- Technical Paper -

FRP ANCHORAGE SYSTEMS FOR THE STRENGTHENING OF INFILL MASONRY STRUCTURES

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ABSTRACT
The objective of this research program is to evaluate the effectiveness of FRP anchorage on the lateral load capacity and ductility of FRP strengthened infill masonry wall. The experimental program comprised twelve full-scale specimens. All specimens consisted of a reinforced concrete (RC) frame that was in-filled with concrete brick masonry and were loaded by out-of-plane uniformly distributed pressure in cycles up to failure. Parameters investigated include the two types of FRP (GFRP, PET) and five types of FRP anchorage (Fiber bolt, Embedded bar, Shear key, Near Surface Mounted bar).
Keywords: GFRP, PET, masonry walls, strengthening, anchorages, debonding, flexural, sliding shear

1. INTRODUCTION

The magnitude 9.0 earthquake struck Japan's main island in March 2011. The need for strong homes and buildings came also to the fore in the wake of the recent earthquakes like the magnitude 6.3 earthquakes that attacked Christchurch, New Zealand and China. Many of unreinforced masonry structure are prone to failure when subjected to overstress caused by earthquake or tornado. Conventional strengthening takes cost, long application time and adds more weight to the structure. For the past decades, FRP composites have been successfully used to strengthen masonry structure.

A previous study conducted at North Carolina State University on the strengthening of infill masonry walls with FRP indicated that the type of anchorage system has a strong influence on the overall performance of the FRP strengthening system [1]. Previous studies have shown that FRP strengthening of masonry infill can lead to a substantial increase in load carrying capacity when proper anchorage of the FRP to supporting elements is provided. In cases where inadequate anchorage is used, the mode of failure can shift from a ductile flexural failure to a brittle and premature shear sliding failure.

This study intends to explore various anchorage systems to determine which are effective in terms of increased load carrying capacity and ductility. Strengthened system with a new type of FRP, PET (Polyethylene Terephthalate), and GFRP are proposed for the experimental program. These two types of FRP are anchored to the supporting members using five different types of anchorage: overlap, shear restraint anchorage, wrapping around an embedded FRP bar, FRP anchor bolts, FRP shear keys, and Near Surface Mounted Bars.

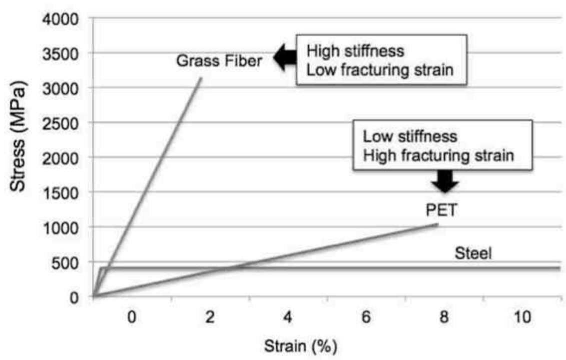

Fig.1 Stress strain relationship between PET and GFRP

2. EXPERIMENTAL PROGRAM

2.1 Test Specimens

The experimental program composed twelve full-scale specimens (2250mm high and 1200mm wide), including un-strengthened (C1) specimens and eleven strengthened specimens. All specimens consisted of a reinforced concrete (RC) frame (which simulates the supporting RC elements of a building structure) that was in-filled with concrete bricks. The strengthened specimens were reinforced with externally bonded FRP sheets applied to the exterior face of the masonry infill. The test specimens are designed to find out the most effective anchorage system for FRP strengthening of infill masonry walls.

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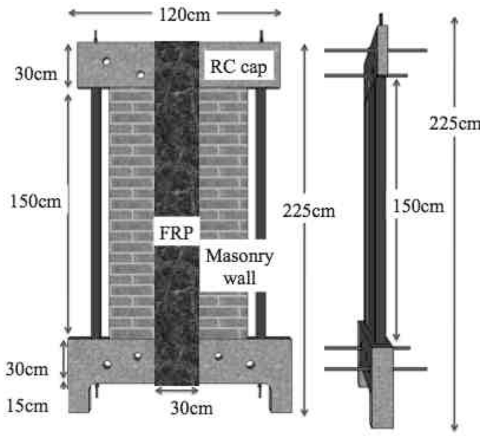


Fig.2 Test Specimens Geometry

Table.1 provides details of the parameters included in the experimental program.

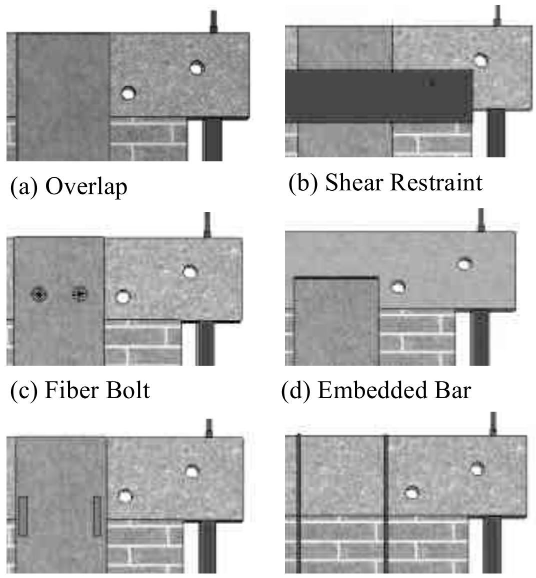
Table 1 Test matrix of the experimental program

Specimen ID	FRP Type	Anchorage Type
C1	-----	-----
S1-G-O	GFRP	Overlap
S2-P-O	PET	
S3-G-SR	GFRP	Shear Restraint
S4-P-SR	PET	
S5-G-FB	GFRP	Fiber Bolt
S6-P-FB	PET	
S7-G-EB	GFRP	Embedded Bar
S8-G-SK	GFRP	CFRP Shear Key
S9-P-SK	PET	
S10-E-NSM	Epoxy material	Near Surface Mounted
S11-GR-NSM	Cementicious material	

2.2 Type of anchorage system

FRP strengthening and anchorage are detailed in following sections.

1. Shear restraint (SR) anchorage consists of steel plates bolted to the RC caps. The plates were clamped over the FRP sheet to provide mechanical anchorage and extend 5 cm beyond the masonry/RC cap interface to resist sliding shear along this interface. Thickness of steel plates is 1 cm, height and width are 20 cm and 61 cm respectively.
2. Fiber bolt (FB) anchorage consists of a bundle of fibers embedded perpendicular to the face of the RC cap and flayed outward at the surface to resist pullout of the FRP sheets. The specimens were strengthened with a 30cm overlapping FRP sheet onto the RC cap. The FRP sheet was fixed to the RC caps with carbon fiber bolt anchors with 1cm diameter and 15cm long. The embedment length of anchors was 5cm into the RC caps and 1.27cm diameter holes. The remaining 10cm were flayed outward toward the masonry wall.
3. Embedded bar (EB) anchorage consists of wrapping the FRP sheets around an 1cm CFRP bar embedded near in the surface of the RC cap and running parallel to the masonry/RC cap interface. Dimension of groove is 1.27cm and 1.27cm.
4. Shear keys (SK) anchorage consists of short near surface mounted CFRP strips embedded perpendicular to the masonry/RC cap. These are intended to resist sliding shear along the interface. The FRP sheet was overlapped above these shear keys. Dimension of CFRP strips were 30cm long, 1.27cm deep and 0.23cm thick. Dimension of groove was 1.27cm wide and 1cm deep. Half-length of CFRP strips 15cm were embedded into RC caps and the remaining length of CFRP strips were embedded into masonry wall.
5. Near Surface Mounted (NSM) anchorage consists of surface mounted CFRP strand sheet embedded perpendicular to the masonry/RC cap. For this system, two different types of material were used for the adhesion of fiber strengthening to reinforce masonry structures. The one is the Epoxy (E) and the other is rapid curing cementious material (GR) which is an alternative to epoxy for fiber strengthening of reinforced concrete structures and consists of a family of magnesium phosphate cement products. This cementious material have not only high compressive strength, usually 42-70 MPa, but also the fastest setting time, usually less than 10 minutes and have good fire and heat tolerances which makes it a better product for high heat and fire applications [2].



(a) Overlap (b) Shear Restraint
(c) Fiber Bolt (d) Embedded Bar
(e) Shear Key (f) Near Surface Mounted Bar

Fig.3 Strengthened specimens with anchorage

2.3 Fabrication and material properties

Tables 2 and 3 show the material properties test results and properties of FRP systems.

Table 2 Material properties test results

Property	ASTM	Average Strength
Concrete compressive strength	C39	78.2 MPa
Masonry prism compressive strength	C1314	13.0 MPa
Concrete brick compressive strength	C140	29.8 MPa
Mortar compressive strength	C109	8.8 MPa

Table 3 Composite Gross Laminate Properties of FRP Systems (Provided by Manufacturers)

Property	GFRP	PET
Ultimate tensile strength in primary fiber direction	467 MPa	751 MPa
Elongation at break	1.76%	7%
Tensile Modulus	20.9 GPa	10.0 GPa
Laminate Thickness	0.127 cm	0.084 cm

2.4 Test setup

The test specimens were loaded out-of-plane with a uniformly distributed pressure to simulate the differential pressure induced by a tornado. An airbag was used to apply static pressure in increasing cycles up to failure. The loading protocol was based on ASTM E 72 (Standard Test Methods of Conducting Strength Tests of Panels for Building Construction) and ACI 437.1R-07 (Load Tests of Concrete Structures: Methods, Magnitude, Protocols, and Acceptance Criteria).

The airbag was placed within a steel frame between the brick walls and the laboratory reaction wall. This system was used to simulate the out-of-plane rigidity of existing RC structures. In addition to the out-of-plane rigidity, vertical tie rods were used to simulate the vertical rigidity of RC structures. The test specimens were supported by a 30 cm deep steel HSS to achieve alignment with the holes in the laboratory reaction wall.

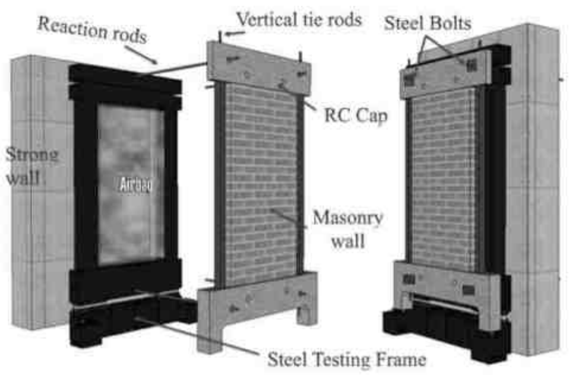


Fig.4 Details of test specimen set-up

3. EXPERIMENTAL RESULTS

3.1 General

This section gives the test results for each specimen. In each specimen, the elastic limit and ultimate applied pressure were determined. The elastic limit corresponds to the pressure, which induced a major loss in stiffness. The ultimate applied pressure was the maximum pressure applied before the masonry walls totally collapse.

The load-deflection behavior and the out-of-plane displacement along a vertical line at mid-width is described. A slip between the masonry and the RC caps at the top and bottom of the wall is also given. In addition, the strain in the FRP sheets at mid-width is given. The failure mode is later described and photographs of the specimen at failure are provided.

For all specimen, the shrinkage cracks was found in the bed joint along the top interface between the masonry / RC cap in the pre inspection. However this shrinkage cracking was later closed due to arching action of the masonry wall. Arching action can provide a significant contribution to the out-of-plane resistance of unreinforced masonry walls as shown in Fig.5. Summary of test results are given in the Table.4.

Table 4 Summary of test results

Specimen ID	Elastic limit (kPa)	Max Load (kPa)	Max Displ (cm)	Failure Mode*
C1	3.5	15.5	3.6	FF
S1-G-O	28.3	36.1	2.2	DB
S2-P-O	19.3	29.0	3.8	DB
S3-G-SR	28.3	112.3	6.0	FR
S4-P-SR	33.1	98.0	16.2	NF
S5-G-FB	11.7	60.7	5.4	AR&AP
S6-P-FB	36.5	50.4	12.2	AR&AP
S7-G-EB	47.6	68.3	5.4	AP
S8-G-SK	39.3	56.1	4.0	AP
S9-P-SK	16.5	38.3	3.3	AP
S10-E-NSM	17.9	25.0	2.5	AP
S11-GR-NSM	16.5	36.6	3.1	AP

- Failure modes: FF – Flexural Failure; DB – FRP Debonding; FR – FRP Rupture; NF – No Failure (stop testing); AR- Anchor Rupture; AP – Anchor Pull out

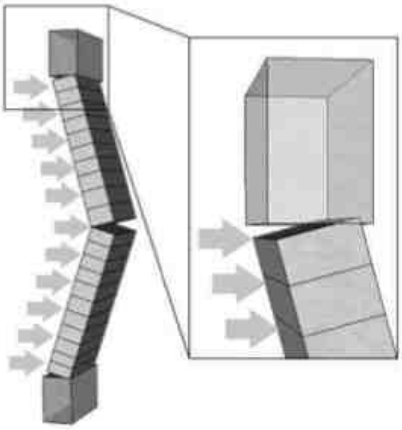
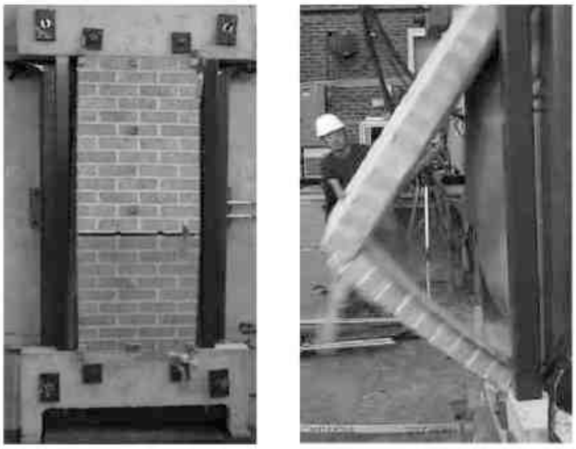


Fig.5 Example of wall arching action

3.2 Control and overlap system

C1 specimen failed in the flexural mode characterized by the formation of a main horizontal crack. The flexural failure is common failure mode in unstrengthened masonry walls. As these cracks widen and developed, they can divide the walls into two panels. Eventually this can lead to collapse of the wall.



(a) Front view (b) Profile view

Fig.6 Flexural failure in C1 specimen

The overlap anchorage system showed modest increase in strength and the ductility almost remains the same or worse, which imply the masonry wall still experience a brittle failure mode compared with control wall. It should be noted that this system needs longer overlap length, which may make this system unpractical since the longer length may not be provided in actual structures.

Fig.7 FRP debonding in S2-G-O specimen

Fig.3 shows the local debonding of FRP sheet around the anchorage. As a result of shear sliding, debonding was caused by the slip between the RC caps and the masonry wall. The model developed by Dai et al. was used for the prediction of overlap anchorage strength [3]. The dowel load carrying capacity is analogous to the load carrying capacity of a FRP sheet. Predicted load carrying capacity is 7.6 to 18.3 kPa for GFRP and 3.4 to 7.1 kPa for PET respectively. The model can be used to quantify the behavior of the FRP sheets in the overlap region as they debond, but the overall load carrying capacity might be influenced by a variety of other factors.

3.3 Shear restraint system

Obviously, the shear restriction anchorage system enhances the masonry wall most significantly, nearly 3 to 4 times as overlap system on lateral load capacity. It seems to be quite effective. However, Shear Restraint anchorage system may not be practically acceptable due to its heavy weight and massive size. This result showed the maximum increase in strength. Shear Restraint proves that the anchorage system with high capacity can develop the full capacity of FRP strengthening system, which is controlled by FRP rupture.

The requirement for ductility is more crucial than the enhancement of strength alone. PET fiber as strengthening material of masonry infill wall was proved to be quite effective. Because PET fiber with lower strength and higher fracture strain can match with masonry wall, which also have lower strength.

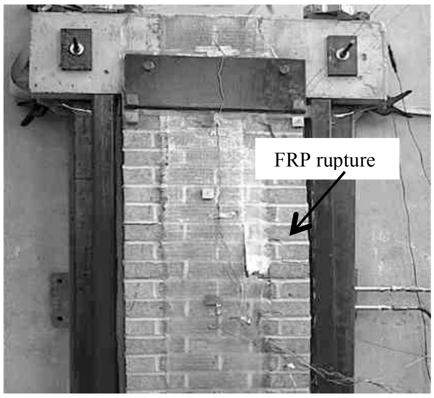


Fig.8 FRP rupture in S3-G-SR specimen

S3-G-SR specimen failed in the FRP rupture. This FRP rupture is a mostly desired failure mode, since the FRP utilized the full tensile strength of the reinforcement capacity. The primary rupture developed from the right edge of the FRP sheet near mid-height along the bed joint toward to the center of the FRP sheet as shown in Fig.8. A second rupture formed along the interface between the top steel plate and the FRP sheet.

The two rupture lines quickly joined and then the wall was suddenly collapsed. FRP rupture is usually achieved when the FRP is appropriately bonded and anchored to the wall.

3.4 Fiber bolt system

Fiber bolt approach had little effect on the stiffness of the walls but was successful in adding stability to the system, which aided in the formation of the arching mechanism. The additional stability allowed the walls to further develop in-plane clamping forces created as a result of the arching action, leading to modest increases in the out-of-plane capacity. These walls obtained the ductile failure with much displacement capacity since the anchorage does not restrain the relative slip between RC caps and masonry wall compared with control wall.

Fig.9 Anchor rupture and pullout of fiber anchors

S5-G-FA and S6-P-FA specimens failed in the rupture and/or pullout of the FRP anchors from the RC cap as shown in Fig.5. Debonding occurred at the RC cap up to the position of the fiber bolt anchors, but did not develop far beyond the level of the anchors until failure. Failure occurred shortly after one or more of the anchors ruptured or pulled out. The sudden loss of resistance caused the remaining anchors to rupture or pull out and the wall collapsed. The model developed by Smith et al. was used for the estimation for pullout strength of fiber bolt [4]. Predicted pullout strength is 79.3 kPa. However, anchors were subjected to a combined pullout/shear loading that could lead to a variety of potential failure modes not considered in this analysis, including anchor shear and anchor fan debonding.

3.5 Embedded bar system

The embedded bar system affected wall behavior in similar manner than that of the fiber bolt system strengthened with GFRP sheet. The deflection was similar magnitude, but the maximum load was little higher. This might be because the embedded bar anchor was covered with the entire width of FRP sheet and the anchorage does not restrain the relative slips between RC caps and masonry wall compared which increase out-of-plane resistance.

Fig.10 Anchor pullout of embedded bar anchors

3.6 Shear key system

The shear key system affected wall behavior in an entirely different manner than that of the fiber bolt system. The use of the shear key strengthening system resulted in a significant increase in both the stiffness and the capacity of the walls comparing with control walls. However, the wall deformation remained the same as control wall due to the presence of shear keys. As a result of rigid body deformation, these specimens does not lead to greater arching action which can be expected higher out-of-plane resistance of the masonry infill wall.

Fig.11 Anchor pullout of shear key anchors

3.7 Near Surface Mounted bar system

The NSM approach behaved similarly to overlap approach and shown to offer the close amount of strength and ductility using less FRP on surface of wall compared to overlap system, which is related to the confinement provided by the surrounding concrete cover. This technique has the potential for the development of greater strain in the FRP prior to debonding due to better confinement from the three bonded sides than comparable externally bonded applications which are usually not confined and bonded only on one side. However, the NSM anchorage system did not show higher capacity than that of other anchors such as fiber bolt, embedded bar and shear key system. This is because the anchorage material, CFRP strand sheet, was too stiff. It is thus guessed that the low stiffness of material should be used to strengthen the masonry infill wall. This might result in greater deformation of the wall, leading to larger increase of wall capacity. Grancrete might be able to use as the worthy option which alternative to epoxy adhesive.

Fig.12 Anchor pullout of NSM anchors

4. CONCLUSIONS

The following conclusions can be drawn from the experimental observations.

(1) The increase of flexural capacity and ductility of masonry infill was proven to be promising by

applying the additional FRP anchorage. Increase in strength of between 1.6 to 7.2 times and the change in displacement capacity ranged between 0.6 to 4.5 times of the control specimen. The shear restrain anchorage systems enhance the masonry wall most significantly on lateral load capacity, which provide over 6 times as control specimen. The embedded bar, fiber bolt and shear key anchorage systems also can enhance the masonry wall on lateral load capacity, which provide over 3 to 4 times as control specimen. Maximum load and deflection were similar magnitude for these anchorage systems.

(2) The failure mode was best correlated to the type of FRP anchorage. The specimens, embedded bar, shear key and NSM failed in the pullout of the FRP anchors from the RC cap. Anchors were subjected to a combined pullout/shear loading. Shear sliding of the masonry wall induces direct pull-off force much rather than bond slip force of each anchorage thus the anchorage strength mostly governed by the direct pull-off resistance. Further work is needed to study the interaction between the flexural behavior of the masonry infill and the shear sliding and pullout of anchors that occurs at the interface between the masonry infill and the RC frame.

(3) In case the FRP sheet and some additional anchorage are attached to the masonry wall, the type of anchorage would govern the capacity of masonry infill wall. Typically, GFRP anchorage system always provided greater strength, while PET anchorage system always provided greater ductility of masonry infill wall. PET system might be a good option to enhance the out-of-plane resistance due to the high deformability of PET sheet by developing beneficial arching action.

(4) The arching action experienced by all masonry infills can result in significant increases in the out-of-plane load capacity for both strengthened and control walls. In terms of resisting the out-of-plane load, too stiff material should not be used for the NSM system. Using less stiff material allows the greater flexural deformation, which lead to the greater arching of the infill wall. This prevents the infill wall from slide out from RC caps in early stage and result in higher lateral load capacity.

(5) Although there is little or no previous use of anchorage system such as embedded bar, shear key, CFRP strand sheet for NSM bars and Grancrete for alternative adhesive material, these anchorage systems were proven to be used as an anchor for strengthen masonry infill walls as with existing anchors. This experimental program did not test variety of different conditions such as different diameters, embedment depths, concrete strengths, however, recommended anchorage system at the current stage is the fiber bolt anchorage system. Fiber bolt anchorage has both installation easiness and can enhance load carrying capacity and ductility by increasing the number of fiber bolts since material cost is not much different.

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