First Middle East Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures
8 – 10 February 2011, Dubai, UAE

SMAR 2011

Influence of FRP reinforcement layout and geometry on different masonry brickwork panels

R. Cuzzilla[1], G.P. Lignola[1], A. Prota[1], and G. Manfredi[1]

[1] Department of Structural Engineering, University of Naples "Federico II", Naples, Italy

ABSTRACT: The structural damages due to recent earthquakes, led the scientific community to develop new strengthening systems for masonry structures. The present work started from available experimental programs related to masonry panels made of clay bricks or natural stone blocks. FEM was used in order to describe the global behavior of tested specimens, in terms of shear capacity and cracking pattern. The finite element method, and particularly detailed micro-modeling, was adopted as a numerical simulation tool for masonry panels made of different masonry brickworks. The reinforcement has been applied considering two design solutions: a) diagonal fibers strengthening layout, b) horizontal fibers strengthening layout. The FRP dimensions have been modified considering several parametric analyses to determine the influence of FRP system, carried out on different brickwork according to the experimental programs available in literature. FE models highlighted that the influence of strip spacing is not so meaningful, despite some code formulations provide significant differences.

1 INTRODUCTION

Unreinforced masonry (URM) structures have shown their vulnerability to major events such as earthquakes, severe wind, blast and impact. The repair and retrofit of existing masonry structures have been traditionally accomplished using conventional materials and techniques. Nowadays, FRP systems are a valuable option to consider for strengthening, however, only few codes deal on retrofit of masonry structures with composite materials (e.g. ACI 440.7R-10 and CNR DT200). The in-plane performance of FRP-strengthened walls is highly dependent on the type of masonry and the FRP layout. The benefit in terms of shear capacity is inversely proportional to the strength of the URM wall and grid or diagonal layouts of FRP strips lead to different strength increments. ACI 440.7R-10, for instance, suggests to add the FRP shear contribution to the nominal strength of the URM, and such contribution depends linearly on the width of the FRP strips and inversely on their center-to-center spacing.

FE models highlighted the influence of FRP width and spacing on shear strengthening of different brickwork masonry panels. Experimental programs on different brickwork masonry panels (larger than about 1x1 m^2), available in literature have been considered herein: namely Alcaino & Santa Maria (2008) for hollow clay bricks, Stratford et al. (2004) for solid clay bricks and Faella et al. (1992) for tuff blocks. The FE models were validated in Cuzzilla (2009), e.g. showing an average difference between theoretical and experimental strength lower than 10%;

and based on validated models, parametric analyses have been performed varying the FRP width and spacing. The main results of the latter analyses are shown herein.

2 FINITE ELEMENT MODELING

The numerical activity was carried out using available data in FE code TNO DIANA rel. 9.2. The micro-modeling criterion was taken into account and thus, both brick and mortar materials were described separately by means of non linear elements (Lourenço 1996). Brick elements and mortar joints were separately modeled as isotropic continuum elements without frictional interfaces between them, according to the smeared crack approach. This technique was already used in Lignola et al. (2009), where the global behavior of tuff masonry panels was analyzed by changing the mortar thickness in order to reproduce irregularities and defects of real applications. Hence, plane stress elements were selected because there is no bending outside the plane of the structure. The post elastic behavior was modeled according to Rankine/Von Mises criterion to define the tensile and compression performances respectively, by means of the tensile (f_t) and compressive (f_c) strengths and tensile (G_{ft}) and compressive (G_{fc}) fracture energies. The quasi brittle behavior of both materials has been simulated by using post peak linear softening according to Figure 1. Relevant mechanical properties of materials are reported in Cuzzilla (2009).

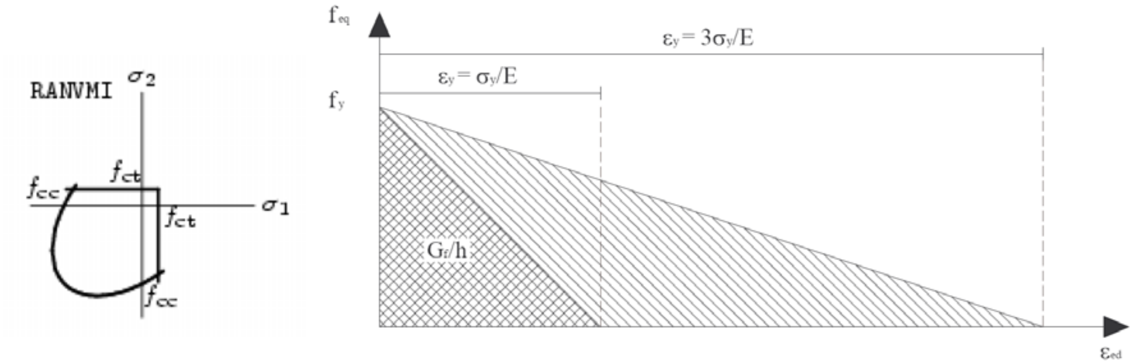

Figure 1. Rankine/von Mises criteria and post peak linear softening behaviour

The CQ16M element, an eight-node quadrilateral isoparametric plane stress element, based on quadratic interpolation and Gauss integration was used. The FRP strips were modeled assuming perfect bond to the substrate by using special GRID reinforcement bonded elements, available in DIANA software.

Numerical simulations have been performed by applying gravity/vertical load on the top surface of the panels; moreover the horizontal actions were modeled by means of controlled displacements induced by an hydraulic jack placed in a reference point on the panel. The FRP geometric dimensions, on both diagonal and horizontal layouts, were varied. Considering the horizontal strengthening system, the reinforcement width, b_f, was ranged between 100 mm to 300 mm; the reinforcement was also spaced, p_f, according to many values. Panels were coded as H_b_f _p_f. The diagonal strengthening configuration was modeled by providing a strip width (b_f) ranging from 100 mm to 400 mm. Such panels were coded as D_b_f _# where # is equal to 2S only if two overlapped strips were applied, to investigate the effect of FRP thickness.

The structural behavior of masonry panels has been investigated to determine the influence of a wide variability of FRP geometrical combinations, similarly to the variability found during the experimental tests, but involving only few different geometrical combinations.

3 NUMERICAL SIMULATION RESULTS

3.1 Alcaino & Santa Maria (2008)

3.1.1 Diagonal reinforcement

The masonry panels tested by Alcaino & Santa Maria (2008) were made of hollow clay bricks and premixed cement mortar; at the sides of the panel, two steel D25 bars were placed to ensure the in-plane shear mechanism. The gravitational load equal to 98 kN was applied on the top surface of the panel and the horizontal actions were applied by means of controlled displacements. The URM panel provided a maximum shear capacity equal to 140.5 kN; the crack pattern have shown a clear large diagonal crack and a network of microcracks extending on the lateral surface of the panel.

The results have been summarized in the following Table 1, specifying the maximum shear strength, its increment (Δ) compared to the URM panel shear capacity.

Table 1. FEM results for Alcaino & Santa Maria (2008) panels. Diagonal layout

Panel	FEM Shear Capacity	Δ Shear Capacity
URM	140.5 kN	n.a.
D_100	185 kN	32.2 %
D_200	215 kN	53.6 %
D_300	256 kN	82.9 %
D_400	268 kN	91.5 %

A CFRP having modulus of elasticity of 250 kN/mm^2 and nominal maximum strength of 4.3 kN/mm^2 was adopted. The increment of CFRP strip width leads to a progressive maximum shear capacity increment; in fact the maximum shear capacity increment obtained by simulating the D_100 panel (diagonal CFRP strip 100 mm wide and 0.13 mm thick) compared to the URM panel shear strength is equal to 32.2 %, rising to 91.5 % considering the masonry panels retrofitted with strips 400 mm wide. In Figure 2 a comparison between experimental and FEM crack pattern is shown.

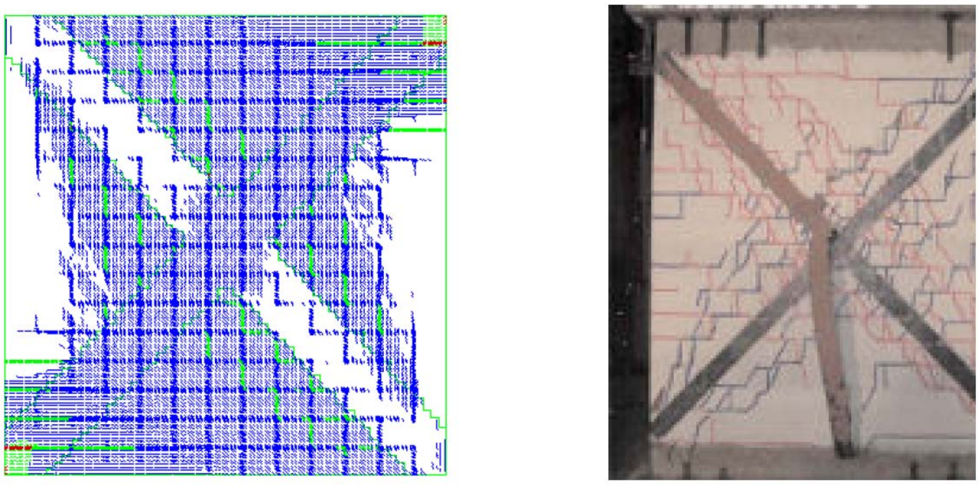

Figure 2. Numerical/Experimental comparison. Smeared Crack plot (D_100) vs. experimental pattern.

The crack patterns of reinforced panels show a greater spread of microcracks on the lateral surface of the panels. The largest strip width leads to a greater spreading of microcrack and to a better stress distribution.

The same FRP area was taken into account applying, in some cases, also a second CFRP strip on the first one, as reported in Table 2. The FEM results show a better behavior of the masonry panel strengthened by using one layer of diagonal strips (characterized by a greater CFRP strip width) compared to the performance of the masonry panel strengthened by using two CFRP layers (characterized by smaller CFRP strip width) in terms of shear capacity.

Table 2. Comparison between different CFRP diagonal layouts

Diagonal layouts	Description	FRP cross section	V_{max}	ΔV_{max}
D_100_2S	2 strips 100 mm wide	26 mm^2	197 kN	n.a.
D_200	1 strips 200 mm wide	26 mm^2	215 kN	9.1 %
D_200_2S	2 strips 200 mm wide	52 mm^2	251 kN	n.a.
D_400	1 strips 400 mm wide	52 mm^2	268 kN	6.8 %

3.1.2 Horizontal reinforcement

The horizontal reinforcement configuration has been characterized by CFRP horizontal strips, varying the strips width and the spacing between them. The results of unreinforced and reinforced masonry panel in terms of maximum shear capacity obtained by FEM were reported in the following Table 3. It is clearly seen the reduced effect of the spacing if compared to the effect of the width increments.

Table 3. FEM results for Alcaino & Santa Maria (2008) panels. Horizontal layout

Panel	FEM Shear Capacity	Δ Shear Capacity
URM	140.5 kN	n.a.
H_100_455	206 kN	47.0 %
H_100_555	204 kN	45.7 %
H_100_655	203 kN	45.0 %
H_150_455	216 kN	53.6 %
H_150_555	210 kN	50.0 %
H_150_655	207 kN	47.9 %
H_200_455	223 kN	59.3 %
H_200_555	215 kN	53.6 %
H_200_655	213 kN	52.1 %
H_300_455	238 kN	70.0 %
H_300_555	232 kN	65.7 %
H_300_655	227 kN	62.1 %

3.2 Stratford et al. (2004)

3.2.1 Diagonal reinforcement

Stratford et al. tested masonry panels made of clay bricks and premixed cement mortar. The gravitational loads were applied on the specimen top section by means of two forces both equal to 50 kN and 600 mm spaced each other; the horizontal actions were applied by means of controlled displacements. GFRP strengthening was applied, but, for comparison purpose with previous brickwork, previous CFRP solutions were taken into account during the numerical simulations; hence CFRP properties are the same. The results are summarized in Table 4.

Table 4. FEM results for Stratford et al. (2004) panels. Diagonal layout

Panel	FEM Shear Capacity	Δ Shear Capacity
URM	112 kN	n.a.
D_100	174 kN	51.3 %
D_200	237 kN	106.0 %
D_300	272 kN	136.5 %
D_400	307 kN	167.0 %

The increment of CFRP strip width leads to a progressive shear capacity growth; in fact the maximum shear capacity increment obtained by analyzing the D_100 panel is equal to 51.3 % compared to the URM panel, while an increase of about 167 % has been reached for the masonry panel reinforced with strips 400 mm wide. In this case the shear strength increases were higher if compared to previous specimens (Alcaino & Santa Maria 2008) whose URM shear capacity was also higher.

The capacity of the panel D_100_2S is slightly higher than the panel D_100, in fact the capacity increments are 62 kN and 71 kN, despite a doubled area of FRP is applied. Conversely the effect of a wider strip is remarkable, in fact the capacity of the panel D_200 is much higher than the panel D_100_2S. The capacity increments are 71 kN and 125 kN, despite the total area of FRP is the same. Hence the effect of better stress redistribution inside the masonry panel is evident (Table 5).

Table 5. Comparison between different CFRP diagonal layouts

Panels	V_{max}	ΔV_{max}
D_100_2S	183 kN	n.a.
D_200	237 kN	30 %
D_200_2S	257 kN	n.a.
D_400	307 kN	19 %

3.2.2 Horizontal reinforcement

The horizontal reinforcement configuration leads to small increments in terms of shear capacity (Table 6); the maximum percentage increase is equal to 7.1 %. The results are related to the sliding-shear collapse mechanism of the panel, which makes it not effectively strengthened by horizontal strips. In this case, strips further from each other increase slightly the capacity (0.8 %); it is a minor effect because FRP is minimally engaged by the sliding failure mode.

Table 6. FEM results for Stratford et al. (2004) panels. Horizontal layout

Panel	FEM Shear Capacity	Δ Shear Capacity
URM	112 kN	n.a.
H_100_100	119 kN	6.3 %
H_100_200	120 kN	7.1 %
H_100_300	120 kN	7.1 %
H_200_200	119 kN	6.3 %
H_200_400	120 kN	7.1 %
H_200_600	120 kN	7.1 %
H_300_300	119 kN	6.3 %
H_300_600	119 kN	6.3 %
H_300_900	120 kN	7.1 %

3.3 *Faella et al. (1992)*

3.3.1 Diagonal reinforcement

The masonry panels tested by Faella et al. (1992) were made of tuff blocks and premixed cement mortar. A gravitational load was applied on the top surface of the panel equal to 130 kN and horizontal actions were applied by means of controlled displacements. CFRP strips width increments lead to progressive increases of the maximum shear capacity (Tables 7-8) in FEM.

Table 7. FEM results for Faella et al. (1992) panels. Diagonal layout

Panel	FEM Shear Capacity	Δ Shear Capacity
URM	102 kN	n.a.
D_100	119 kN	17.0 %
D_200	129 kN	26.0 %
D_300	146 kN	43.0 %
D_400	160 kN	57.0 %

Table 8. Comparison between different CFRP diagonal layouts

Panels	V_{max}	ΔV_{max}
D_100_2S	119 kN	n.a.
D_200	129 kN	8.4 %
D_200_2S	146 kN	n.a.
D_400	160 kN	9.6 %

The shear capacity obtained by evaluating the D_100 panel is 17.0 % higher than the URM panel shear capacity, passing to about 57.0 % for the panel strengthened by using strips 400 mm wide. In this case the shear strength increases were lower if compared to previous specimens (Stratford et al. 2004) having a higher URM shear capacity. In this case the brickwork is totally different, being the tuff a natural stone having lower strength and stiffness.

The capacity of the panel D_100_2S is almost equal to the panel D_100 despite a doubled area of FRP is applied. Conversely the effect of a wider strip is remarkable, in fact the capacity of the panel D_200 is much higher than the panel D_100_2S despite the total area of FRP is the same. Hence the effect of the stress redistribution inside the masonry panel is evident. Similarly the FRP having the smallest width (either one or two overlapped strips) is not able to avoid clear cracking along the compressed strut, while the wider strips lead to greater spreading of the micro-crack network and thus, to a better stress distribution (Figure 3).

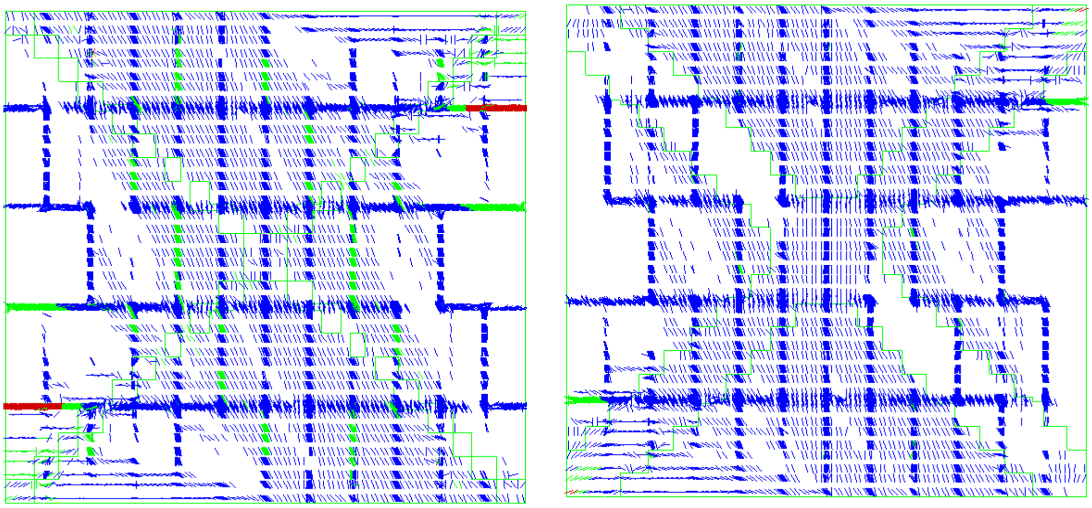

Figure 3. FEM Smeared Crack plot for diagonally strengthened panel: D_100 (left) vs. D_200 (right).

3.3.2 Horizontal reinforcement

Regardless of the strip width and spacing, the percentage variation of shear capacity compared to the URM panel shear capacity is almost equal to 30 % (Table 9).

Table 9. FEM results for Faella et al. (1992) panels. Horizontal layout

Panel	FEM Shear Capacity	Δ Shear Capacity
URM	102 kN	n.a.
H_100_100	133 kN	30.4 %
H_100_200	132 kN	29.4 %
H_100_300	131 kN	28.4 %
H_200_200	133 kN	30.4 %
H_200_400	132 kN	29.4 %
H_200_600	129 kN	26.5 %

Also in the case of strips 300 mm wide and having 300 to 900 mm spacing (not reported in Table 9) the same trend is shown. The spacing clearly affects the shear capacity (having less increments when spacing increases), while the width of the strips seems to be not relevant, even if the strength increment (almost constantly 30%) lies in the middle of the increments provided by different amounts of FRP applied diagonally (ranging between 17% and 57%). It is worth nothing that the total amount of FRP applied in horizontal layout (at least three rows) is generally higher than the amount of FRP applied on the two diagonals of the panel.

4 FINAL REMARKS

This work aims at highlighting the influence of width, thickness and spacing of FRP strips applied as external retrofit of URM panels made of different brickwork. Solid and hollow clay bricks as well as natural tuff blocks were considered. Diagonal and horizontal strips were investigated. The same FRP reinforcement (quantity and geometry) applied on different brickwork, yields to different results.

The main outcomes for diagonal FRP strips on clay bricks confirm that the strength is inversely proportional to the strength of the URM panels. In fact given the same amount of FRP, the strength increase is higher for the URM panel having lower strength. In the case of tuff masonry, being the blocks weaker, the strength increment is lower. The FRP contribution (as an additive capacity term to the URM shear strength) was not the same for all the brickwork, despite the same amount of FRP was applied. Thus, the simple superposition of FRP strip systems and masonry structure in terms of the shear capacity appears not to be effective. The strip width, more than the thickness, seems to have influence on FRP retrofitted panels.

The horizontal strips arrangement appears to be strongly related to the failure mode, while diagonal arrangement provided shear capacity improvement and better stresses distribution independently from the collapse mechanism. Sliding shear mechanism makes ineffective the application of horizontal strips. When diagonal failure controlled the failure mode, the center-to-center spacing increments led to slight shear capacity reductions (about 10 % to 15 % in present cases). Conversely the FRP strip width seemed to have much beneficial influence on the panel performances.

4.1 References

ACI 440.7R. 2010. *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Unreinforced Masonry Structures* American Concrete Institute, Farmington Hills (MI).

Alcaino, P and Santa Maria, H. 2008. Experimental response of externally retrofitted masonry walls subjected to shear loading. *Journal of Composite Construction, ASCE*, 12(5): 489-498.

CNR-DT 200. 2004. *Guide for the design and construction of externally bonded FRP systems for strengthening existing structures*. Roma, Italy: Published by National Research Council.

Cuzzilla R. 2009. *Seismic assessment and retrofit of historical masonry structures*. Ph.D. Thesis in Seismic Risks (XXII cycle): Università degli Studi di Napoli "Federico II", Napoli, Italy.

Faella G, Manfredi G and Realfonzo R. 1992. Cyclic behaviour of tuff masonry walls under horizontal loading. *6th Canadian Masonry Symposium*, Saskatoon (Saskatchewan, Canada, 15-17 June 1992).

Lignola GP, Prota A and Manfredi G. 2009. Non-Linear Analyses Of Tuff Masonry Walls Strengthened With Cementitious Matrix–Grid Composites. *Journal of Composite Construction, ASCE*, 13(4):243-51

Lourenço PB. 1996. *Computational strategies for masonry structures*. Ph.D. Thesis: Technische Universiteit Delft, ID numbers OL15425683M – ISBN 10 9040712212.

Stratford T, Pascale G, Manfroni O and Bonfiglioli B. 2004. Shear strengthening masonry panels with sheet GFRP. *Journal of Composite Construction, ASCE*, 8(5):434-443.

TNO DIANA rel. 9.2. International Software Company for FEA applications in civil and geotechnical engineering.