Seismic retrofit system for single leaf masonry buildings in Groningen

Ö.S. Türkmen
Eindhoven University of Technology, Eindhoven, Netherlands (QuakeShield, Groningen, Netherlands)

A.T. Vermeltfoort & D.R.W. Martens
Eindhoven University of Technology, Eindhoven, Netherlands

ABSTRACT: Due to recent seismic activity in the Netherlands, the demand of adequate strengthening and retrofitting techniques increased, especially for single leaf masonry. Two Dutch companies founded in the region have initiated an experimental program to study the applicability of existing stand-alone seismic retrofit systems on the unique and challenging situation in Groningen. During the out-of-plane experiments it was concluded that the existing materials used in stand-alone retrofit systems were insufficient and needed improvement. By applying special developed glue and combining two stand-alone seismic retrofit measures, an amplifying effect in terms of load bearing capacity and ductility was reached. The proposed patented seismic retrofit system is tested in bending on wallettes and on walls which were loaded in-plane.

1 INTRODUCTION

In Groningen, an area in the North-East of the Netherlands, earthquakes occur as a result of the subsidence of the ground at relatively shallow depth beneath the earth's surface. This is caused by the extraction of gas from the Groningen gasfield. These so-called "induced" earthquakes distinguish themselves from the common and well known "tectonic" earthquakes, which occur as a result of ground movements in the deep crust. Another distinctive aspect is that the soft claylike soil in Groningen transmits the vibrations better compared to a rocky soil.

Research and measurements done by KNMI provides a contour plot of peak ground acceleration (PGA) of the Groningen area (NPR 9998). The maximum value in this contour plot is 0,36g with a return period of 475 years. Further research into the expected values in the subsoil is necessary and is carried out under the responsibility of the NAM (Nederlandse Aardolie Maatschappij) and the Dutch State.

The majority of buildings in the North-East of the Netherlands is composed of unreinforced single leaf masonry, only designed to withstand wind loads. Investigations by Hageman, included in the NPR 9998, show that critical houses can withstand not more than 0,03g. The to be built buildings are being designed to be able to withstand 0,6g.

The fact that there is less experience with induced earthquakes than with tectonic earthquakes, the presence of a claylike soil, and the fact that the buildings in the Groningen region were initially not designed to withstand earthquakes, make the situation of Groningen unique and therefore a challenge for scientists and engineers. To prevent building collapse, with likely casualties, it is necessary to improve the earthquake resistance of the current buildings in the area, while at the moment they do not comply to the earthquake design rules according to the NPR 9998.

Worldwide several materials and techniques are being used to improve the seismic performance of existing URM walls. These include: a) stitching and grout/epoxy injection, b) re-pointing, c) bamboo reinforcement, d) post-tensioning using rubber tires, e) various types of mesh reinforcement or f) one of the advanced materials like Fibre-Reinforced Polymer (FRP) or Engineered Cementitious Composites (ECC), which are efficient though costly (Bhattacharya et al. 2015).

Some key aspects need to be taken into account when selecting a suitable solution. Adding considerable mass to the structure increases earthquake-induced inertia forces, so lightweight solutions are preferred. Ductility is one of the most important seismic requirements for all kinds of construction (Reitherman & Perry 2009). Unreinforced masonry, which lacks ductility, often fails in a brittle manner. When it is shaken severely it cracks and falls apart in a number of pieces. Therefore it is essential to "tie it together".

The Dutch companies Oosterhof Holman and SealteQ have joined forces to provide a solution for the previously stated problem with Dutch innovation capacity and international knowledge, together with the Universities of Eindhoven, Groningen and Delft.

The challenge is to find and develop a suitable seismic retrofitting system for the single leaf masonry buildings in Groningen. The system must increase ductility without adding considerable mass.

In this paper, several solutions are studied and the most promising one are tested on a smaller scale in bending using wallettes and on larger in-plane loaded walls.

2 EXPERIMENTAL PROGRAM OF OUT OF PLANE TESTING

2.1 *Test set up*

One of the most critical deficiencies of historic clay brick unreinforced masonry (URM) buildings is the out-of-plane (OOP) failure mechanism induced by lateral earthquake loads. From this point of view, the experimental program started with three-point bending tests on wallettes, conducted to conform with NEN-EN 1052-2. Figure 1 shows the OOP test set-up. A schematic overview of the setup is provided in Figure 2.

Figure 1. OOP test set-up

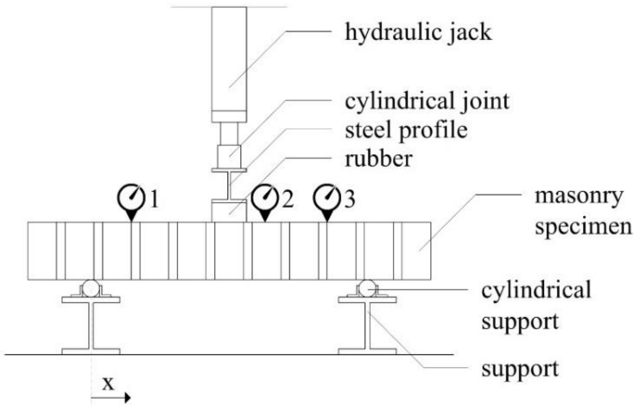

Figure 2. Scheme of OOP test set-up

2.2 *Experiments, first series*

The first series of specimens was intended to get more insights in the behavior of the various potential retrofitting solutions. The specimens were built with conventional clay brick masonry from the Groningen area. Material properties of the bricks and mortar used are given in Table 1.

Table 1. Material properties used bricks and mortar

Material property	Unit	Clay brick	Mortar
Density	kg/m3	1566	2990
Young's modulus	GPa	6,05	0,70
Compressive strength	MPa	20,0	12,5-32,5

In the first series of tests, specimen length was 580 mm, and its averaged width was 540 mm. The span between the cylindrical supports was 480 mm. Three digital dial gauges measured the out of plane displacement with an accuracy of 0,1 mm on three points, 60 mm, 480 mm and 540 mm from the support, as presented in Figure 2. The capacity of the hydraulic jack was 62 kN.

2.3 *Potential solutions*

Based on several techniques that are available to improve the seismic performance of existing URM walls, potential solutions have been selected (and combined) for testing on the OOP test set-up:

- Strengthening layers based on either cement or a specific polymer
- Externally bonded (EB) FRP sheets or plates
- Near surface mounted (NSM) FRP rods or strips. For the conducted experiments the NSM rods/strips were placed with an interdistance of 250 mm.

An overview of the materials used for reinforcement is shown in Figure 3. More than a 100 options and variations have been tested.

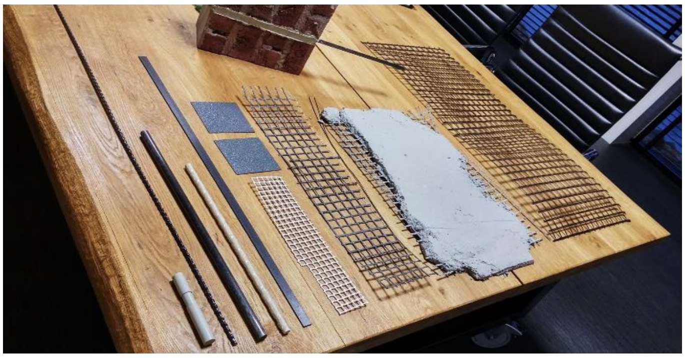

Figure 3. Overview of the used strengthening materials

EB sheets or plates and NSM FRP bars or strips are the two FRP application techniques that are commonly used. Using the NSM strip technique provides several advantages over the EB technique, including significantly higher axial strain at debonding, minimal negative impact upon the aesthetics of the structure, and reduced installation time. (Petersen et al. 2009, Seracino et al. 2007)

The combination of individual retrofit measures is also investigated to observe the possible amplifying effect on load bearing capacity and ductility. Therefore, a strengthening layer and NSM strips, in grooves, are placed on the bottom surface of masonry specimens, as shown in Figure 4.

An overview of the most important (un)reinforced specimen(s) of this series is given in Table 2.

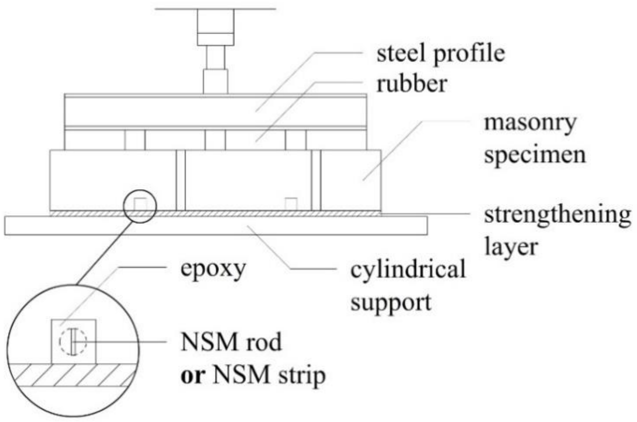

Figure 4. Schematic vertical section over the masonry specimen in the test set up with the position of the strengthening layers and reinforcement indicated.

Table 2. Description of a select number of specimens for the first series of OOP experiments.

Specimen	Description
A.G0	Unreinforced masonry
A.G1	2x NSM Carbon rods (15mm), imbedded in a hard epoxy glue
A.G4	PP-net imbedded in a polymer based layer
A.G3	PP-net imbedded in a polymer based layer; 2x NSM Carbon rods (15mm), imbedded in hard epoxy glue
A.G8	Carbon-net imbedded in a cement based layer; 2x NSM Carbon rods (15mm), imbedded in hard epoxy glue
A.G9	Carbon-net imbedded in a cement based layer
A.G10	Carbon-net imbedded in a cement (PUTZUNA) based layer.
A.G11	Carbon-net imbedded in an epoxy layer
A.G12	2x NSM Carbon strips (15x2,8mm), imbedded in a special developed adhesive

Load-mid span deflection diagrams are shown in Figure 3. The displacement is value as indicated by the second digital gauge, as shown in Figure 2.

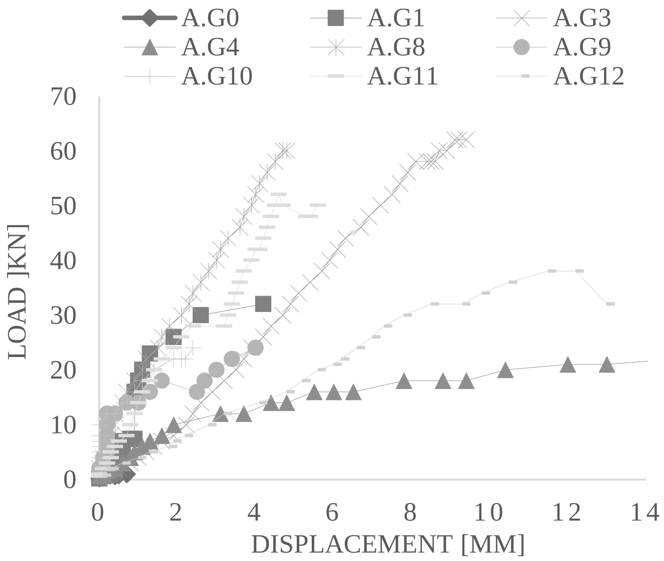

Figure 5. OOP test results first phase

Table 2 shows a wide range of possible (combined) seismic retrofit systems each with its own stiffness, from stiff solutions like specimen A.G3, to flexible options like specimen A.G4. Specimens A.G3 and A.G8 could not be tested to failure because of the limited capacity of the hydraulic jack.

Looking at the results of the combination of NSM carbon rods with a polymer based layer with an imbedded PP net, the larger load bearing capacity is clear. In terms of OOP performance, combining individual retrofit systems can be of significant added value.

The comparison between specimens A.G3 and A.G8 show the difference in flexibility. Specimen A.G3 had a polymer based reinforcement layer with an imbedded PP net and provides a more flexible behavior during OOP testing than specimen A.G8 with a cement based reinforcement layer with an imbedded carbon net. A.G3 also was the strongest.

Another interesting finding was the failure mechanism during the OOP testing of specimen A.G1, as shown in Figure 6. Stress concentrations parallel to the groove caused a crack between the hard epoxy glue and the masonry bricks. Applying carbon strips imbedded in a special developed visco-elastic adhesive (A.G12) prevents this type of failure. This visco-elastic adhesive (special type of epoxy) is more suited while it reduces stress concentrations in the adhesive-brick interface.

Figure 6. Cracking parallel to the groove due to the used hard epoxy glue

2.4 *Experiments, second series*

The goal of the second series OOP experiments was to optimize the most potential solutions from the first series. Some adjustments on the set up were made. The span was increased from 480 mm to 700 mm reducing the expected failure load and allowing the use of the same hydraulic jack as for the first test series. The position of gauge no. 2 was shifted 10 mm to the right (x=70mm).

Rubber strips were added between cylindrical support and specimen to improve the load distribution along the width of the masonry. Figure 7 shows the schematic overview of updated the setup.

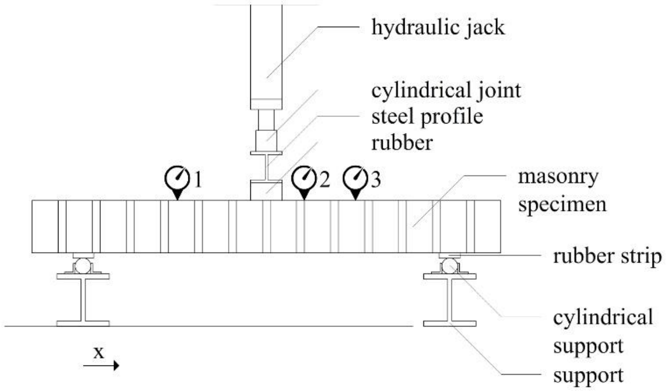

Figure 7. Updated schematic view OOP test set-up

An overview of the applied reinforcement in the specimens of this series is given in Table 3. For each seismic retrofit solution three specimens were built and tested.

Table 3. Overview of the applied reinforcement, second series of OOP experiments

Code	Description
B.G0	Unreinforced masonry
B.G1	PP-net imbedded in a polymer based layer; 2x NSM Carbon strips (15x2,8mm), imbedded in in a special developed ductile glue
B.G2	Carbon-net imbedded in a cement based layer; 2x NSM Carbon strips (15x2,8mm), imbedded in in a special developed ductile glue
B.G3	PP-net imbedded in a polymer based layer; 2x NSM surface treated glassfiber rods (15mm), imbedded in in a special developed ductile glue;
B.G4	Carbon-net imbedded in a cement based layer; 2x NSM surface treated glassfiber rods (15mm), imbedded in in a special developed ductile glue;
B.G5	PP-net imbedded in a polymer based layer

Two of the three URM specimens collapsed under their own weight soon after they were positioned on the supports. The third URM specimen failed under a load of 0.9 kN. No displacement could be measured.

The load displacement diagram of the three specimens of reinforcement system B.G1 is shown in Figure 8. The diagrams of B.G2 are given in Figure 9.

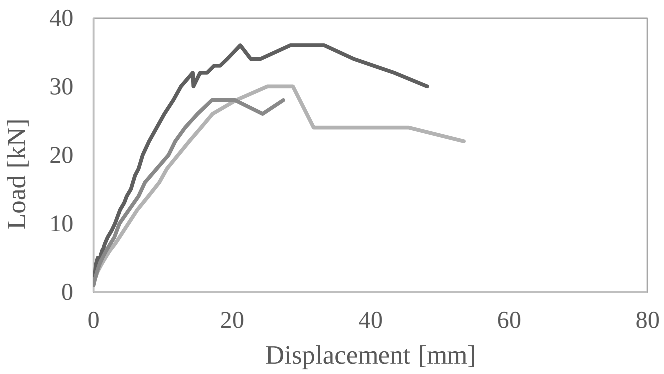

Figure 8. OOP test results of the three specimens of B.G1

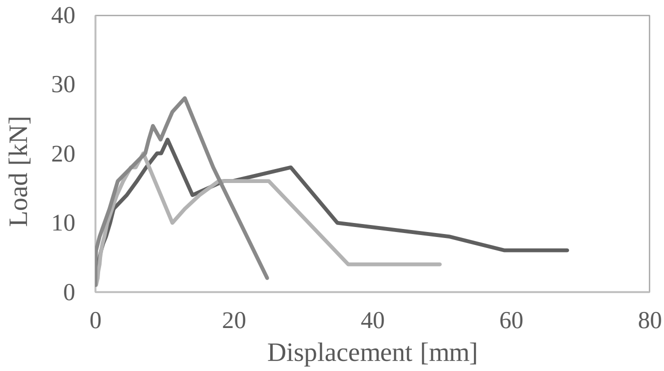

Figure 9. OOP test results of the three specimens of B.G2

B.G1 has an average maximum load of 31.4 kN and a corresponding displacement of 29.8 mm. The values for B.G2 were significantly lower; 23.4 kN and 10.1 mm respectively. This implies that the polymer based layer with imbedded PP-net is more effective for OOP loading while it results in a higher failure load, higher displacements and a less brittle post-peak behavior.

The mass added to the masonry is also significantly smaller for the polymer layer, less than 1 kg/m2 versus more than 40kg/m2.

Imbedding a carbon based net instead of a PP-net in the polymer layer can be of added value for the retrofit system due to the better material properties of carbon: tensile strength of 560 MPa versus 30 MPa.

Another major difference between the polymer based reinforcement layer and the cement based alternative, is the way the specimens recovers after the load is removed. B.G1 had a significant recovery as shown in Figure 10. After the load on specimen B.G2 was released, Figure 11, the specimen remained in its final form. This indicates that, in specimen B.G1, the connection between the carbon strip and the special developed ductile glue is still intact and bonded. Consequently, the masonry specimen bends back to near its initial state.

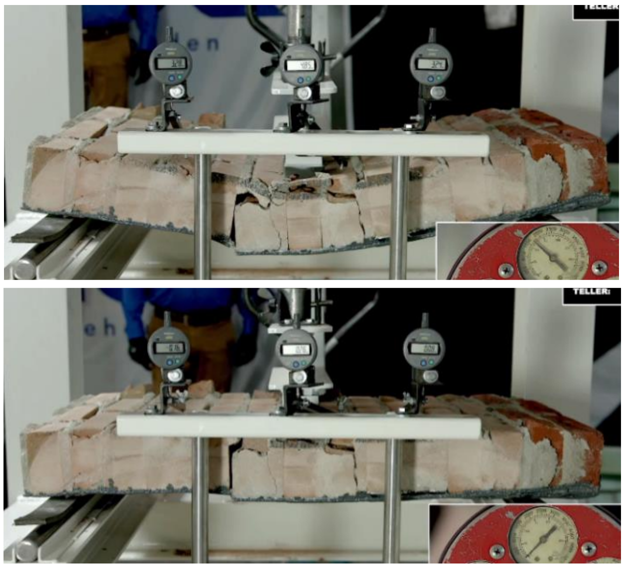

Figure 10. Snap shot of B.G1-1 when the maximum displacement is reached (top) and after the load is released (bottom)

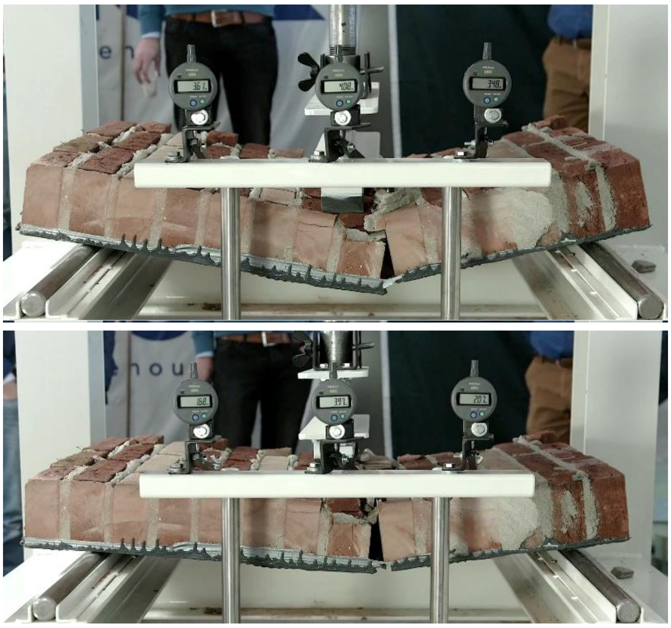

Figure 11. Snap shot of B.G2-1 when the load is released

Figure 12 shows the OOP test results of B.G3.

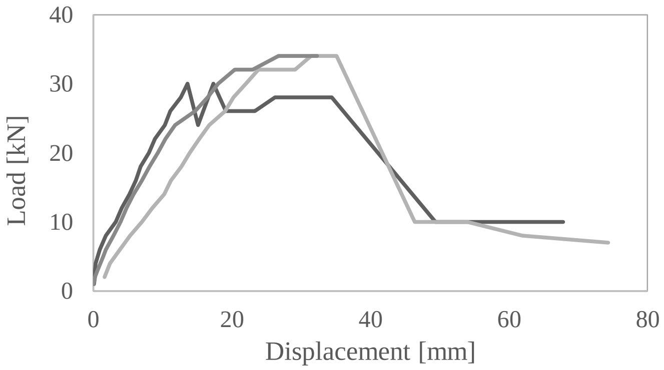

Figure 12. OOP test results of the three specimens of B.G3

The sudden drop in load of specimen B.G3 during the post-peak phase indicates a detachment of the glue and the sand-coated glass fiber rods. This is also confirmed by the reversed bending of the specimen when the load is released at the end of the test, Figure 13. Unlike specimen B.G1, specimen B.G3 is not able to reach the near initial state after the load is released. Even though the glass fiber is sand coated for better bonding, the special developed glue is more suited for carbon strips.

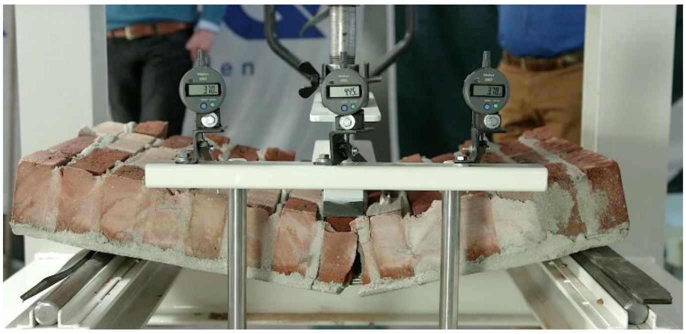

Figure 13. Snap shot of B.G3-1 when the maximum displacement is reached (top) and after the load is released (bottom)

Figure 14 shows the load displacement diagrams for three specimens with only a polymer based strengthening layer. The significant added value of combining two individual retrofit systems becomes clear.

By also adding NSM strips next to a reinforcement layer, an amplifying effect of ductility in the post peak phase is induced and thus a sudden failure mechanism (without pre-warning) is prevented.

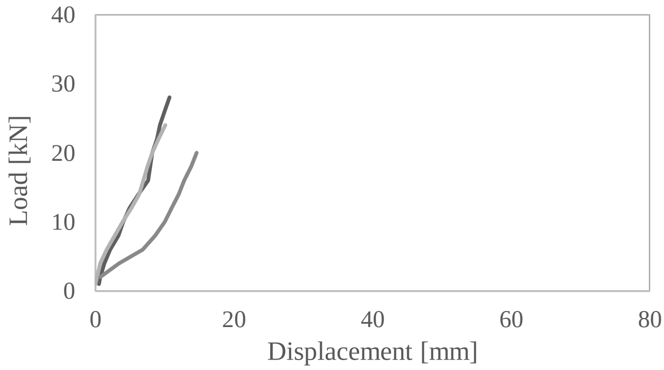

Figure 14. OOP test results of the three specimens of B.G3

2.5 *Mathematical model*

For low loads, the specimen is still not cracked and therefore its reaction is relatively stiff. Once cracked, stiffness is smaller and may be represented by a straight line, as to be seen in Figure 15.

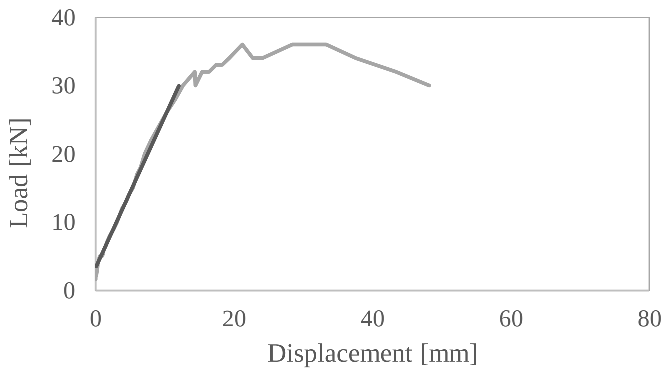

Figure 15. Stiffness of the specimen B.G1-1.

In the final phase, mesh and strips will act together to form a tie, resisting the bending moment in combination with the compressive stresses at the top edge. A rectangular stress block may be assumed, consequently with a relatively small compressive zone. Then, for specimen B.G1-1 the estimated compression force equals 64.8 kN. Based on test results the pull out load of the two strips with an anchorage length of half the span length (350 mm) is 35kN. The force in the mesh is approximately 30 kN. Due to different stiffnesses of mesh and strips their cooperation is not yet completely understood. Further research is needed.

2.6 *Proposed retrofit system*

Based on the findings of the OOP test results, a patented seismic retrofit system is proposed as shown in Figure 16.

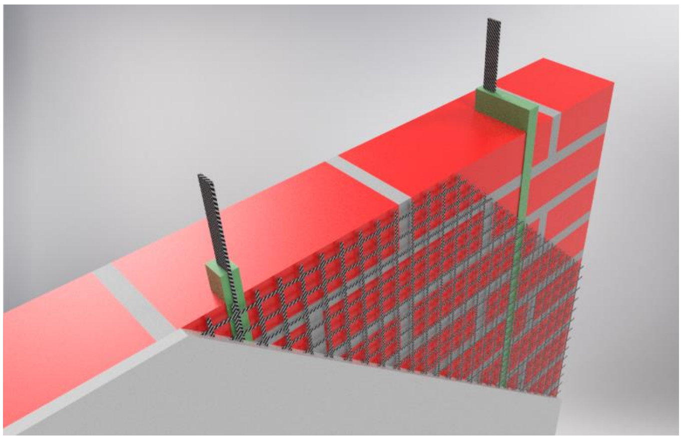

Figure 16. Proposed retrofit system QuakeShield

The strengthening process starts by milling deep and shallow grooves with a pre-calculated center to center distance, based on the required seismic strengthening of the building. The carbon strips will be imbedded in the grooves using a special developed visco-elastic adhesive. These grooves are made on two separate depths while strengthening for OOP loading in both directions is needed and only one side of the surface is treated.

By using this retrofitting method, either the habitants of the building can remain inside during the retrofitting process by working from the outside, or the outer esthetics of the buildings can remain intact by applying the retrofit system from the inside of the building.

After the strips are placed, a carbon net is placed on the surface. Finally either a cement based or a polymer based layer is applied.

As shown in Figure 15, this system has an optimum side (i.e. surface with final layer) and a non-optimum side where the tensile capacity is achieved by the deep placed carbon strips. In order to obtain a first impression of the load-displacement behavior of the specimen in the weakest situation, i.e. when the non-optimum side is in tension, two OOP tests were conducted as indicated in Figure 17.

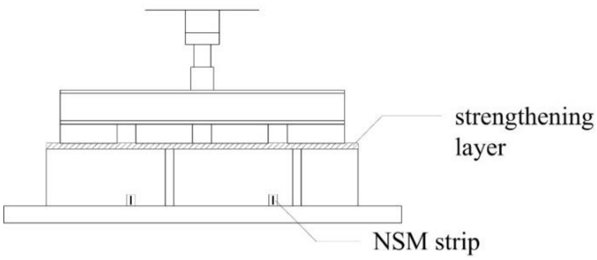

Figure 17. Schematic vertical section over the masonry specimen in the test set up with the position of the strengthening layers and reinforcement indicated of the non-optimum side

The results of the OOP loading of the specimen in the weakest direction, Figure 18, show that both the ultimate load and the corresponding displacement reduce with 29.9% (from 31.4 kN to 22.0 kN) and 9.6% (from 29.8 mm to 26.9 mm) respectively, compared with the BG.1. Additionally, the post peak behavior is affected. More research is needed to further optimize the strengthening of the non-optimum side.

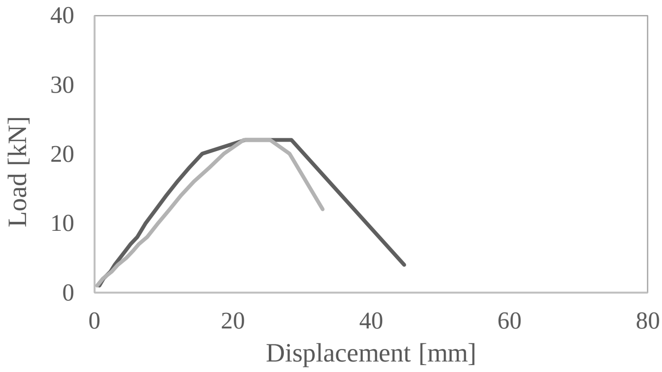

Figure 18. OOP test results of the non-optimum side

3 IN-PLANE EXPERIMENTAL PROGRAM

3.1 *Test construction*

To test masonry wall panels in shear a horizontal load can be applied on the horizontal top edge. Several boundary conditions are possible at the horizontal top edge and at the sides.

In order to conduct these kind of tests, a construction was built based on the testing equipment used by ESECMASE.

Figure 19. In plane test installation

The cantilever configuration has been chosen, which represents the case in which the wall is not loaded by the floor or the floor is a deformable diaphragm.

The dimension of the masonry walls was 4000 x 2500 x 100 mm3, and they were built on a concrete beam of 4000 x 200 x 200 mm3.

Load were applied via two vertical and one hydraulic jack using a computer controlled system measuring oil pressure.

The applied vertical pre stress during testing was 0,6 MPa and intended to remain constant during testing. However, it varied within a margin of 5%.

The horizontal load was applied in steps of 5 kN with a speed between 0,58 kN/s and 1,97 kN/s. Load decrease varied between 0,58 kN/s and 3,36 kN/s. The time to apply one load step varied between 2.5 and 9 sec. The horizontal force was measured by two load cells. The vertical forces were calculated using the oil pressure.

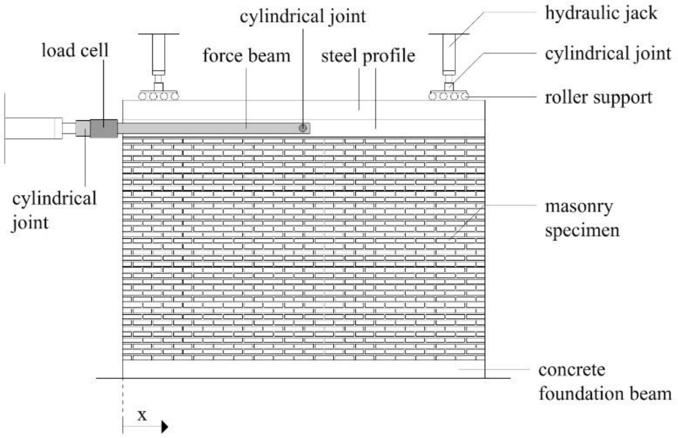

Figure 20. Schematic view of the in plane test installation

The displacement is measured on the specimen at seven different locations. The in plane horizontal displacement was measured on the 4th brick from the top, and the 2nd brick from the bottom. Three vertically installed sensors measured the vertical displacements of the roof beam and two diagonally placed sensors were used to map the deformation of the walls. Laser sensors with an accuracy of 7 microns have been used.

The dimension of the masonry test walls was 4000 x 2500 x 100 mm3. The walls were built on an concrete beam of 4000 x 200 x 200 mm3. The beam was used to anchor some of the carbon strips, using steel rods, 650 mm in length, 12 mm in diameter. These steel rods were drilled 150 mm into the foundation and imbedded in a non-ductile glue. The other 500 mm was, together with the carbon strips, imbedded in the visco-elastic glue. Figure 21 gives a schematic overview of the reinforced and anchored wall specimen with no openings.

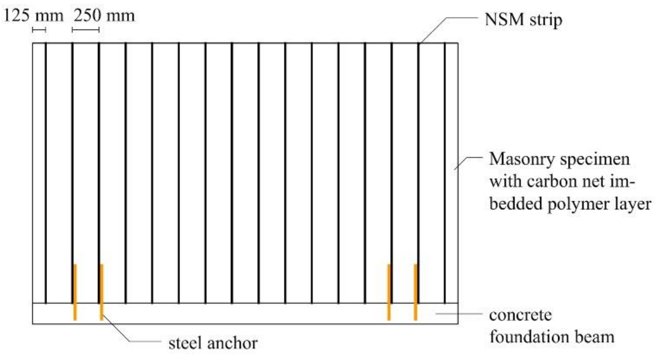

Figure 21. Schematic view of the reinforced and anchored wall specimen with no opening

3.2 *Test results in-plane experiments*

Figure 22 shows the force-displacement hysteresis plot of both the QuakeShield reinforced masonry (QSRM) and URM wall specimen with no opening. The indicated displacement is the difference between the upper in-plane sensor (4th brick from the top) and bottom (2nd brick from the bottom).

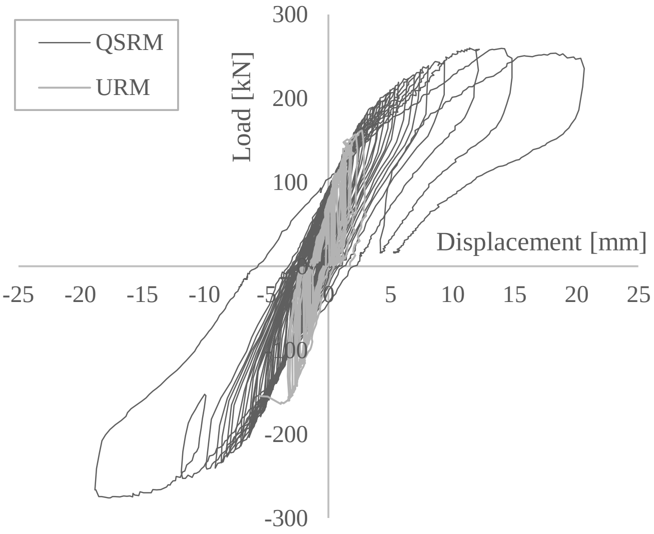

Figure 22. Force-displacement hysteresis plot of both the reinforced/anchored masonry wall and URM without an opening.

The maximum in-plane load reached with the unreinforced specimen was 164 kN at a displacement of 3.84. QSRM gave the values 276 kN an 17.59 mm respectively. The anchors prevented bed joint failure and improved the function of the reinforcement considerably. The polymer layer with an imbedded carbon net prevented the development of crucial cracks by spreading the forces more evenly over the entire surface. The two critical cracks in the URM wall eventually led to collapse. The failure pattern of both specimens is shown in Figure 23.

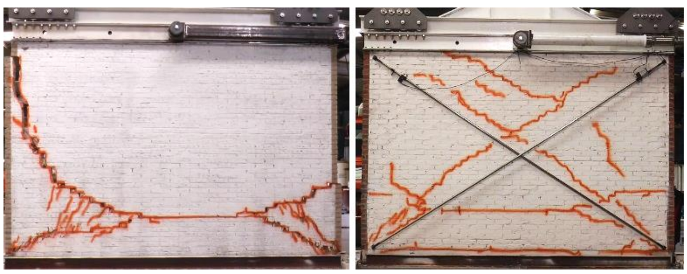

Figure 23. End state of both the reinforced/anchored masonry wall (right) and URM (left) without an opening.

Walls with openings have also been tested for in plane capacity. An overview of the results is given in Table 4. Even though the increase in load resisting capacity by using QuakeShield becomes less when there are fewer bricks due to openings, the added value in terms of ductile behavior remains significant compared to URM.

Table 4. Overview of the in-plane test results

Specimen	Max. Load (kN)		Corr. Displ. (mm)	
	URM	QSRM	URM	QSRM
No opening	164	276	3.84	17.59
Door opening	150	202	10.95	19.00
Window opening	126	167	10.09	23.45
Door opening low	165	204	6.41	23.98

4 CONCLUSIONS

An experimental study was presented that consisted of several clay brick masonry wallets that were tested to investigate the behavior of stand-alone or combined seismic retrofit systems. The following can be concluded from the first part of the study:

- In terms of OOP performance, combining individual retrofit systems is of significant added value.
- In terms of crack prevention, a visco-elastic glue is more suited for the application of imbedding FRP strips than a rigid adhesive.
- A polymer based strengthening layer (rather than a cement based layer) is more effective for OOP loading due to higher load bearing capacity, higher displacements and more ductile post-peak behavior. Using a polymer based layer also prevents significant detachment between the imbedded FRP strips and the adhesive.
- Glass fiber rods are less suited to be imbedded due to the (partial) debonding from with the glue.

A second part of the experimental study was presented which investigated the behavior of the proposed retrofit system used for in-plane loaded walls. Conclusions were:

- Anchoring the carbon strips into the foundation beam prevented bed joint failure. This increased the added value of the reinforcement.
- The polymer based strengthening layer with an imbedded carbon net prevented the development of crucial cracks by spreading the forces more evenly over the entire surface.

5 RECOMMENDATIONS

The small scale OOP experimental program will be continued in order to gain more knowledge, especially when loaded in the weakest direction.

Further, the effect of out-of-plane cyclic loading on the load-deformation behavior under pre-compression of QSRM members also warrants more attention. This will be done by a test setup as proposed by Griffith et al. (2012).

The in-plane experimental program will also be continued. More knowledge is needed in the in-plane behavior of QSRM, especially in creating a good connection using the anchors and FRP strips.

ACKNOWLEDGEMENTS

The authors wish to thank and acknowledge Royal Oosterhof Holman and SealteQ for supporting this research into the behavior of a new seismic retrofit system.

REFERENCES

Bhattacharya, S., Nayak, S. & Dutta, S.C. 2014. A critical review of retrofitting methods for unreinforced. In *International Journal of Disaster Risk Reduction* 7: 51–67.

Griffith, M.C., Kashyap, J. & Mohamed Ali, M.S. 2012. Flexural displacement response of NSM FRP retrofitted masonry walls. *Construction and Building Materials* 49, pp. 1032–1040.

Petersen, R.B., Masia, M.J., Seracino, R. 2009. Bond behavior of near-surface mounted FRP strips bonded to modern clay brick masonry prisms: influence of strip orientation and compression perpendicular to the strip. *Journal of Composites for Construction*, Vol. 13, No. 3, May/June 2009, pp. 169-178.

Reitherman, R., & Perry, S.C. 2009. Unreinforced Masonry Buildings and Earthquakes: Developing Successful Risk Reduction Programs. Publication No. P-774, Federal Emergency Management Agency

Seracino, R., Jones, N.M., Ali, M.S.M., Page, M.W. & Oehlers, D.J. 2007. Bond strength of near- surface mounted FRP strip-to-concrete joints. In *Journal of Composites for Construction*, Vol. 11, No. 4, July/August 2007, pp. 401-409.

Schermer, D. 2005. Development of test methods for the determination of masonry properties under lateral loads in WP7, incl. test methods for European standardization. Institut für Baustoffe und Konstruktion Technische Üniversität München