toward this wall. The connection of the walls where realised with two stiff reinforced concrete slabs (thickness 0.1 m) in each storey.

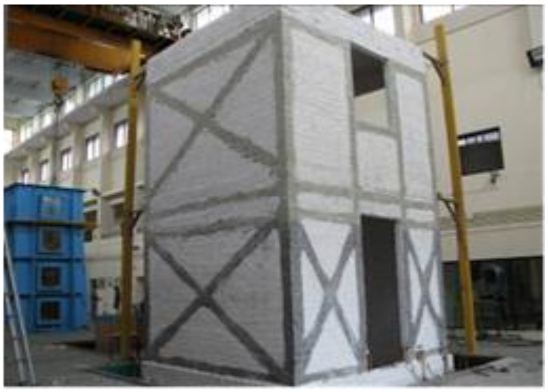

Figure 4.1. Clay brick building with stripe application (east – north side)

Figure 4.2. Application with quadaxial textile (west-south-side)

While the first unreinforced building got only a painting the second one was strengthened with glass-fibre-stripes UNIE410 which were glued with an epoxy resin Araldite LY556. The stripe configuration was like timber framing and was applied in X-Style to the masonry surface (see figure 4.1).

For the third building the full covering solution with the multiaxial textile embedded in a cement based matrix was chosen. Therefore the mortar *Sika MonoTop-722-Mur* was applied directly to the whole masonry surface on the outside and the textile was embedded into the fresh mortar.

The testing was conducted on a 3-D shaking table at SERC in Chennai (India) and was divided in twelve different steps. The ground shaking was scaled to different peak ground acceleration and increased in each test up to the maximum possible level like presented in the table below:

Table 4.2.

Test step	**PGA [g]**	**max. horizontal ground displacement**	**Building unreinforced**	**Building with stripes**	**Building with multiaxial textile**
1	0.05	+/- 7.9 mm	X		
2	0.075	+/- 11.9 mm	X		
3	0.1	+/- 15.9 mm	X	X	X
4	0.15	+/- 23.6 mm	X	X	X
5	0.2	+/- 31.6 mm	X	X	X
6	0.3	+/- 47.3 mm	X	X	X
7	0.4	+/- 63.3 mm	X	X	X
8	0.45	+/- 70.9 mm	X		
9	0.5	+/- 67.7 mm		X	X
10	0.55	+/- 74.4 mm		X	
11	0.6	+/- 80.9 mm			X
12	0.7	+/- 94.2 mm			X

The response spectrum as input was according to the Indian Standard 1893:2002. While the maximum horizontal accelerations (X and Y direction) were kept similar, the vertical component (Z direction) was only two-third to that given in the X and Y axes. The response spectrums in vertical and horizontal direction for the third test are presented in figure 4.3 and 4.4. To mention is that both horizontal response spectra are similar.

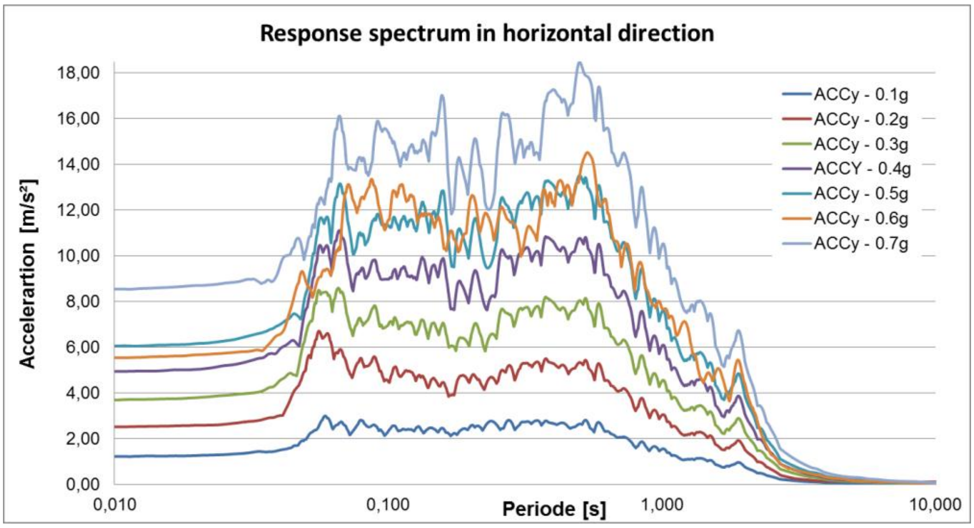

Figure 4.3. Response spectrum for the earthquake acceleration in the north-south direction

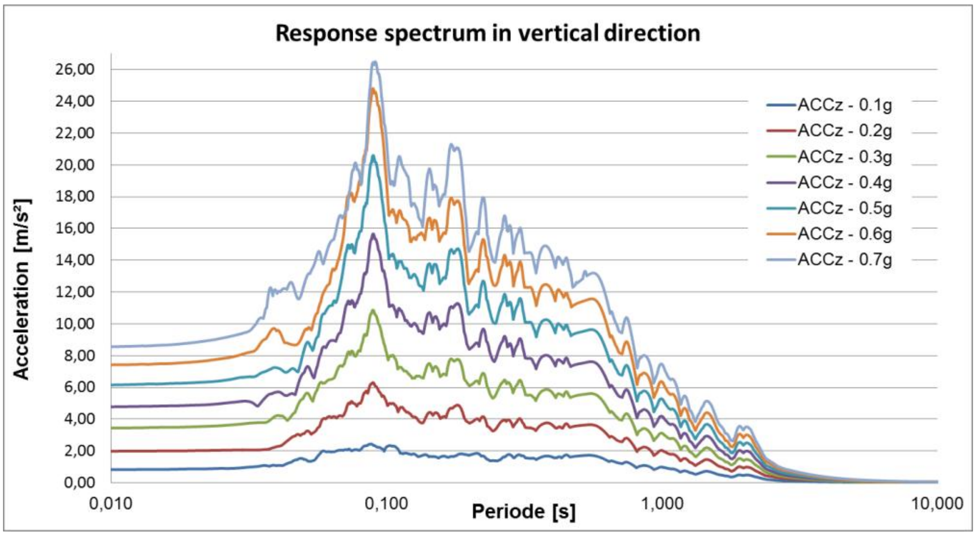

Figure 4.4. Response spectrum for the earthquake acceleration in the vertical direction

All three buildings failed similar in shear sliding of the horizontal mortar joint around the building in the first 5 brick rows on the bottom. Through rocking of the buildings also in the corner of the door in the first level horizontal cracks were observed. The method with X stripes lead to force concentration in the corners of the building which resulted in cracking of bricks and failure in the bonding of the glass fibre to the stone surface. On the wall side without opening additionally to the horizontal shear failure a vertical crack with a length of approximately 90 cm on the left corner was developed in each case. The solution with the quadaxial textile leads on this location to several fine cracks. No cracking of the fibres were observed.

In the first test the unreinforced building reached maximum possible peak ground acceleration (PGA) after 0.45 g. The stripe application could hold together the shear cracks till the step of 0.55 g which is in comparison an increase of 22 %. Much better was the result with the full covering solution. In this case a maximum PGA of 0.7 g lead to failure and means a 55% higher earthquake load than for the unstrengthened masonry.

In comparison to the uniaxial shaking table test in the chapter before, the main difference was introduced with the vertical acceleration component. This lead to very unsteady and a wide range of normal stresses σ_d between 0.05 N/mm² and 0.25 N/mm² in the bed joint dependent on the time like shown in figure 4.5.

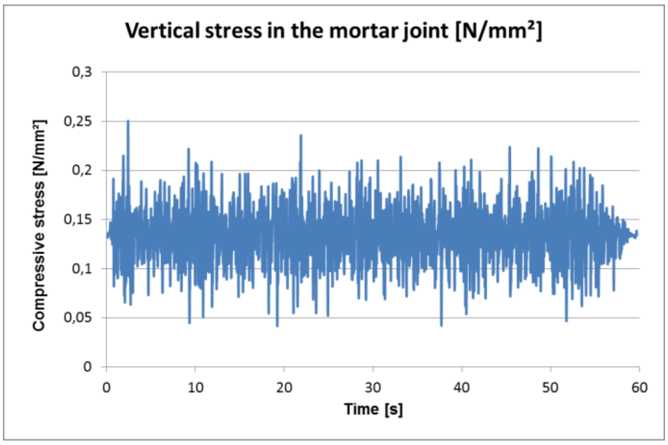

Figure 4.5. Calculation of the stresses in the failed mortar joint

This shows that the shear resistance f_{vk} is time dependent and equation (3.5) in the EC6 can be written as follows:

$$f_{vk}(t) = f_{vk0} + 0.4 \cdot \sigma_d(t) \tag{4.1}$$

This shows the importance of the vertical component for the calculation of masonry buildings. In building 3 with vertical and diagonal fibres the normal stress σ_d was increased through the vertical force-component of the fibres after small displacement. The result was a 55% higher earthquake capacity through this effect.

5. CONCLUSIONS

Two different full scaled buildings under real time earthquake loading showed an increase of 50% and 55%, if the outside surface was strengthened with a 4-axial glass-/polypropylene-fibre textile together with a cement based mortar matrix. In comparison to a stripe application the full covering solution has the double efficiency. The realistic 3-D shaking shows the force reduction due to the vertical component, if friction in consequence of the normal stress is reduced. Together all results show a significant increase in strength and ductility which are the key factors for many old existing buildings in earthquake risk zones.

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