FLEXURAL AND SHEAR STRENGTHENING OF MASONRY WALLS WITH FRP COMPOSITE MATERIALS: STATE-OF-ART

M. Derias and R. El-Hacha*

Department of Civil Engineering, University of Calgary, Canada.
E-Mail: relhacha@ucalgary.ca

ABSTRACT

Extensive researches had been done in past years with respect to strengthening masonry walls in flexure and shear. This paper will cover an assemblage of researcher’s achievements of strengthened masonry walls subjected to in-plane and out-of-plane loadings. Different types of masonry units (such as bricks and concrete blocks) used in structural masonry walls or non-structural masonry walls (infill). Masonry walls strengthening were done using various types of composite materials which includes Steel Reinforced Polymers (SRP) and Fibre Reinforced Polymers (FRP) composed of carbon, glass and aramid fibres. The paper includes Un-Reinforced Masonry (URM) walls and under-reinforced masonry walls. Failure modes occurred in masonry walls according to both flexural and shear is described. Bond influence of composite materials on masonry walls strengthened with FRP or SRP is discussed.

KEYWORDS

Flexural, CFRP, GFRP, masonry, shear, SRP, strengthening, walls, in-plane, out-of-plane, un-reinforced.

INTRODUCTION

History of Fibre Reinforced Polymer (FRP)

Worldwide many civil infrastructures, commercials, and residential buildings are deteriorated and needed to be rehabilitated urgently. In the United States, nearly 11% of the nation’s highway bridges are structurally deteriorated and 19% are functionally deteriorated (Tann et al., 1999). In the United Kingdom, over 10,000 concrete bridges needed to be rehabilitated structurally (Zhou et al., 2001). In the rest of Europe, it is estimated that the repair of concrete structures due to the corrosion of reinforcing steel bars costs over USD 600 million annually. Fibre Reinforced Polymer (FRP) materials have been used for repair and strengthening concrete structures. FRPs have various advantages including; high resistance to corrosion, high strength-to-weight ratio, high durability, ease of installation. FRP have different disadvantages including; high initial cost, poor performance at high temperature, very sensitive to Ultra-Violet (UV) rays, and linear stress-strain curve with no yield plateau. Some of the FRP applications that are very valuable in construction industry such as, internal and external reinforcement of concrete structural elements include Externally Bonded (EB) strengthening and rehabilitation system, Near Surface Mounted (NSM) system in flexural and shear strengthening, and hybrid structures. Most commonly used is EB FRP sheets or plates. EB FRP can be easily used for strengthening curved shapes or odd shapes such as I-shape or T-shape. EB is cheaper compared to NSM technique (Hassan, 2002). Premature debonding is a drawback for EB FRP technique. NSM is another technique using FRP is becoming a feasible strengthening technique for existing concrete structures in flexural and shear increasing capacity. Advantage of this technique is anchored inside the concrete structural element or inside the mortar joint in masonry walls. This technique is as well less sensitive to surface preparation compared to EB technique has more consistent quality. NSM FRP technique is protected after installation because it is embedded inside the concrete and mortar joints as well.

History of Masonry Structures

Deficiency in masonry structures can occur in different depicts such as overloading, dynamics both in vibrations, foundation settlement and both in-plane and out-of-plane deformations. Un-Reinforced Masonry (URM) structures represent significant percentage worldwide. Figure 1 shows the threat of URM walls failure due to
out-of-plane and in-plane loads in Turkey 1999 earthquake. For more literature regarding to out-of-plane and in-plane URM refer to publications by Tumialan (2003), Van Den Einde (2003), Galati (2004), and Shrive (2006).

Summarizing the problem of URM walls which might be either structural or non-structural walls as interior partitions or exterior walls; the main problem of URM walls is addressed in anchorage system which might be weak or voided and that is shown in Figure 1(c). FRP is one of the effective and sustainable strengthening techniques for masonry structures. The strengthening of URM walls with FRP to resist in-plane and out-plane loads as a result of wind pressure or earthquake loads. The most important properties of strengthening work are the control of labour and shutdown costs as opposed to material costs, time, site constraints and long term durability. Moreover, the mechanical properties and the advantages of FRP are enormous compared to the conventional materials used in strengthening for structural and non-structural purposes regarding initial and installation costs and improved corrosion protection, flexibility and easily using infield and slight changes in member sizes after repair. There is a vital point counted to use FRP from structural point of view. The dynamic characteristics of the structure remain unchanged due to small weight, stiffness addition and seismic resistance increases as well.

EXPERIMENTAL AND ANALYTICAL PROGRAMS

1987: A group of researchers investigated shear walls reinforced with vertical and inclined reinforcement which have low modulus polypropylene braids and the possibility of adopting FRP composites for the strengthening of masonry was initially investigated by (Croci et al., 1987).

1995: A researcher investigated the ductility improvement, crack distribution, and load capacity on masonry shear walls (Schwegler, 1995). The masonry walls been examined were dimensioned as 3.60×2.0 m (12×6.5 ft), strengthened by CFRP sheets in the diagonal direction and were anchored to the interconnecting slab as shown in Figure 2. Figure 3 shows the experimental results which expressed that the strengthened masonry walls represented an elastic behaviour up to 70% of the maximum shear force. What is been also expressed that load carrying capacity of the walls lowered due to large number of cracks formation in masonry units. Masonry walls strengthened from one side and two sides were compared. For the walls strengthened from one side, the load carrying capacity is halved and the eccentric effect of this layout showed minimum improvement on shear carrying capacity. In the other, the walls strengthened from two sides, fine cracks were observed perpendicular to the sheets and the crack spacing was constant and didn’t get wider.

The shear behaviour of masonry walls strengthened with CFRP laminates was investigated by Laursen et al., (1995). The masonry walls specimens were square walls of dimensions 1.8×1.8 m (6×6 ft) and were constructed from concrete masonry blocks and fully grouted. The walls were reinforced vertically and horizontally with reinforcement ratios of 0.14% and 0.54%, respectively. The control specimen walls failed due to shear. After repairing these walls by closing the large diagonal shear cracks with epoxy filler and epoxy injection and repairing the smashed compression toe with mortar epoxy mortar. The repaired walls were strengthened with CFRP laminates from two sides of the wall and a supplementary layer was placed at the ends to act as confinement. The retrofitted walls were similarly strengthened but only from one side of the wall and the results are shown in Figure 4. The significant improvement due to the CFRP laminates that the failure mode was changed from shear failure to flexural failure. The following improvement deformation of nearly 100 % and also avoid brittle failure mode.
1996: Another group of researchers examined the flexural behaviour of URM walls strengthened with GFRP sheets (Ehasni et al., 1996). The masonry walls specimens were of dimensions 215 mm, 100 mm and 1450 mm (8.5 in, 4 in, and 57 in) in width, height, and length, respectively. Also two variant types of mortar were used, type M and type M∗ mentioning that the mix ratios were 1:1/4:3 and 1:1/4:5 of cement:lime:sand, respectively and owned compressive strength, 32 MPa and 28 MPa for the two types of mortars, respectively. The specimen walls were loaded by four-bending-points. The tension failure occurred where limited amount of strengthening were used. When the specimens were fully strengthened, the flexural capacity was improved significantly by 24 times the control specimen. Also the interesting remark that the type of mortar shows slenderness effect and the specimen’s failure mode is the crushing of masonry units. Figure 5 shows the results of load deflection correlation for two types of mortars been used.

A researcher surveyed concrete block masonry walls strengthened with plastic fibre bars (Hamid, 1996). The Masonry walls were of dimensions 1.2×2.6 m (4×8.5 ft) and were reinforced with #4 plastic fibre bars. The walls were simply supported and subjected to out-of-plane loading. The author declared that the strengthened walls improvement in the flexural capacity and deflection capacity as well as shown in Figure 6. This had been accomplished due to the presence of the reinforcement bars and grout high tensile strength.

1998: Out-of-plane bending, in-plane bending and in-plane shear on masonry walls strengthened with EB FRP sheets were investigated by Triantafillou (1998). An experimental work consisted of twelve specimens to verify the analytical model developed by this author. The results showed increase in the bending capacity due to out-of-plane bending response. For in-plane bending case the tests shows considerable strength increase in the area fractions of reinforcement placed in the high stress concentration. To achieve the full in-plane flexural strength, attention should be directed to anchorage by means of short developing length or lack of clamping at the laminates curtailment position which may cause premature failure in the form of peeling of FRP laminates beneath the adhesive. For in-plane shear case the capacity of FRP-strengthened walls was quite high.

The strengthening of existing buildings stressed in bending by seismic loads was studied by Kolsch (1998). The system invented by the author was based on Externally Bonded (EB) carbon sheets installed in the cement-based matrix to play a role in enhancing the flexural strength and load carrying capacity. The results of this study reflected two important aspects. (1) Significant enhancement in flexural capacity and load carrying capacity. (2) This system avoided both partial and complete failure of the masonry wall in the excepted direction due to the seismic loading.

1999: The flexural behaviour of URM walls strengthened with various composite materials was investigated by Hamilton et al. (1999). The masonry walls were of dimensions 0.6×1.8 m (2×6 ft) and constructed from concrete masonry blocks. Figure 7 showed the correlation between the ratio of $M_{\text{Experimental}}/M_{\text{Theoretical}}$ and the reinforcement ratio index $\omega_{\text{FRP}}$ expressed in Eq. 1.

$$\omega_{\text{FRP}} = \frac{\rho_{\text{FRP}} E_{\text{FRP}} t}{f_m' h}$$

where:
Figure 8 shows the failure modes occurred which reflected four modes including debonding of FRP, FRP rupture, masonry block shear failure, and face shell pullout, but the most occurred failure mode through the specimens is the debonding of FRP from the masonry. There were two types of FRP composites used which were GFRP and AFRP. Two parameters were investigated; the first parameter is to utilize FRP material efficiently was to elaborate the spacing of the FRP till rupture of FRP is achieved. The second parameter is to utilize cheaper material such as GFRP.

\[ \rho_{FRP} = \text{FRP reinforcement ratio} \]
\[ t = \text{thickness of masonry units} \]
\[ E_{FRP} = \text{FRP modulus of elasticity} \]
\[ f_m' = \text{masonry concrete strength} \]
\[ h = \text{height of the wall} \]

The correlation presented in the previous results of the investigation done by Velazquez (1998) and Hamilton et al., (1999), where AFRP and GFRP laminates were used as strengthening materials. The tests reflected that specimens failed due to debonding of FRP laminates. From Figure 8 we could focus that the average \( \frac{M_{Exp}}{M_{Theor}} \) is around 0.5 and for design considerations the effective strain in FRP laminates can be limited as 50% of the ultimate strain as expressed in Eq. 2. The reinforcement ratio index, \( \omega_{FRP} \), can be limited to 0.5 as well to avoid shear failure. The main objective of both tests done by (Velazquez, 1998 and Hamilton et al., 1999) is to approve these limits.

\[ \varepsilon_{FRP\ eff} = 0.5 \varepsilon_{FRP\ u} \] (2)

An experimental program was conducted by a group of researchers to study the shear capacity of URM walls (Marshall et al., 1999). Fifty four triplets (consists of 3 bricks per specimen) to investigate the shear capacity of URM walls strengthened with FRP. Six triplets specimens where un-reinforced with FRP and were considered as control specimens. The rest of specimens were divided into two strengthening techniques. The first technique was strengthened with glass epoxy and the other was strengthened with carbon epoxy. The strengthening was applied on both sides of brick triplets and the strengthening dimension varied around 45 to 135 mm wide. The glass technique was composed of 1 layer, and for the carbon technique 1, 2 and 3 layers. The strengthening was applied to mortar joints were aligned 0 to 90 degrees randomly. Moreover, the authors decided to build extra specimens composed to seventy eight triplets to study the effect of fibre alignment. The conclusions of this experimental program as expressed by the authors were: (1) The strength was increased significantly due to multiple layers of strengthening material; (2) The failure mode under 45 kN (10 kips) was due to deforming between the brick and mortar joint; (3) The failure mode for the loads in the range of 45-66 kN (10-15 kips) was due to the crushing of brick or shear bond failure; (4) The failure mode for loads above 66 kN (15 kips) was due to brick crushing; (5) FRP material showed good enhancement in shear of mortar joints; (6) As the width of strengthening increased the shear capacity increased; (7) The carbon strengthening technique showed better results than glass strengthening technique; and, (8) The critical and the best results of this test showed that 60 mm width of strengthening is the best option.
Another group of researchers investigated the type of masonry units due to out-of-plane loading on URM walls strengthened with FRP (Roko et al., 1999). Twenty five specimens were tested and were strengthened with CFRP tapes. The outcomes and the results of this experimental program were summarized as follows: (1) FRP enhanced the ductility and the strength of URM walls significantly; and (2) The different masonry unit types showed straight effect on bond strength and the failure mode.

2000: Half-scale URM walls subjected to out-of-plane cyclic loading were tested by Velazquez-Dimas et al., (2000). The masonry walls were of dimension 1.2×1.4 m (48×56 in) and with slenderness ratio of 28. Two walls were strengthened on both sides with GFRP strips. The first wall was strengthened with to be alike the balanced ratio of 1.0% (crushing of masonry and rupture of FRP simultaneously). The second wall was strengthened with three times the reinforcement of the balanced ratio 3%. The first wall failure was by debonding of FRP. While the second wall failure was due to high in-plane shear stresses. Figure 8 shows the test results, which reflected significant improvement in strength and deformation potentials were attained. The authors declared that the second wall implied a resistance of 24 times the own weight of wall and the deflection obtained is approximately 5% of total height of wall. A recommendation was commenated by the authors to limit the strengthening reinforcement ratio too times the balanced ratio 2 %to avoid stiff behaviour and get reasonable hysteresis relationship.

A FRP structural re-pointing system investigating the utilization of FRP bars of clay units’ bricks was proposed by Tinazzi et al. (2000). The masonry walls were reinforced with #2 GFRP embedded in horizontal groove joints within epoxy paste. The panels dimensions were 600×60 mm (2×2 ft) and 90 mm (3.5 in) in thickness. The failure mode of URM panels was due to joint sliding through the compressed diagonal. On the other hand, the walls strengthened with GFRP bars reflected a significant improvement of 45% to the URM walls. The failure mode was changed from joint sliding to failure in masonry paste interface.

2001: The load-deflection of URM strengthened with GFRP was studies by Albert et al., (2001). This study is summarized in an experimental program of ten URM walls and an analytical model to verify the results. This study carried into two phases, the first phase is non-linear regarding the stiffness of masonry and second phase is linear regarding the stiffness of GFRP. This research foretold the cracking load deflection at cracking as well.

The strengthening effect of FRP and URM walls in order to withstand the out-of-plane loading was investigated by Hamoush et al., (2001). This study was carried on fifteen wall panels with two strengthening techniques. The first technique was strengthened with fibre system composed of a woven fabric in one direction with E-glass roving in the orthogonal direction. Kevlar yarns were utilized in the other direction as fibre mesh. The second technique was strengthened using a continuous fabric mesh from glass mixed with Tyfo Hi-Clear epoxy and subjected to uniform lateral load by using air bag wall apparatus. (1) Strengthening of URM walls by externally bonded composite overlays increases the flexural strength. (2) Shear strength of the masonry wall systems has a major influence on the failure loads of the system. Most of the tested walls failed by shear at the end connection of the fiber system with the masonry walls. Figure 10 showed the load fibre strain correlations for various walls.

Hamilton and Dolan (2001) investigated the out-of-plane flexural capacity of URM and RM concrete masonry walls strengthened with GFRP E-glass fibres oriented perpendicular to the bed joints and compared test results with the general design flexure equations. The comparison revealed that the equations over forecasted the actual capacity by less than 20% of the test specimens.
2002: The effect of retrofitting mortar bedding hollow concrete masonry in-filled steel frame using GFRP face shell subjected to in-plane lateral loads was investigated experimentally and analytically by El-Dakhakhani (2002). The experimental program comprised of two phases. Phase one consisted of fifty-seven URM tested under various loading conditions with different parameters studied such as the types of fibres, number of plies and the fibre orientation. Test results showed that using GFRP laminates on URM walls enhanced the strength capacity; post peak behaviour and failure mode. The compressive strength was increased by 90% and the shear strength was improved as well by using fourteen folds. Phase two investigated the in-plane seismic behaviour of URM in-fill walls retrofitted with GFRP and subjected to cyclic loading. Six full-scale single bay and story steel frames with various wall configurations were tested. Results showed that the GFRP laminates contained the hazardous of URM damages and avoided catastrophic failure as well both shear and tension cracking. The GFRP increased the lateral load capacity, and enhanced the post peak behaviour and avoiding the out-of-plane delamination. The enhancement of load capacity and the avoidance of sudden drop were due to the walls stabilization using GFRP. Phase three proposed on analytical model for the in-filled masonry walls retrofitted with GFRP. This model replaced each masonry wall with non-linear, compression-only and diagonal strut which estimated the stiffness and the lateral load capacity of concrete masonry in-filled steel frames. The proposed model for designing the URM walls retrofitted with GFRP was presented to avoid various failure modes.

2003: The effect of strengthening of URM walls with GFRP strips was investigated by Tumilan et al., (2003). The main objective of the researchers was to distinguish the behaviour difference in URM walls strengthened with GFRP strips adhered to plaster (SP walls) and without plaster (SM walls) to the control specimen not strengthened named UP walls and UM walls again with and without plaster respectively. This investigation reflected the enhancement of moment capacity and ductility of URM walls strengthened with GFRP. This study forecasted the mid-height deformation through analytical models and out-of-plane load carrying capacity as well. Figures 10 (a) showed the comparison of the four walls types and (b) comparison between experimental and analytical results respectively.

2004: Ward (2004); studied another out-of-plane load on masonry walls which was blast attack. The author worked on several techniques in strengthening existing masonry structures. Some of these techniques such as using elastomeric spray, FRP and Durisol brick. For the elastomeric spray was been used with urea- or polyurea-based coating to the thickness of 15 mm. Once the coating dried, forms a tensile membrane which enhanced the flexural capacity of the masonry significantly and reducing spalling. The Durisol brick is a hollow concrete block composed of wood slices as an aggregate instead of sand and stone. Durisol block provides an effective solution to retrofit masonry structures to resist the effects of explosions.

Thirteen masonry walls strengthened with three different FRP techniques were tested by Tan et al., (2004). Each wall dimensions were 1000×1000 mm (39.4×39.4 in) and 110 mm (4.3 in) in thickness. FRP used in strengthening were GFRP, CFRP, and Fiberglass woven with three different anchorage systems for each strengthening technique. The first anchorage system was by grinding and roughening the surface in order to enhance the bond strength. The second system was by using fiber anchor bolts. The third system was using bar as an anchor in a groove at the end of the FRP strengthening technique. This study showed an enhancement of the out-of-plane strength. There were four different modes of failure observed; punching shear, flexural bond failure by debonding of the FRP, FRP rupture, and flexural compression failure. In all the strengthening techniques, the load carrying capacity was increased as the thickness of FRP increased. Also the anchorage effect led to one of the failure modes; the punching shear or crushing of brick in compression. The combo effect of grinding the surface and fibre bolt anchorage showed significant increase in the wall strength. As well as the authors represented an analytical model to forecast the load capacity increment to validate the experimental program.
CONCLUSIONS AND FUTURE RECOMMENDATIONS

The conclusion of this paper will express the insufficiency of researches in topics which have to be studied in the next few years. This paper reveals several of the researches done in the last 20 years. It is so obvious from this context that there are a lot of missing circles such as the area of fire on masonry walls research is not yet covered, there are no researches been done due to elevated temperature. For the topic of chemical environmental on masonry walls still not studied. For the topic of strengthening using SRP on masonry walls still not studied. There are no researches done regarding the fire, moisture, or high or low temperature individually to study the masonry walls for flexural and shear behaviour. For future recommendation, researchers have to focus on these deficiencies in bond regarding these effects because the only bond in masonry walls is concentrated in the mortar joints. Secondly, there are several models proposed by researchers through their individual works. There are a lot of design guidelines on concrete structures. These are the design guidelines such as ISIS Canada and ACI design guidelines for FRP (ACI 440R-96, 440.1R-06, 440.2R-02, 440.3R-04, 440.4R-04, ISIS Design Manuals No.3 and No.4). There is no design code especially for FRP, and the only code that includes within its chapters design topics about FRP is chapter 16 in the CHBDC code (CAN/CSA-S6-06) and the CAN/CSA-S806-02. For the masonry structures, to the best knowledge of the authors not many design guidelines exist for strengthening masonry structures using FRPs; may be the only design guideline available that includes part for masonry structures strengthened with FRPs is represented in the Italian CNR document (CNR-DT 200, 2004). After more than 20 years of researches in this field regarding FRP and its application as internal reinforcement for new construction, and as external reinforcement for strengthening and rehabilitation of structures, there must be a code to be developed to lead all the engineers using FRP.

REFERENCES

ACI 440.1R-06. “Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars” American Concrete Institute, Detroit, Michigan, USA, 2006 66 p.
ACI 440.2R-02. “Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures” American Concrete Institute, Detroit, Michigan, USA, 2002, 45 p.
ACI 440.3R-04. “Guide Test Methods for Fibre-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures” American Concrete Institute, Detroit, Michigan, USA, 2004, 40 p.
ACI 440.4R-04. “Prestressing Concrete with FRP Tends” American Concrete Institute, 2004, 35 p.


Tumialan, J.G. (2001). Strengthening of Masonry Structures with FRP Composites,Doctoral Dissertation, Department of Civil Engineering, University of Missouri-Rolla, Rolla, Missouri, USA.


