DESIGN CRITERIA FOR FRP SEISMIC STRENGTHENING OF MASONRY WALLS

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ABSTRACT :
Masonry structures have been the primary building typology for millennia in many countries and also nowadays many masonry buildings are realized. Seismic events have shown their vulnerability to in-plane actions even if they behave properly for gravity loads. This often requests to retrofit masonry walls for in-plane loads and a sound solution is provided by fiber-reinforced polymer (FRP) materials. FRP have emerged as a valid alternative to traditional materials used for retrofitting unreinforced masonry (URM) walls. Recent guidelines give information on the use of such FRP systems and recommendations on the design and construction of FRP systems used to strengthen URM structures. URM walls are usually strengthened applying FRP strips along the diagonals of the wall or in the direction parallel to the mortar joints. The shear resistant mechanism of strengthened walls with FRP strips along the diagonals of the wall is also discussed in this paper. The lateral strength of FRP strengthened walls can significantly increase if anchor systems are installed at the ends of FRP strips. This is due to the fact that the failure mode of strengthened walls could change from intermediate to end debonding if FRP strips present anchors at the ends. An assessment of design formulas for evaluating lateral strength of unreinforced and FRP reinforced masonry walls is presented. A comparison between theoretical predictions and experimental data is performed using outcomes of shear-compression tests on URM and FRP strengthened masonry available in literature. The study points out that the evaluation of the design FRP strains at failure could be dependant also on the masonry typology.

KEYWORDS: masonry, debonding, in-plane strengthening, FRP.

1. INTRODUCTION

During recent seismic events masonry structures have demonstrated their seismic vulnerability even if for centuries they have shown a proper behavior to resist gravity loads. This has lead to increasing the lateral load resistance of masonry walls. Composite materials made of fibers in a polymeric matrix, also known as FRP composites, have emerged as an alternative to traditional techniques. A considerable number of research projects have been conducted to study the effectiveness of FRP systems related to shear strengthening of masonry walls and have confirmed the effectiveness of this technique (Marcari et al. 2007, Marshall 2002, Marshall and Sweeney 2002, Moon at al. 2007). The in-plane seismic performance of unreinforced masonry walls (URM) before and after their retrofit using fiber reinforced materials is investigated. FRP materials are usually applied in different geometric layouts on masonry walls. In this paper walls with two different FRP layouts have been analyzed: FRP strips installed parallel to the mortar joints and FRP strips arranged along the diagonals of the wall. A comparison between theoretical and experimental data is performed based on the shear-compression tests carried out on FRP strengthened masonry walls available in literature. An assessment of available design formulas for evaluating the in-plane performance of URM walls and the contribution of FRP strengthening system is performed. At present, the available guidelines are the CNR DT200 (2004) and a draft version of ACI 440 Committee. The CNR DT200 (2004) provides only information on the design of FRP systems for increasing the in-plane strength of URM walls when vertical and horizontal strips in the form of a grid are used, while the current ACI 440 draft provides also formulas for evaluating the FRP lateral strengthening of masonry walls retrofitted with FRP placed along diagonals.

2. LATERAL STERNGTH OF URM WALLS

The behavior of masonry walls under in-plane loads depends on different parameters mainly related to their geometrical and mechanical properties as well as to the loading and boundary conditions. The following failure modes can be generally recognized: diagonal tension; joint sliding; flexural cracking (Magenes et al.1997, FEMA 306). The Diagonal Tension failure mode is characterized by diagonal cracks distributed for almost the entire height of the wall along the principal stress directions occurring on both mortar joints and masonry bricks, depending on the relative strength between mortar and bricks. The nominal lateral strength corresponding to the diagonal tension is based on Turnšek and Čačovič's failure criterion, which assumes that this failure occurs when the value of maximum principal tensile stress is attained. This value is taken as conventional tensile masonry strength, neglecting the anisotropic behavior of the masonry. This criterion is applicable if the wall is slender and fixed at both ends. The Joint Sliding failure occurs on the bed joints since these are weaker than masonry units and can develop either along a horizontal plane (generally for masonry with staking sequence) or along a stair-stepped diagonal crack (when vertical and horizontal mortar joint are differently interested). The nominal lateral strength corresponding to the attainment of joint sliding is evaluated according to Mohr-Coulomb's criterion in which shear strength is related to cohesion and friction angle. The Flexural Cracking is a failure mode characterized by formation of flexural cracks at the tension zone and crushing of the toe due to attainment of compression strength of masonry. For all possible failure modes related to URM walls, the FEMA 356 (2001) provides formulas for evaluating the design lateral strength. Accordingly, the nominal lateral strength of URM walls can be computed as follows:

$$V_n^{URM} = \min(V_{dt};V_{bjs};V_{fc}) \tag{1}$$

where V_{dt}, V_{bjs} and V_{fc} are the nominal lateral strength corresponding to attainment of: diagonal tension, joint sliding and flexural cracking, respectively.

3. LATERAL STERNGTH OF FRP STRENGTHENED WALLS

The CNR DT200 (2004) proposes the following approach to evaluate the lateral strength of FRP strengthened walls. The lateral strength, V_{Rd}, can be computed according to CNR DT200 (2004) as:

$$V_{Rd} = V_{Rd,m} + V_{Rd,f} \tag{2}$$

where $V_{Rd,m}$ and $V_{Rd,f}$ are the masonry and FRP contributions, respectively. For FRP reinforcement applied in the direction parallel to mortar joints, the CNR DT200 (2004) proposes the following formulation for calculating the FRP shear contribution:

$$V_{Rd,f} = \frac{1}{\gamma_{Rd}} \times \frac{0.6 \times d_f \times A_{fw} \times \varepsilon_{fd} \times E_f}{p_f} \tag{3}$$

where γ_{Rd} is the partial factor for resistance model (equal to 1.20 for shear), d_f is the distance between the compression side of the masonry and the centroid of FRP flexural strengthening, A_{fw} is the area of FRP shear strengthening in the direction parallel to the shear force, E_f is the Young modulus of FRP reinforcement, p_f is the center-to-center spacing of FRP reinforcement measured perpendicularly to the direction of the shear force and ε_{fd} is the design strain of FRP reinforcement, defined as the minimum between FRP ultimate strain (obtained by a standard uniaxial tensile test on FRP coupons) and debonding strain. In the aim of performing a comparison with experimental results, in the following γ_{Rd} and all material factors will be assumed equal to 1 and the average FRP strain will be used in lieu of the design FRP strain in Eq.(3). According to CNR DT200 (2004), the mean debonding strain is calculated as:

$$\varepsilon_{fm,end} = \sqrt{\frac{2 \times \Gamma_{Fm}}{E_f \times t_f}} \tag{4}$$

where t_f is the thickness of FRP reinforcement, and Γ_{Fm} is the mean specific fracture energy of the FRP strengthened masonry, equal to:

$$\Gamma_{Fm} = c_1 \times \sqrt{f_{mm} \times f_{mtm}} \tag{5}$$

in which f_{mm}, is the mean compressive strength of masonry, f_{mtm}, is the mean value of the tensile strength of masonry and c_1 is an empirically determined coefficient. Unless specific data are available, the CNR DT200 (2004) suggests to take c_1 equal to 0.015. This guideline proposes for evaluating the FRP strain corresponding to intermediate crack debonding for FRP externally bonded RC elements the following formula:

$$\varepsilon_{fm,int} = k_{cr} \times \varepsilon_{fm,end} \tag{6}$$

with k_{cr} equal to 3.
According to current ACI 440 draft, the nominal shear strength of the FRP strengthened wall can be computed by adding the FRP contribution, V_f, to the nominal strength of the URM wall, V_n^{URM} as:

$$V_n = V_n^{URM} + V_f \tag{7}$$

The nominal lateral strength of the FRP strengthened wall is the minimum between the nominal shear strength given in Eq.(7) and the lateral strength corresponding to toe crushing of URM wall. The FRP contribution to the shear strength, V_f, can be determined for FRP laminate as:

$$V_f = p_{fv} w_f \frac{d_v}{s_f} \cos\alpha \tag{8}$$

where w_f is the width of the FRP laminates, d_v is the actual depth of masonry in direction of shear force, s_f is the center-to-center spacing between each strip, α represents fibers inclination with respect to the horizontal axis and p_{fv} is computed according to:

$$p_{fv} = n t_f f_{fe} \tag{9}$$

where n is the number of plies of FRP laminates. The term d_v/s_f is set equal to 1 when FRP sheets are applied along diagonal walls.
The formula provided by current ACI 440 draft for evaluating the FRP lateral strength of strengthened walls with FRP strips along the diagonals wall is based on a truss model. On the base of this truss mechanism, the masonry strut carries compressive stresses and the diagonal FRP strips withstand tensile stresses. According to this resistance mechanism, the FRP shear contribution is given by the horizontal component of the tensile force sustained by the FRP tie (Figure 1).

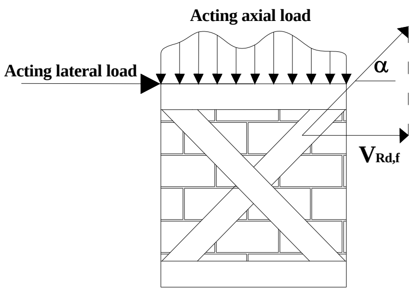

Figure 1 Mechanical model for FRP shear contribution in diagonal layout

The truss model adopted for describing the resistance mechanism of masonry walls strengthened with FRP strips applied along diagonals has been also suggested by Taghdi et al. (2000), Stratford et al. (2004) and Krevaikas et al. (2005). The effectiveness of truss model for evaluating the FRP lateral strength of strengthened walls with FRP strips along the diagonals wall has been also confirmed by Prota et al. (2008).
The effective stress f_{fe} can be computed according to Eq.(10) :

$$f_{fe} = E_f \varepsilon_{fe} = E_f \kappa_v \varepsilon_{fu} = E_f \kappa_v C_E \varepsilon^*_{fu} \tag{10}$$

with ε^*_{fu} the ultimate rupture strain of the FRP reinforcement and C_E the environmental reduction factor that is assumed equal to 1 for performing the comparison with experimental results. The coefficient for shear controlled failure modes κ_v is given by Eq.(11):

$$\kappa_v = \begin{cases} 0.40 & for\, \omega_f \le 0.20 \\ 0.64 - 1.2\omega_f & for\, 0.20 < \omega_f \le 0.45 \\ 0.10 & for\, \omega_f > 0.45 \end{cases} \tag{11}$$

with ω_f for SI equal to:

$$\omega_f = \frac{1}{85} \frac{A_f E_f}{A_n \sqrt{f'_m}} \tag{12}$$

where A_f is the cross-sectional area of FRP external reinforcement, A_n is the area of net mortared/grouted section and f'_m is the specified masonry compressive strength.

4. EXPERIMENTAL DATABASE ON SHEAR-COMPRESSION MASONRY WALL TESTS

Zhao et al. (2003) investigated the in-plane behavior of clay masonry walls. Four unreinforced brick walls were built with 240 mm in thickness, 1400 mm in width and 1000 mm in height. During the tests, the vertical compressive stress was kept constant at 1.2 N/mm^2 corresponding to a vertical nominal load of 430.2 kN. The compressive strength was equal to 11.64 N/mm^2 for clay brick units and 16.89 N/mm^2 for mortar. Some walls were strengthened using continuous carbon fiber sheets, with X-shaped strengthening pattern and a number of plies of the CFRP laminates set equal to one. The mechanical properties of CFRP were: 0.1035 mm in thickness, 280 GPa in modulus of elasticity, 2100 MPa in tensile strength and 1.4-1.5 % for the ultimate strain. The authors stated that during the tests the FRP strips peeled off from the wall, for this reason for some walls were placed anchors at the ends of the diagonal strips.

Santa Maria et al. (2006) reported experimental results on full scale masonry walls made of hollow clay bricks. The average prismatic strength tested on masonry bricks was 12.4 MPa. Commercially premixed mortar was used with average compressive strength equal to 28.7 MPa. The masonry walls had nominal dimensions of 1975x2000x140 mm and were subjected to a vertical constant load of 98 kN. The compressive masonry strength exhibited was equal to 11.3 MPa. Two 25 mm diameter steel bars were placed at each end of the walls to avoid flexural failure before shear failure occurred. Some walls were strengthened with FRP. The FRP external reinforcement consisted of woven carbon fabric laminated and bonded on site, applied along diagonals using one ply installed symmetrically on both sides of the wall, with the following mechanical properties: nominal thickness 0.13 mm, characteristic tensile strength 3500 MPa, tensile modulus of elasticity 230 GPa and ultimate tensile strain 1.50 %. Before applying the laminates, the surface of the walls was prepared removing the exterior layer of the bricks with a sander until the clay substrate was exposed. The surface obtained had rounded irregularities, the reinforcement was bonded to the surface using an epoxy resin as recommended by the manufacturer. The authors explained that the failure of the strengthened masonry walls occurred when the strips peeled off at the bottom and strips delaminated in up to 50 % of its length.

The shear strengthening of tuff masonry walls was assessed on full-scale walls subjected to in plane shear-compression tests (Marcari et al. 2007). The dimensions of the tested walls were: 1570 mm high, 1480 mm width and 530 mm deep. Uniaxial compression tests on masonry units were performed and showed a mean compressive strength of 2.1 MPa. Mortar cubes were used for compression tests and an average compressive strength of 2.0 MPa was exhibited. The walls consisted of two-layered walls with the inner part filled with mortar and chips from yellow tuff blocks. The area of the horizontal cross section of the specimen was 0.784 m^2, while the net area was 0.517 m^2. An average compressive strength equal to 1.4 MPa was measured when two walls were tested in uniaxial compression. The vertical load equal to 400 kN was kept constant during the tests. The shear-compression tests were carried out on four as-built walls and fifteen strengthened walls. Two walls (C3a and C3b) were strengthened with grid pattern CFRP unidirectional strips, made with three horizontal and vertical strips 200 mm wide on each face, with thickness of 0.167 mm. Then, two other walls (C4a and C4b) were strengthened with the same layout, but doubling the number of plies (0.333 mm total thickness). The mechanical properties of CFRP reinforcement used were: an elastic modulus of 230 GPa, an ultimate deformation of 1.5 % and an ultimate tensile strength of 3450 MPa. Similarly, four walls were symmetrically strengthened with grid pattern on both sides of the walls, but with glass bidirectional fiber strips. Two walls (G3a and G3b) were strengthened with one GFRP ply of 0.11 mm in thickness; while others two walls (G4a and G4b) were obtained doubling numbers of plies with a total thickness of 0.22 mm. The GFRP elastic modulus was 66 GPA, the ultimate deformation and ultimate tensile strength values were in order of 2.0 % and 1320 MPa. On another set of walls, a different geometric configuration was adopted by arranging FRP laminates along the diagonals of both sides of the walls. Four walls were strengthened with CFRP cross layout (C1a, C1b, C2a and C2b) and three with GFRP cross layout (G1, G2a and G2b), using either one or two FRP plies. In all cases, given the tuff high porosity of the surface, a pre-consolidating resin was applied prior to the usual installation procedure suggested by the manufacturer. About failure modes of strengthened masonry walls the authors observed that: for walls C1 and G1 local debonding of the sheets in tension far from the ends, for walls C2 and G2 debonding of the sheets in tension started near the mid-height of the walls, for walls C3 and G3 debonding of the tensile sheets was first observed in the central strips and for walls G4 was showed the rupture of the tensile sheets.

For all the mentioned walls, the value of the shear strength in the absence of vertical loads, f_{vk0}, has been taken according to tables included in the Eurocode 6 (2001), based on the compressive strength of mortar and nature of masonry units. The masonry shear strength (diagonal tensile strength) f'_{dt}, has been obtained using the table 11.D.1 of O.P.C.M. 3431 as a function of the masonry type.

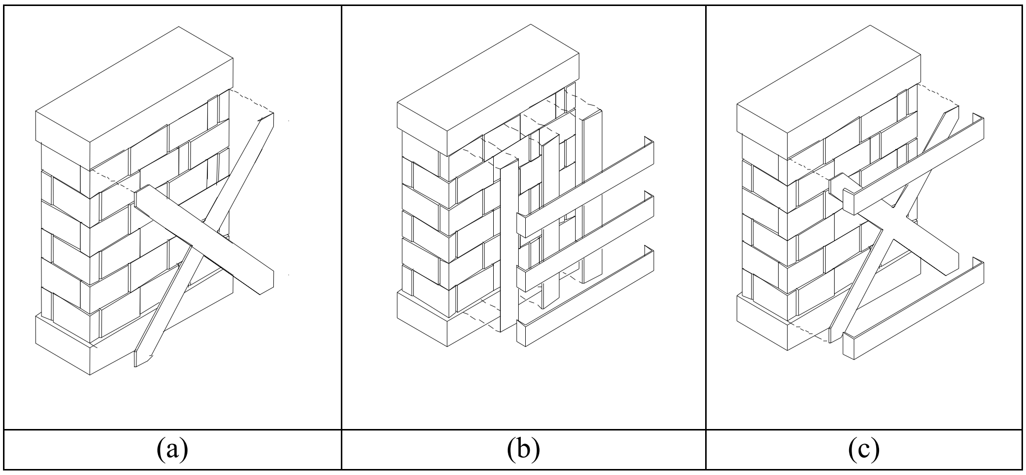

Figure 2 (a) Clay brick walls strengthened with cross layout (Zhao et al. 2003; Santa Maria et al. 2006), Tuff masonry walls strengthened with grid (b) and cross (c) layout (Marcari et al. 2007)

5. COMPARISON WITH EXPERIMENTAL DATA

The calculation of the lateral strength of FRP strengthened walls is computed as the sum of masonry and FRP shear contribution (Eq.(2) and Eq.(7)). The absence of anchorage of vertical strips at the ends of the tested walls induces to assume that the shear masonry contribution ($V_{Rd,m}$ in Eq.(2) and V_n^{URM} in Eq.(7)) is the same as for URM walls (Eq.(1)) (Prota et al. 2008). The FRP shear contribution is computed according to Eq.(3) provided by CNR DT200 (2004) for FRP reinforcement applied in the direction parallel to mortar joints and for this FRP layout a similar formula is given by current ACI draft. For masonry walls strengthened with FRP strips placed along diagonals, the CNR DT200 (2004) provides no information. For this case, the FRP shear contribution is evaluated according to truss model, computing the mean debonding strain according to formulas suggested by CNR DT200 (2004). This approach has been first applied to walls with grid layout tested by Marcari et al. (2007) and an average value for coefficient c_1 equal to 0.045 has been calibrated for tuff masonry walls in order to better fit the experimental results. The outcomes are summarized in Table 1.

Table 1 Comparison between theoretical and experimental results on walls tested by Marcari et al. (2007)

					CNR DT 200 (C1=0.045)				ACI 440			
	PANEL	ρ_H %	VEXP. [KN]	VRd,m [KN]	$\varepsilon_{fm,int}$ %	VRd,f [KN]	VRd [KN]	$\frac{V_{EXP.}}{V_{Rd}}$	ε_{ffe} %	VRd,f [KN]	VRd [KN]	$\frac{V_{EXP.}}{V_{Rd}}$
GRID LAYOUT	C3	0.024	198.2	140.5	0.305	52.97	193.5	1.02	0.150	65.34	205.8	0.96
	C4	0.048	220.4	140.5	0.216	75.02	215.5	1.02	0.150	130.68	271.2	0.81
	G3	0.016	196.2	140.5	0.703	23.31	163.8	1.20	0.800	65.87	206.4	0.95
	G4	0.032	215	140.5	0.497	32.96	173.5	1.24	0.470	78.34	218.8	0.98
CROSS LAYOUT	C1	0.012	172.8	140.5	0.305	32.29	172.8	1.00	0.428	45.12	185.6	0.93
	C2	0.023	203.8	140.5	0.216	45.54	186.1	1.10	0.150	31.62	172.1	1.18
	G1	0.008	155.8	140.5	0.703	14.00	154.5	1.01	0.800	15.94	156.4	0.99
	G2	0.015	163.4	140.5	0.497	19.80	160.3	1.02	0.800	31.87	172.4	0.94

In the same experimental campaign, tuff masonry walls strengthened with CFRP and GFRP strips arranged along the diagonals wall were tested. The presence of horizontal strips at the ends of the walls avoided the end debonding of diagonal strips (Figure 2). The intermediate debonding strain is calculated through Eq.(6) and also in this case an average value for coefficient c_1 equal to 0.045 allows for a good agreement with experimental results. The outcomes of calculations are reported in Table 2; it is pointed out that the effective strain has been computed using Eq.(6).
A further comparison on clay brick URM walls with cross layout has been carried out with tests results by Zhao et al. (2003) and Santa Maria et al. (2006) (Table 2). The absence of anchorage of vertical strips at the ends of the tested walls suggests computing the masonry shear contribution equal to that of URM walls. The absence of any kind of anchors of diagonal strips suggests to compute the mean strain according to Eq.(4) given by CNR DT200 (2004). The FRP shear contribution can be computed according to truss model, adopting formulas provided by CNR DT200 (2004) for evaluating the mean FRP debonding strain at failure, with an average value of 0.3 estimated for clay brick masonry and according to current ACI 440 draft adopting Eq.(8). This value of c_1 equal to 0.3 for clay brick, is similar to that proposed by Briccoli Bati et al. (2007); they performed a set of experimental results related to FRP adhesion tests on clay brick and found a value of c_1 equal to 0.2. The results of this calculation are reported in Table 2.

Table 2 Comparison between theoretical and experimental results on walls tested by Zhao et al. (2003) and Santa Maria et al. (2006)

					CNR DT 200 (C_1=0.3)				ACI 440			
AUTHORS	PANEL	ρ_H %	$V_{EXP.}$ [KN]	$V_{Rd,m}$ [KN]	$\varepsilon_{fm,end}$ %	$V_{Rd,f}$ [KN]	V_{Rd} [KN]	$\frac{V_{EXP}}{V_{Rd}}$	ε_{ffe} %	$V_{Rd,f}$ [KN]	V_{Rd} [KN]	$\frac{V_{EXP}}{V_{Rd}}$
Zhao-Zhang-Xie	WALL 2	0.042	332	224	0.665	94.13	318.13	1.02	0.538	76.19	300.19	1.11
Santa Maria -Alcaino	MLC-00-CA-FX-03	0.013	221.7	140.6	0.847	71.16	211.8	1.05	0.601	51.15	191.8	1.16
	MLC-00-CA-FX-01	0.020	255.2	140.6	0.847	106.74	247.3	1.03	0.559	70.50	211.1	1.21

6. CONCLUSIONS

The present paper deals with FRP strengthened masonry walls under in-plane loads. Experimental data have been analyzed and used to assess design formulas. The analysis of FRP strengthened masonry walls points out that:

- if the FRP verticals strips have no continuity at the ends, the masonry contribution can be safely evaluated in the same way as for URM walls;
- the formulas suggested by CNR DT200 and ACI 440M for evaluating the FRP shear contribution for strengthened masonry walls with grid layout provide good agreement with test results; for all analyzed walls the formula provided by CNR DT200 underestimate the experimental masonry lateral strength while formula given in ACI 440M overestimate the experimental masonry shear strength in case of natural stones;
- the truss model adopted for evaluating the lateral strength of FRP strengthened walls with strips applied along diagonals provide a good agreement with test results; this has been done by evaluating the FRP strain at failure according to formulas provided by both CNR DT200 (2004) and current ACI 440 draft.

The effectiveness of design formulas for the evaluation of the FRP contribution is strongly dependant on the value of the effective FRP strain. Values of c_1 coefficient for the evaluation of this strain have been here proposed. The comparison between theoretical and experimental results has allowed to calibrate the c_l coefficient. Based on the limited number of available test data, this preliminary assessment has provided a value of 0.045 for

FRP strips installed on natural stone masonry walls and 0.3 in the case of FRP strips applied on clay brick masonry walls. It is necessary to have more test results to derive values of the coefficient c_1 based on a reliability analysis and eventually derive a relationship for different substrates and failure modes (end or intermediate debonding). At the same time even the current ACI 440 draft provides a formula for evaluating the effective strain based on FRP reinforcement index ω_f that is function of specified masonry compressive strength f'_m then of masonry tipology.

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