STRENGTHENING OF MASONRY WALLS WITH GLASS FIBER STRAPS

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SUMMARY

Test results of unstrengthened and strengthened brickwork masonry walls, are presented. The walls were strengthened with glass fiber straps of one layer. Two series of walls were tested. In the first series, masonry walls were subjected to monotonically increasing vertical compression load and in the second series, walls were subjected to constant vertical compressive and monotonically increasing horizontal load. Test results of strengthened brickwork masonry walls were compared with results of unstrengthened walls.

INTRODUCTION

Today, the possibility of increasing carrying capacity of masonry walls by strengthening them using fiber reinforced polymer (FRP) materials is being explored more than ever. Analyses of strengthening with carbon and alkaline resistant glass fabrics and straps are generally most common. Straps and fabrics are installed on walls by epoxy glue, which, in the same time, serves as the matrix of the newly created composite. This type of strengthening has more advantages than traditional means. Its implementation does not damage the bearing system of a building; the process of strengthening is simple, economical, does not consume much time and does no harm to functionality of the building. Tests conducted at the laboratory of Civil Engineering Department, University of Zagreb, were performed on unstrengthened and strengthened brickwork masonry walls. Masonry elements in this research were made of solid masonry units (bricks) and weak mortar.

In the first series of tests, the small masonry wall specimens were subjected to increasing vertical compression load. Unstrengthened brickwork masonry walls as well as masonry strengthened with glass fiber straps were tested. The aim of these tests was to investigate efficiency of walls strengthened with glass fiber straps regarding enhancement of compressive resistance when compared to unstrengthened walls. Strengthened masonry walls using FRP products that were tested by other researchers (e.g. Bieker et al. 2002) showed that strengthening of masonry walls and columns with glass fiber fabric increased carrying capacity up to 300%.

In the second test, masonry walls were subjected to constant vertical compressive and variable horizontal load. Dimensions of all wall specimens were $l/t/h$ = 103/12/106 cm. One specimen type was unstrengthened brickwork masonry wall and other specimens were strengthened

walls. The aim of the research and testing of specimens of the second series was to investigate efficiency of walls strengthened with glass fiber straps regarding enhancement of resistance to horizontal force as well as ductility when compared to unstrengthened walls.

MATERIAL PROPERTIES

Masonry units which were used in this testing were old clay bricks taken from a building that was constructed in the year 1941. This building was prepared for demolition. Dimensions of the bricks were w/h/l = 12/6.5/25 cm. Some of bricks had cracked angles and their dimensions varied by ± 0.8 cm in length. This type of masonry units was used in the research in order to get as close as possible representative specimen of old existing masonry walls. The compressive strength of bricks was determined according to European norms EN 772-1 (2000). The mean value of compressive strength of unit was 18.58 MPa with standard deviation 4.53 MPa. The density of the bricks was 2.06 g/cm^3. The wall specimens were constructed with mortar, of which volume ratio of components (cement:lime:sand) was c:l:s = 1:2:8, in order to achieve mortar type M2.5, (mortar compressive strength of 2.5 MPa). The mortar was tested in accordance with the European norm EN 1015-11 (2000). The mean value of compressive strength of mortar was 6.27 MPa, which was greater than the strength value that corresponds to mortar type M2.5. The tensile strength of mortar was 1.38 MPa.

Straps and fabrics of glass fibers were used for the strengthening of masonry walls, along with the epoxy glue and leveling mortar. In this research, properties of glass fiber straps were tested. The testing of tensile strength of glass fiber straps was done according to Standard ASTM D 3039/D 3039M (1995) on straps of six bundles, each bundle was 2.63 mm wide, which gave the 15.8 mm wide strap, that was close to the value (15 mm) which was the value recommended by the Standard. Straps were stretched at the speed of 2 mm/min. Extensometer, type *Multisens B066608,* was used for deformation measurement. The extensometer was placed in the middle of the strap, on the length of 50 mm. The mean values of 5 tested straps were: ultimate force of strap on unit width: $f_{f,max}$ = 312.26 kN/m; modulus of elasticity, assuming the equivalent thickness of strap fabric given by manufacturer was 0.48 mm: E_{strap}=38508 MPa; deformation at failure: $\varepsilon_{f,max}$ = 14,9 ‰. Properties of levelling paste declared by manufacturer were: compressive strength > 80 MPa; tensile strength > 30 MPa; strain at failure 12 ‰; modulus of elasticity in compression 3000 MPa.

MASONRY WALLS SUBJECTED TO MONOTONICALLY INCREASING VERTICAL COMPRESSION LOAD

Dimensions of all wall specimens were *l/t/h* = 51/12/55 cm. One specimen type was unstrengthened brickwork masonry wall and the other two specimen types were strengthened walls. Drawings of specimens are given in Figure 1, and the list of wall specimen's types is given below:

a) Unreinforced-unstrengthened masonry walls (designated as 1/1, 1/2 and 1/3). b) Masonry walls strengthened with horizontal and diagonal glass fiber straps (designated as 2/1, 2/2 and 2/3). c) Masonry walls strengthened with horizontal glass fiber straps at the wall surface (designated as 3/1, 3/2 and 3/3). Masonry walls of type b) were strengthened with glass fiber straps of one layer, each 50 mm wide. Straps were placed horizontally at the top and bottom of specimens and along two diagonals at each side of the wall. The diagonal straps were of one layer, 50 mm wide (Figure 1b). Masonry walls of type c) were strengthened with wrapped glass fiber straps of one layer, each 50 mm wide, placed at the top, bottom and mid

height of specimens i.e. at three levels (Figure 1c). Each strap had uniaxially oriented fibers in its length direction. Straps and fabric were glued at wall's surface after the specimens reached certain strength, i.e. four months after construction. Surfaces of the walls, which were intended to be used for strengthening, were well brushed, coated with primer, and then leveled with mortar and leveling paste.

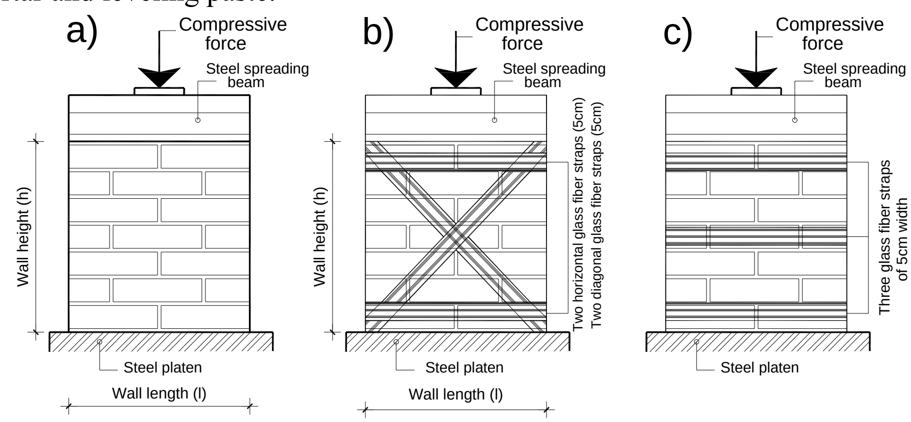

Figure 1. Shape and types of masonry wall specimens for compressive load testing.
a) unstrengthened, b) strengthened with diagonal straps, c) strengthened with horizontal straps

After the surfaces of walls were leveled, glass fiber straps were glued at surfaces using epoxy glue. Lap length of straps was 40 cm. All masonry wall specimens were tested with central compressive load according to European norms, EN 1052-1 (1998).

Test method and results of masonry wall testing

The test method was identical for all specimens. Each masonry wall was placed on the steel platen of the testing machine in a leveled layer of gypsum mortar. Then, on the top surface of the wall a layer of gypsum mortar was placed and while the gypsum mortar was still fresh, a steel spreading beam was placed on top of it. After placing the steel spreading beam, wall was slightly pressed vertically by the machine in order to distribute gypsum mortar underneath as evenly as possible. The role of the steel spreading beam was to enable, with its stiffness, the even distribution of vertical load on a wall. Even distribution obviously happened because the wall failures were identical, i.e. there were no concentrated cracks observed on the part of the specimen beneath the beam. After positioning the wall, 4 vertical and 2 horizontal measuring devices (LVDTs) for measuring deformations, were fixed on wall sides (see Figure 2).

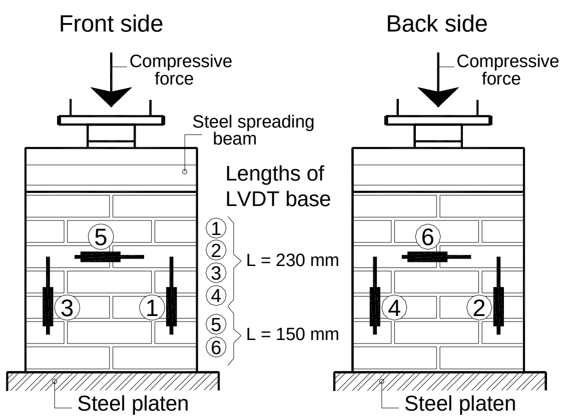

Figure 2. Positions of LVDTs at masonry wall specimen's front and back side

The gauge lengths of LVDTs no. 1, 2, 3 and 4 were 230 mm. The horizontal deformations (strains ε_h) were measured by LVDTs no. 5 and 6. The gauge lengths of LVDTs no. 5 and 6 were 150 mm. Uniform (steady) increase of compression force was applied to the wall specimens until failure. The speed, i.e. the increase of the compression load was 8.4 kN/min. This gave the compressive stress to the wall of 0.137 MPa/min. Failure of unstrengthened brickwork masonry specimens happened within 30 minutes. Since the testing machine had manual control for the increase of compressive force, all the walls were tested without unloading i.e. with constant increase of the force until failure. Figure 3 shows photo of masonry at failure.

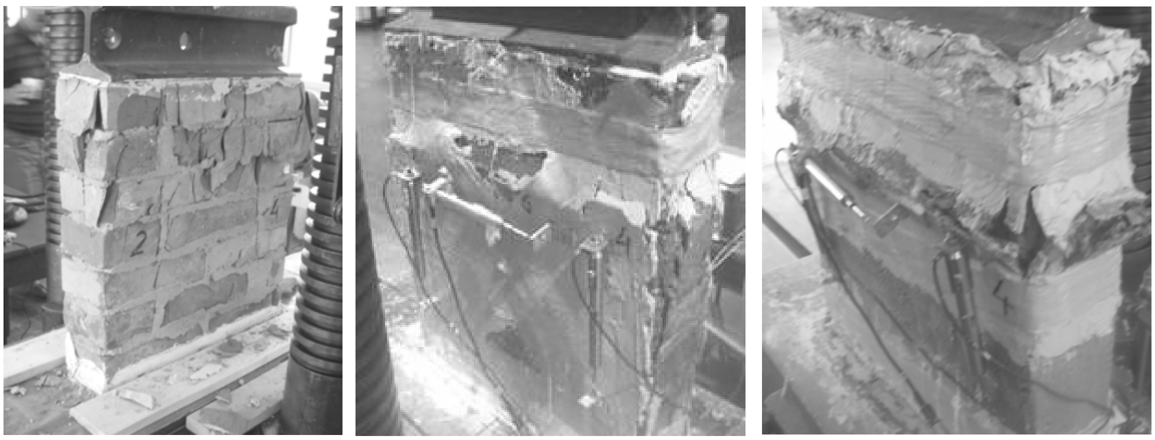

Figure 3. Specimens at failure due to vertical compression load. Specimens from left to right: unstrengthened; strengthened with diagonal straps; strengthened with horizontal straps

Maximum stresses, i.e. stresses at failure are shown as groups of vertical bars in Figure 4. The significant increase in carrying capacity (compressive strength) of walls that were strengthened with horizontal glass fiber straps (specimens 3/1, 3/2 and 3/3) compared to unstrengthened walls (specimens 1/1, 1/2 and 1/3) is apparent: 6.21 MPa compared to 3.83 MPa. Walls with diagonal straps failed at average compressive stress of 5.92 MPa. Considering stresses at failure, glass fiber straps increased carrying capacity of walls by 55 to 65%, comparing with unstrengthened walls.

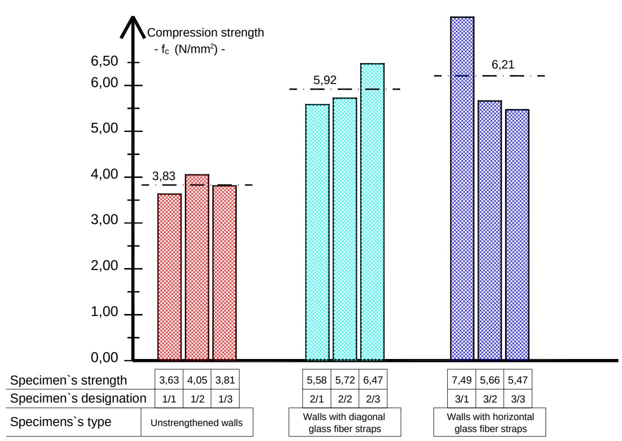

Figure 4. Compressive strengths of masonry wall specimens and their average values

Stress-strain diagrams of wall's behavior under the compressive stress are depicted in Figure 5. Horizontal and diagonal straps restrained horizontal stretching of a wall after appearance of vertical cracks, so the horizontal strains of these specimens were for 1/3 smaller than for unstrengthened specimens (Figure 5). In walls strengthened with glass fiber straps increasing of horizontal strain happened at compressive stress of 5.0 to 6.0 MPa, while unstrengthened walls have shown such behavior at much smaller compression stress i.e. at 2.74 MPa.

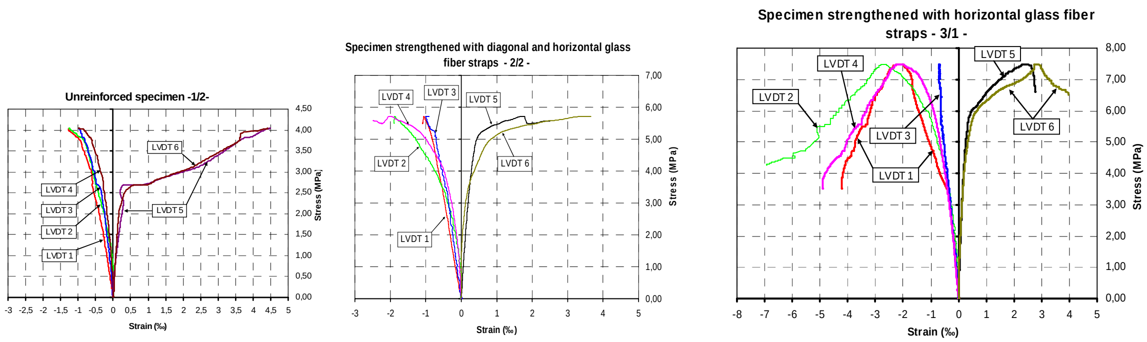

Figure 5. Diagrams "stress – strain" for masonry wall specimens. Specimens from left to right: unstrengthened; strengthened with diagonal straps; strengthened with horizontal straps

During the first test it was noticed that LVDTs, that were fixed on bricks, had tendency to fall down at high compressive stresses because process of peeling of bricks started, so it was impossible to get a real "σ - ε" diagram at stresses that were close to the failure (after peak stress). Because of that fact, during testing, the movement of the (movable) lower base of the testing machine was measured too by the use of LVDT no. 7. This movement contains deformation of masonry wall at its full height and the deformation of gypsum mortar. Such, gypsum mortar deformation, has influence only at a low force or low stress (less then 30 kN or 0.49 MPa) and therefore displacement that happened below this force (stress) was not accounted for.

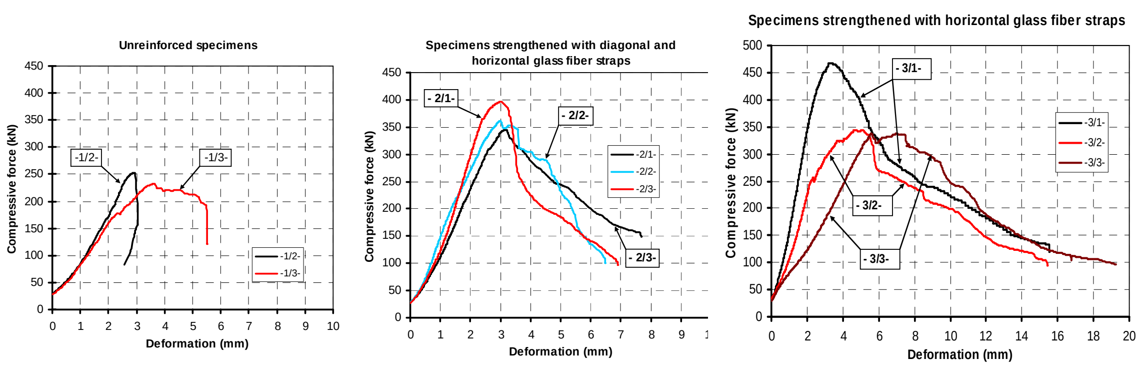

Figure 6. Diagram "force –deformation" in vertical direction for masonry wall specimens.

MASONRY WALLS SUBJECTED TO CONSTANT VERTICAL COMPRESSIVE AND VARIABLE IN-PLANE HORIZONTAL LOAD

Length and height dimensions (l and h) of all this type of masonry wall specimens were about two times greater than dimensions of specimens that were subjected to compression stresses, i.e.: $l/t/h$ = 103/12/106 cm. One specimen type was unstrengthened brickwork masonry wall

and others were strengthened walls. Drawings of specimens are given in Figure 7, and the list of wall specimen's types is given below:
a) Unreinforced-unstrengthened brickwork masonry walls.
b) brickwork Masonry walls strengthened with horizontal and diagonal glass fiber straps.
c) brickwork Masonry walls strengthened with vertical and horizontal glass fiber straps at the wall surface.

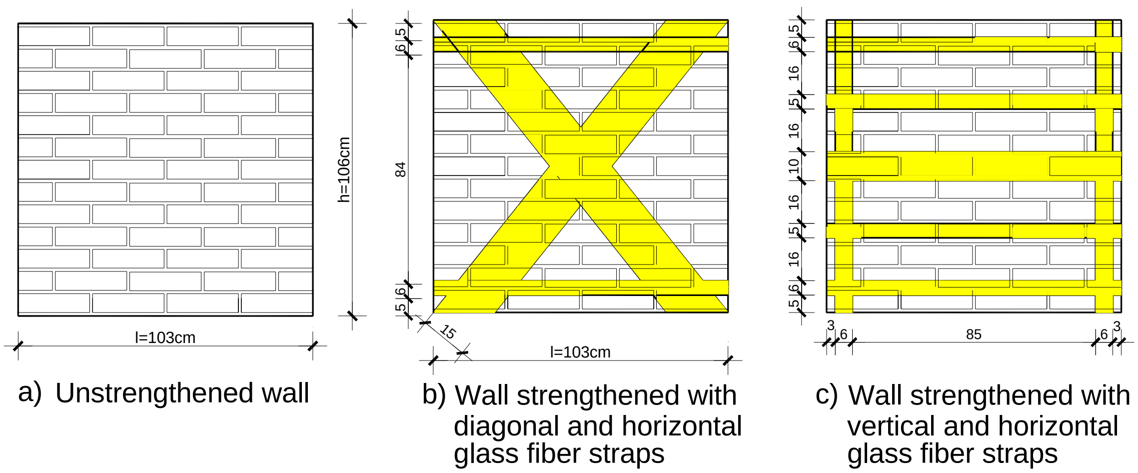

Figure 7. Shape and dimensions of masonry walls and glass fiber straps for specimens subjected to constant vertical compressive and variable horizontal loading

All specimens were prepared in the same way as specimens loaded uniaxially, described before. Masonry walls of types b) were strengthened with horizontal and diagonal glass fiber straps of one layer. Straps were placed horizontally at the top and bottom of specimens and along two diagonals at each side of the wall. The diagonal straps were of one layer 150 mm wide. Masonry walls of type c) were strengthened with wrapped glass fiber straps of one layer, placed at the top, bottom and three mid heights of specimens i.e. at five levels. Top and bottom horizontal straps were each 60 mm wide, adjacent to them horizontal straps were 50 mm wide each, and the strap at mid height was 100 mm wide. Vertical straps 60 mm wide, of one layer, were placed 30 mm from the wall's ends, at front and back side.

Test method and results of testing of masonry subjected to in-plane horizontal loading

Constant vertical force of F=79 kN (F in Figure 8 left) which was about 1/6 of the compression force at failure of unstrengthened wall was applied to the specimen before increasing of horizontal force (H at bottom right). The calculation of vertical force F: $f_c = 3.83$ N/mm^2 = 0,383 kN/cm^2 (see Figure 4), $F = 1/6(f_c \cdot l \cdot t) = 1/6(0.383 \cdot 103 \cdot 12) = 78.9 \approx 79$ kN. In order to prevent the rotation during the testing specimens were fixed by the additional stiffening force V_1 (see Figure 8 left). The testing was performed eight months after the erection of masonry walls. Masonry wall specimens were tested inside the testing frame (see Figure 8 right). The test method was identical for all specimens.
The positioning of each wall was followed by fixing of 4 diagonal (numbers 1, 2, 3 and 4) and 4 vertical (numbers 5, 6, 7 and 8) measuring devices (LVDTs) for measuring deformations on front an on back wall surfaces (see Figure 8 left). The two horizontal LVDTs numbers 9 and 10 measured horizontal displacements of specimen during testing. The gauge lengths of the diagonal LVDTs were 1130 mm. Those LVDTs measured diagonal strains. The gauge lengths of the vertical LVDTs were 650 mm. After applying vertical force of 79 kN, the masonry wall

was subjected to the monotonically increasing horizontal force up to the failure of specimen. Results of testing have shown that strengthening of walls has increased shear resistance of masonry walls as well as their ductility.

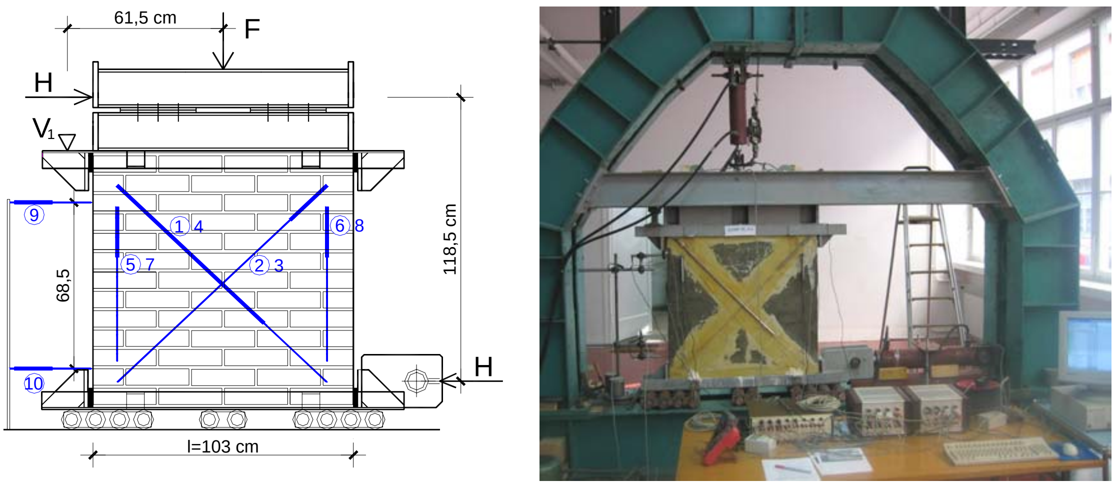

Figure 8. Left) positions of horizontal (H at bottom right) and vertical (F) hydraulic jacks and LVDTs at masonry wall specimen. Right) photo of steel testing frame with position of wall specimen strengthened with horizontal and diagonal glass fiber straps

Maximum horizontal (shear) forces are shown as groups of vertical bars in Figure 9 (left). The significant increase in carrying capacity of shear forces of walls that were strengthened with horizontal glass fiber straps compared to unstrengthened walls is 86 %, i.e. 164.2 kN compared to 88.4 kN. Walls with diagonal straps failed at average shear force of 162.2 kN. Considering stresses at failure, glass fiber straps increased shear capacity of walls by 83.5 to 86 %, comparing with unstrengthened walls. The figure 9 (right) shows the equivalent tensile strengths (f_t^e) of masonry wall specimens at failure and their average values. The expression of equivalent tensile strengths (f_t^e) is given in equation (1).

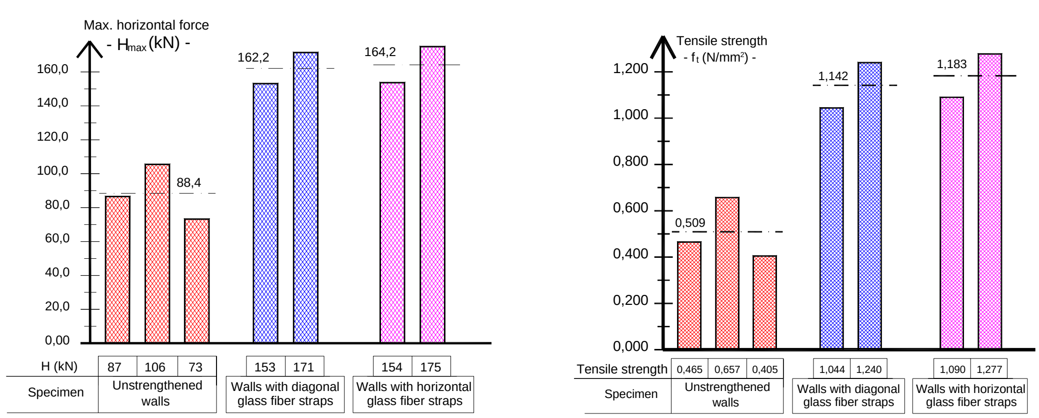

Figure 9. Left) Horizontal forces of masonry walls at failure. Right) Equivalent tensile strengths of masonry wall specimens at failure and their average values

$$f_t^e = -\frac{\sigma_{o1}}{2} + \sqrt{(b \cdot \tau_{R1})^2 + \left(\frac{\sigma_{o1}}{2}\right)^2} \quad (1), \quad \text{equivalent tensile strength,}$$

$$\tau_{R1} = \frac{H_{\max}}{l \cdot t} \quad (2), \quad \text{shear stress at maximum horizontal force (at failure),}$$

σ_{o1} vertical compression stress .

Diagrams ″horizontal force - diagonal displacement″ are shown in Figure 10. Deformations were measured in direction of compression diagonal (LVDTs numbers 1 and 4), and in tension direction (LVDTs numbers 2 and 3).

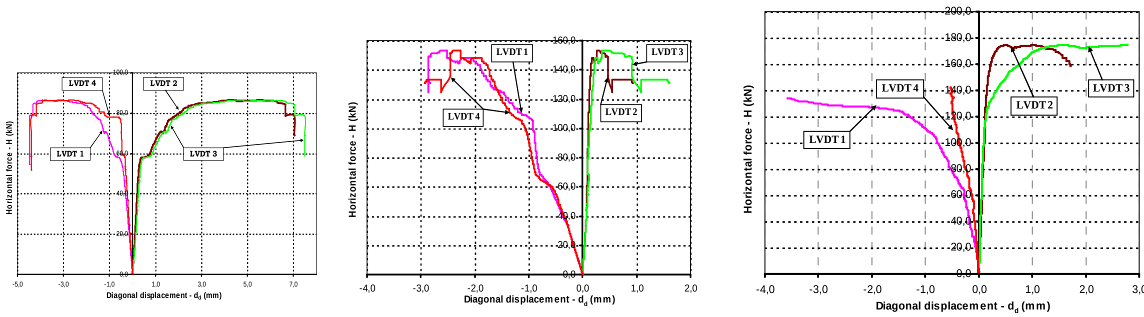

Figure 10. Diagrams ″horizontal force - diagonal displacement″. From left to right: unreinforced masonry; strengthened with horizontal and diagonal straps; strengthened with vertical and horizontal straps

Diagrams ″horizontal force – horizontal displacement″ for all three types of masonry walls specimens are given in Figure 11. It is obvious that strengthening of masonry walls increases the horizontal resistance. Strengthening with vertical and horizontal straps increases the ductility of walls as well.

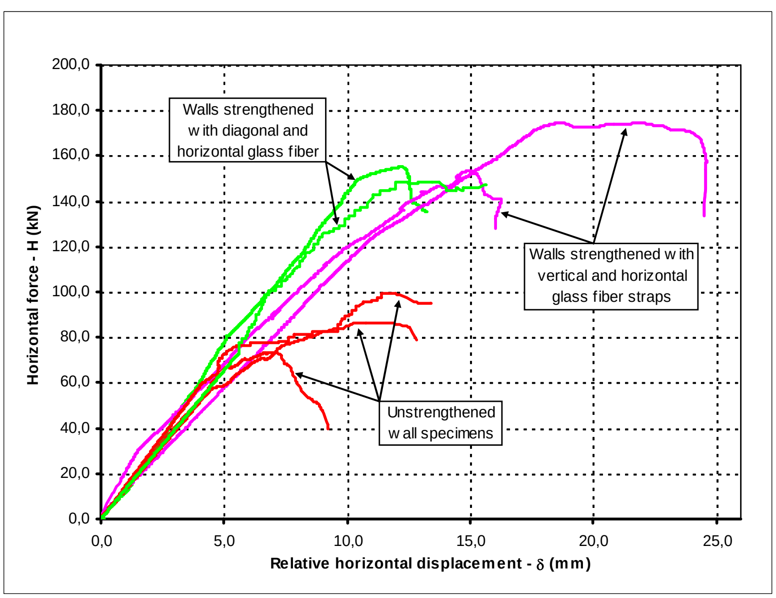

Figure 11. Diagrams ″horizontal force – horizontal displacement″ for one unstrengthened and two strengthened brickwork masonry walls

Figure 12. Masonry walls at failure. Specimens from left to right: unreinforced brickwork masonry; strengthened with horizontal and diagonal straps; strengthened with vertical and horizontal straps

CONCLUSIONS

First series: the experimental results have shown that strengthened walls have increased compressive resistance, and what is even more important, that they showed more ductile behavior than unstrengthened brickwork masonry wall specimens. Considering stresses at failure, glass fiber straps increased carrying capacity of walls by 55 to 65%, comparing with unstrengthened walls. In walls strengthened with glass fiber straps substantial increasing of horizontal strain happened at compressive stress of 5.0 to 6.0 MPa, while unstrengthened walls have shown such behavior at much smaller compression stress i.e. at 2.74 MPa. This meant that appearance of vertical cracks of strengthened walls has happened at 82 to 119 % greater vertical force then for unstrengthened walls.

Second series: these types of strengthening of masonry walls increase the masonry horizontal force carrying capacities by 86 %, while the increase of equivalent tensile strength was 116 %. Strengthening with vertical and horizontal straps increases the ductility of walls as well.

The efficiency of strengthening of masonry walls has been proved. Strengthening by horizontal fiber straps was simpler and even more efficient than that by diagonal straps. Therefore, strengthening with horizontal straps is recommended.

Comparison with other author's research: Bieker et al. (2002) have strengthened their masonry columns (24/24/50 cm) with carbon fiber fabrics which were much stronger than glass fiber fabrics or straps that were used in the research described in this paper. Their results of testing specimens that were strengthened with one layer and made of solid bricks have shown increase of carrying capacity of 150 %. Triantafillou (1998), Tumialan et al. (2001) have tested in-plane and out-of-plane bending resistance of strengthened masonry walls with FRP fabrics or wires, and Velazquez-Dimas et al. (2000) have tested out-of-plane bending resistance. The comparison with the results of other authors could not be relevant while dimensions of specimens, types of masonry units, number of layers, fibers and type of loading were different from those presented in this paper. Though, all research had shown substantial increase of masonry specimen's resistance when strengthened with FRP.

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