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SEISMIC PERFORMANCE OF REINFORCED MASONRY WALLS STRENGTHENED WITH FRCM SUBJECTED TO CYCLIC LOADING

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ABSTRACT

Masonry is one of the oldest and most popular construction materials in the world. Changes in the building code requirements have increased the seismic demands on existing masonry structures. This may require strengthening of masonry buildings to sustain these new requirements. Strengthening of existing masonry buildings is one of the techniques that are used for increased flexural capacity. Evaluation of seismic performance of strengthened reinforced masonry wall is of high interest. The performance of seven strengthened masonry specimens was investigated in this study. The strengthening used in this study was a fiber reinforced cementitious matrix (FRCM) system. One reinforced walls constructed in running bond and one constructed in stack bond were tested as control specimens. The other specimens were strengthened using different types of fibers in the FRCM system. The simply supported walls were tested under an out-of-plane cyclic load applied along two line loads. The behavior of the specimens is discussed with emphasis on the load deflection response, energy dissipation and stiffness degradation. The test results indicated that the behavior of the masonry walls was significantly dependent on the type of fiber used. A significant increase in the out-of-plane strength of the reinforced walls strengthened with FRCM system was observed compared to the unstrengthened reinforced wall. Different modes of failure occurred in the strengthened specimens, including a flexural failure through the concrete block, as well as fabric slippage within the matrix and debonding of FRCM fabric from the matrix attached to masonry substrate.

KEYWORDS: *seismic, masonry, FRCM, cyclic*

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INTRODUCTION

Masonry is the most commonly used and one of important construction materials in the world. Reinforced masonry is obtained by placing and grouting vertical steel reinforcement in the open cells of masonry units. There is a large number of existing building around the world and in North America, especially in California have been constructed with reinforced masonry since 1930. The old reinforced masonry walls don't meet the current seismic standards so, with each new earthquake, strengthening strategies are developed [1]. Past research in related to the seismic response of masonry structures has focused on in-plane shear behavior of walls since these provide the primary lateral load resistance and in the path of load transfer [2]. Research on the strengthening of masonry structures subject to out-of-plane bending on the other hand, has focused exclusively on strengthening unreinforced masonry (URM) using fiber reinforced polymer (FRP). The strengthening of URM with FRP composites used either as externally bonded (EB) or near surface mounted (NSM) reinforcement has resulted in excellent performances[3]. FRP with epoxy has some drawbacks, including the inability to be applied on a wet substrate, poor behavior of the resin at high temperatures (above the glass transition temperature), fire hazards, emission of toxic fumes, and moisture impermeability [4,5]. The drawbacks justify the need to explore alternative strengthening techniques to masonry structures. A new strengthening technique has recently been developed that uses fabric-reinforced cementitious matrix (FRCM), also known as textile-reinforced mortar (TRM) and textile-reinforced concrete (TRC). The feasibility of using FRCM as an alternative external strengthening technology to improve the out-of-plane behavior of unreinforced masonry walls has been investigated [6]. Nine clay brick walls were strengthened with different amounts of FRCM and the result showed significant improvements in the structural performance of the walls in terms of flexural capacity and stiffness. Ebead et al. [7] Investigated the efficiency of FRCM in enhancing the flexural capacity and deformation characteristics of RC beams, and the type and amount of fiber were considered. Test results showed that the flexural capacity of the strengthened beams increased by 77% for the3-layers carbon FRCM system and by 27% for a 2-layers Polypara-phenylene-benzo-bisthiazole (PBO) FRCM system.

Unreinforced masonry walls strengthened with TRM and subjected to cyclic out-of-plane loading have also been investigated [8]. The effectiveness of TRM overlays was evaluated in comparison to that provided by FRP in the form of overlays or near-surface mounted (NSM) reinforcement. It was concluded that TRM overlays provide substantial increase in strength and ductility. Compared with FRP, TRM may result in generally higher effectiveness in terms of strength and ductility. NSM strips offer lower strength but higher ductility due to controlled debonding. From the results obtained the authors concluded that TRMs comprise an extremely promising solution for the structural upgrading of masonry structures under out-of-plane loading. In the current study, the behavior of reinforced masonry walls strengthened with FRCM system was investigated with emphasis on the load deflection response, energy dissipation and stiffness degradation. The motivation of the present work is associated with the important influence of FRCM as an effective retrofitting technique and as an alternative technique for masonry structural elements. To achieve this goal, a total of seven reinforced masonry walls, two as reference specimens and five strengthened with FRCM system using different types and amount of fiber were constructed and tested. This paper presents the response and discussion of the behavior of these walls based on cyclic load displacement curves.

AIM AND OBJECTIVE

The principal objective of this study was to find out and discuss the failure mechanism and to investigate the flexural capacity and behavior of reinforced masonry walls strengthened with FRCM and subjected to cyclic out-of-plane loading. This objective was achieved by testing a series of reinforced masonry walls strengthened with different types and amount of fabric and different bond pattern. The test specimens were directly strengthened after construction.

The seismic assessment of masonry performance is reported qualitatively through test observations and quantitatively by evaluating the load deflection response, energy dissipation, and stiffness degradation.

EXPERIMENTAL INVESTIGATION

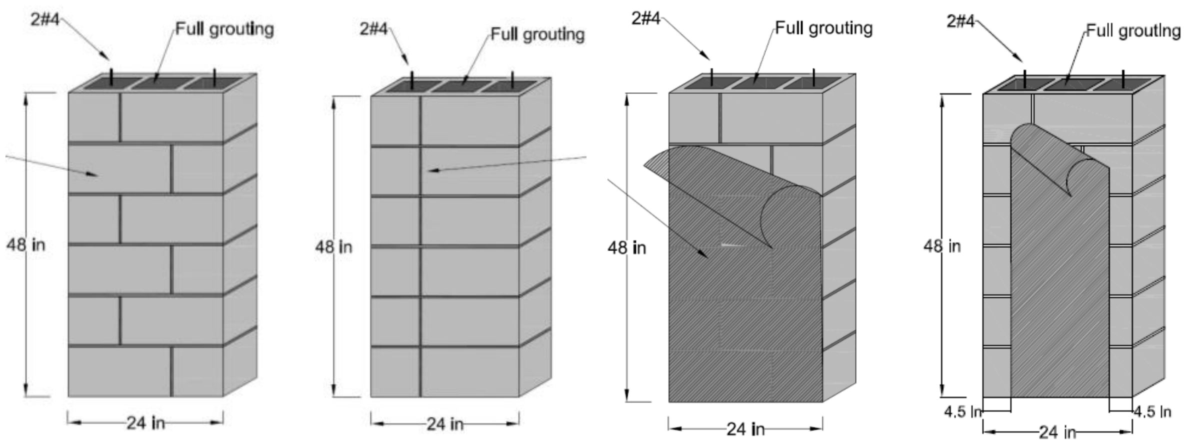
This experimental program investigated the effectiveness of FRCM system on the out- of- plane strengthening of reinforced masonry walls. Seven reinforced masonry walls were constructed and tested. Two of walls were used as control specimens, two specimens were strengthened by a carbon FRCM system and three walls are strengthened using a PBO FRCM system.

Reinforced Wall Configurations

Reinforced masonry specimens had the same overall dimensions and longitudinal main reinforcement. Each specimen was constructed using 152.5 mm (6 in.) standard masonry blocks in running and stack bond and type S mortar. The nominal dimensions of the walls were 1220 mm (48 in.) height by 610 mm (24 in.) length. The steel reinforcement was constant for all specimens (2#4) bars and the walls were fully grouted, which occurred four days after construction to preclude damage to the mortar joints during the vibration process. The strengthened walls are shown in Figure 1.

Wall Specimen Designation

The specimen ID consisted of two parts as shown in table 1. The first part represented fiber information (type and width). The first character identified the fabric types, namely C for carbon fiber and PBO for Polypara-phenylene-benzo-bisthiazole fiber. The second character referenced the layer width. The second part of the ID identifies the number of layers and the wall bond pattern, S for stack and R for running bond.



(b) Running bond (a) Stack bond (c) Carbon FRCM (d) PBO FRCM

Figure 1: Wall Configuration and Strengthening Technique

Table 1: Experimental Test Matrix

Wall	Specimen Designations	Fiber Type	Number of Strips	Wall Pattern	Width of Strip (mm) (in.)
1	Control-R	-	-	running	-
2	Control-S	-	-	stack	-
3	PBO(380)-1R	PBO	1	running	380 mm (15 in.)
4	PBO(380)-2R	PBO	2	running	380 mm (15 in.)
5	PBO(380)-2S	PBO	2	stack	380 mm (15 in.)
6	C(610)-1R	carbon	1	running	610 mm (24 in.)
7	C(610)-2R	carbon	2	running	610 mm (24 in.)

Materials Characterization

Tests were performed to determine the mechanical properties of each component. The properties of the materials used to construct the specimens are summarized in table 2, while the manufacturer given properties of the fabric and corresponding bonding mortar are presented in table 3.

Strengthening Procedure

The FRCM strengthening system consisted of one or two plies of carbon or PBO fabric embedded in a cementitious mortar matrix. There is a specific mortar for each type of fiber such as: mortar type x750 used with PBO fiber and mortar type x25 for the carbon fiber as shown in Figure 2.

Table 2: Material Properties

Material	Properties	Values (MPa)	Method
Concrete Block	Prism Compressive Strength	21	ASTM C1314-12
Mortar Type S	Compressive Strength	17.5	ASTM C109-13
Grout	Compressive Strength	35	ASTM C1019-13
Steel Reinforcement	Yield Strength	471	ASTM A370-13
	Modulus of Elasticity	203000	
Note: 1.0 MPa = 145 psi.			

Table 3: Mechanical Properties of Fabric and Bonding Mortar

Material	Thickness (mm)	Ultimate tensile strength (MPa)	Elongation at break %	Tensile Modulus (MPa)	Method
PBO fiber	0.05	5800	2.15	270000	ASTM D3039-14
Carbon fiber	0.05	4800	1.80	240000	ASTM D3039-14
Mortar x750	-	35	-	-	ASTM
Mortar x25	-	15	-	-	ASTM
Note : 1.0 GPa = 145.03 ksi; 1.0 MPa = 0.145 ksi; 1.0 mm = 0.039 in.					

PBO fabric | inorganic mortar x750 | Carbon fabric | inorganic mortar x25

Figure 2: Fibers and Bonding Adhesive Mortar Used for Strengthening

The FRCM strengthening system installation procedure involved the following steps: the first layer of mortar with a nominal thickness of approximately 5 mm (0.2 in.) was applied onto the masonry, 1-ply of precut fabric was laid next, and then the second layer of mortar about 5mm (0.2 in.) thick was applied and finished. The procedure was repeated in the case of multi-ply strengthening.

Test Setup and Loading Rate

The strengthened reinforced masonry specimens were tested under four-point bending, with simply supported boundaries as shown in Figure 3. An MTS double-acting hydraulic jack with a push-pull capacity of 965 MPa (140 kips) was used to apply a vertical load on the specimen. The load was transferred to the masonry specimen by means of continuous steel plates and bars along the full width of specimens providing two equal line loads. A piece of thick rubber sheet was placed at all interfaces between the steel plate and specimen. The rubber distributed the load evenly and minimized any stress concentration due to unevenness of the wall surface. The distance between these two lines was 200 mm (8 in.). The load was applied in cycles of loading and unloading, as a displacement control, at a rate of 1.25 mm/min (0.05 in. /min). The displacement amplitude increment was 6.35 mm (0.25 in.); double half loading cycle was applied for each amplitude level as illustrated in Figure 4. Displacements at the mid and third spans were measured using three Linear Variable Displacement Transducers (LVDTs) at each side. In addition, strain gauges were installed on the steel reinforcing and fiber to measure their strains during loading.

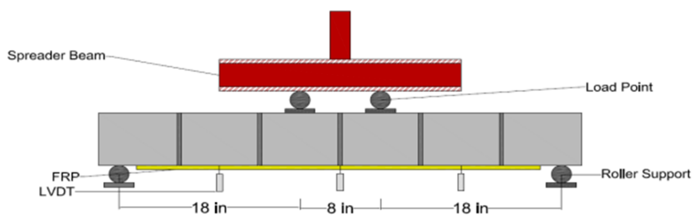


Figure 3: Four Point Load Setup

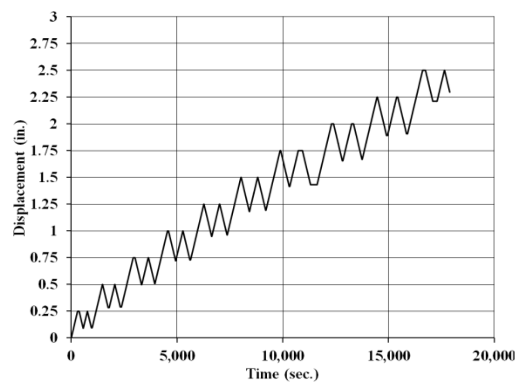


Figure 4: Loading Protocol

TEST RESULT AND DISCUSSION

The loads vs. mid-displacement for all specimens are presented in Figure 5. The general behavior of the strengthened specimens was ductile due to the gradual loss of composite action caused by slippage or debonding of the FRCM system. The debonding occurred at the bonding mortar/fiber interface. The capacity of wall strengthened with 2- layers of carbon fiber increased by 90% compared to that of the control specimen.

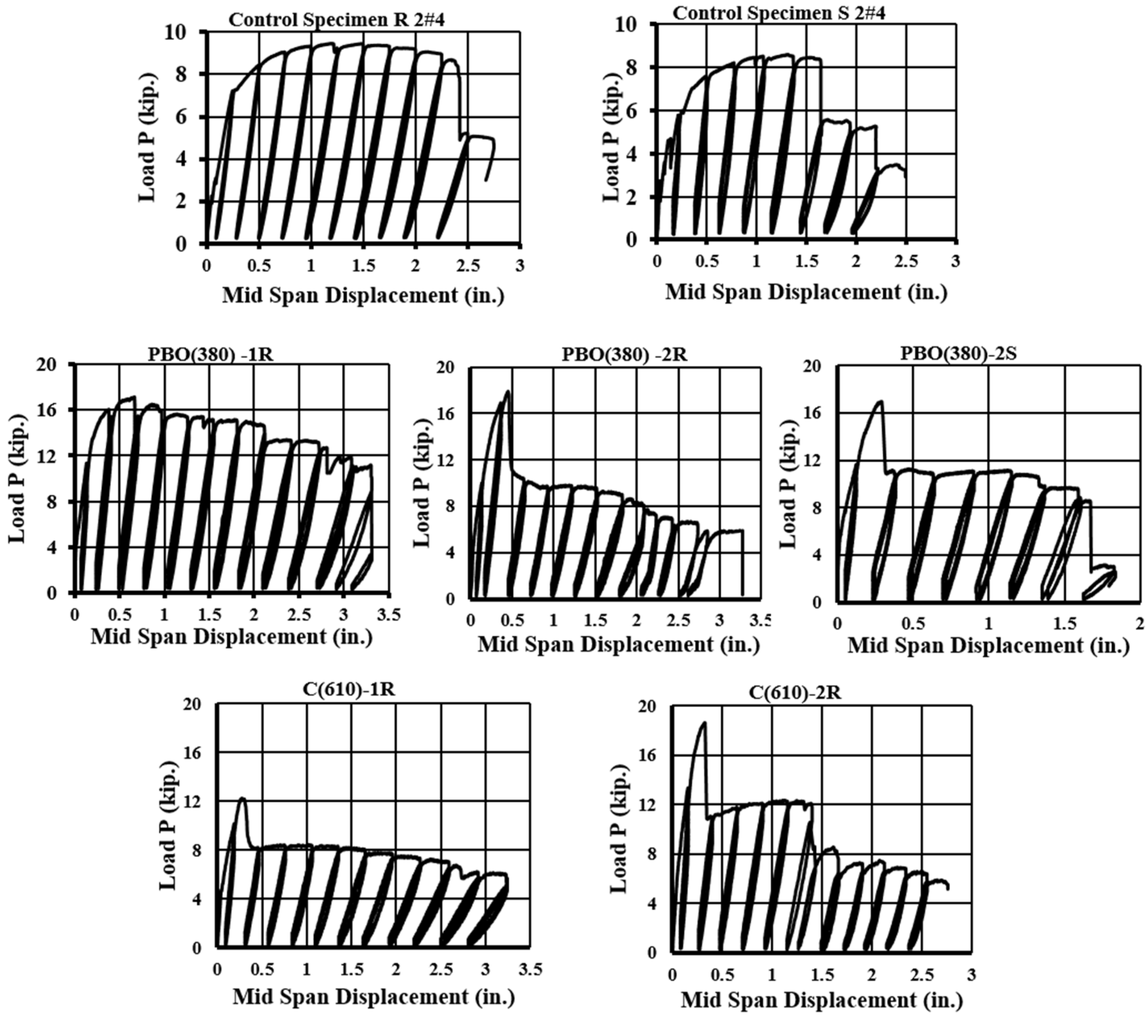


Figure 5: Load Deflection Curve

Cracks Pattern and Failure Modes

The control specimens failed in a typical flexural ductile mode due to the steel reinforcement. The first flexural tensile crack initiated at the block bed joint mortar in the maximum moment region in case of unstrengthened and strengthened wall. Further flexural tensile cracks in the bed joints mortar and through the CMU developed beyond the cracking load due to existing of FRP reinforcement as shown in Figure 6.

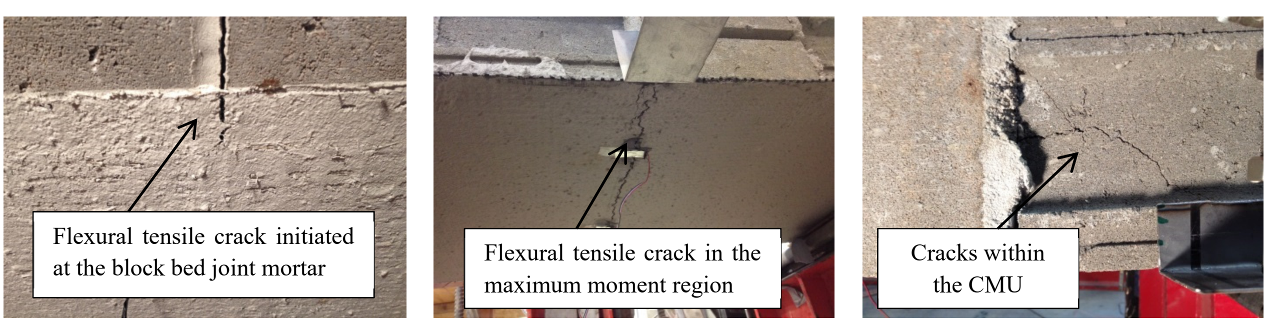


Figure 6: Cracks Developed During Loading

Different modes of failure occurred in the strengthened reinforced walls depending on type of fabric used as shown in Figure 7. Bond failure of FRCM was characterized purely by fiber/matrix slippage as exhibited by specimens strengthened with one ply of PBO. This specimen intentionally anchored by extended the fiber sheet beyond the two supports to study the effect of anchorage regardless the type of anchorage system. For all specimens strengthened with a single layer of PBO fabric, the failure was due to the slippage at the interface fiber/cementitious matrix. The failure was gradual and large slip values were recorded at the interface fiber/matrix while negligible slips values were recorded at the interface cementitious matrix/concrete[9]. The other mode of failure was debonding at the interface fiber/matrix which occurred on the majority of strengthened specimens.

Debonding failure is strongly dependent on the load transfer mechanisms at the masonry/matrix interface. In the FRCM system, the interfacial debonding occurred within the composite; large slips at the fibers/cementitious interface took place while the masonry substrate was not involved in the resisting mechanism.

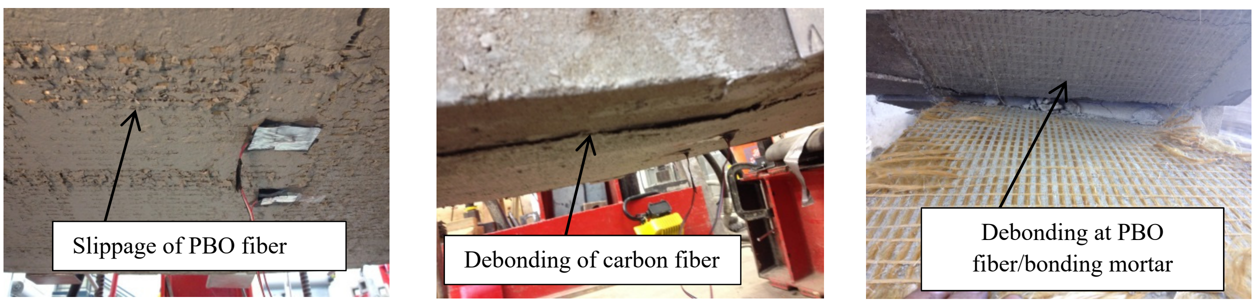


Figure 7: Observed Modes of Failure

Energy Dissipation

For structures subjected to seismic events, energy dissipation is an important property since it reduces the amplitude of the seismic response and, thereby, reduces the strength demands on the structure. Physically it's used as a ductility measurement since it represents the energy consumed by the structural system before failure. Mathematically it represents the area enclosed by loops of loading and unloading for specimens subjected to cyclic loading. The energy dissipated by the masonry wall has been attributed to (1) friction along joints and existing cracks, (2) formation of new cracks, (3) crushing of units, and (4) yielding of main reinforcement [10]. Fiber deformation or progressive rupture, in addition to the cracks in the cementitious material would dissipate energy.

As expected, for low drifting levels, the friction along joints was small and consequently the energy dissipation was low, which characterized the condition before significant inelastic deformation in the masonry and elastic level of the main steel reinforcement. For higher drifting levels, the energy dissipation increased significantly with an almost linear increase in the amount of energy dissipated associated with the increasing number of cyclic loading. The formation of longitudinal and diagonal cracking, yielding of main reinforcement and the cracks in the cementitious matrix were the reasons for the increased energy dissipation. The energy dissipated by masonry wall strengthened with FRCM and using different types and amount of fibers is shown in Figure 8. The specimen strengthened with 1 ply of PBO FRCM exhibited an excellent behavior in term of ductility and energy dissipation. In this specimen, the fiber was intentionally anchored by extending it beyond the two supports to determine an upper bound capacity. The energy dissipation for this specimen was improved by 55% comparing to the 2 ply PBO without anchorage and 80 % compared with control specimen. Interestingly, for the first 25 cycles, the energy dissipation for specimen strengthened with carbon sheet was less than that of the control specimen for the same cycles. This behavior attributed to the mode of failure that didn't present fully slippage of fiber in the cementitious material in addition to formation of less cracks and damage on the units compared to the control specimen. At the end of the test the strengthened specimen was able to go through more cycles and presented higher energy dissipation than that of the control specimen.

The energy dissipation for individual specimens was normalized with respect to the lowest value to monitor the trend of energy dissipation. The normalized values are shown in Figure 9.

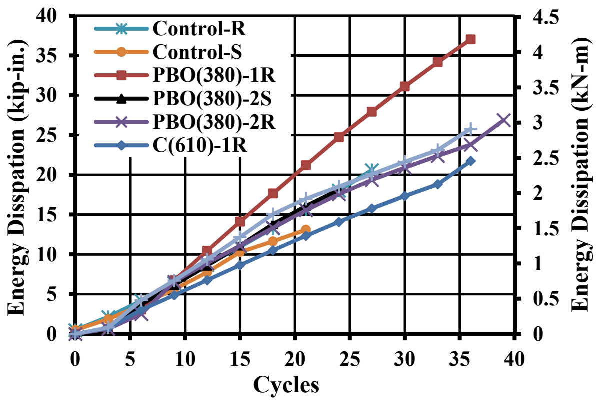


Figure 8: Energy Dissipation for All Specimens

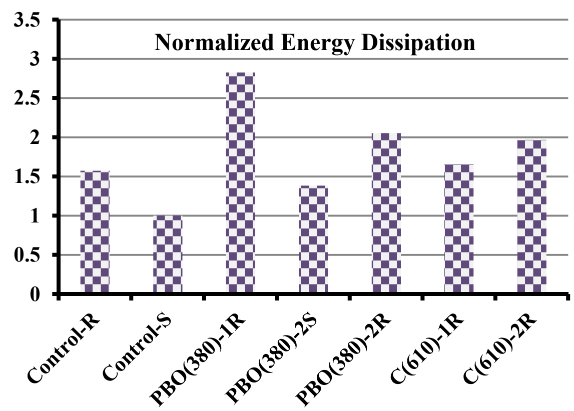


Figure 9: Normalized Energy Dissipation

Stiffness Degradation

The stiffness degradation with increasing loading cycles is shown in Figure 10 for all specimens. This degradation may be attributed to several factors including the nonlinear deformations of the concrete block units, mortar cracking, flexural and shear cracking of masonry units, slippage or yielding of reinforcement, and debonding or slippage of fibers in FRCM system. The strengthened specimen had higher initial stiffness than its corresponding control specimen. This higher initial stiffness can be attributed to the high modulus of elasticity of the fibers attached to the strengthening wall. The stiffness degradation of the strengthened specimens is linear elastic until failure. Therefore, the sudden jump down in stiffness is expected at the stage of FRCM debonding. The control specimen behaved as a ductile member due to the steel reinforcement, but a sudden loss in stiffness of 30% within the first few cycles was observed. The initial stiffness for the strengthened wall dropped down to the level of the control wall stiffness when the mid span deflection was about 25.4 mm (1-in.).

The stiffness degradation was normalized with respect to the initial stiffness of the control specimen. Figure 11present the trend of degradation in stiffness. For the specimen strengthened with 1 ply of PBO and anchor underneath the support, the degradation in stiffness is gradual compared to that of the corresponding control and that of the other strengthened specimens. This is a desirable behavior for structures subjected to seismic events.

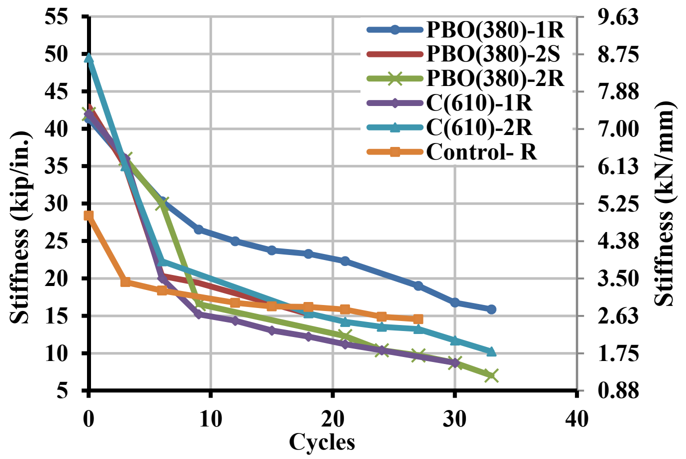


Figure 10: Stiffness Degradation vs. Number of Cycles

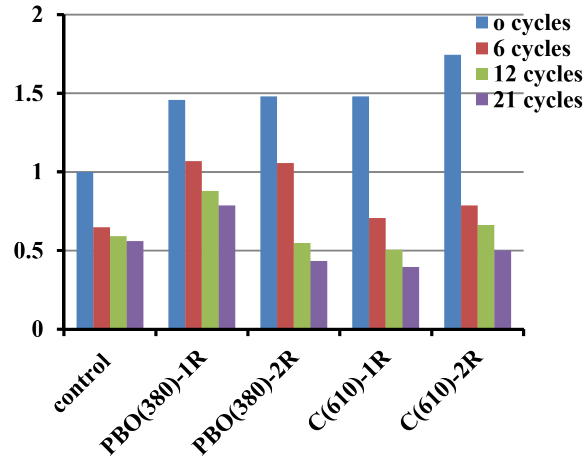


Figure 11: Normalized Stiffness Degradation

CONCLUSION

Test results indicated that FRCM system remarkably increases the lateral load capacity of reinforced masonry walls. Moreover, during the later loading stages, the FRCM system was effective in enhancing the stiffness of the strengthened walls. The energy dissipated increased significantly and was dependent on type and amount of fiber of the FRCM system. The specimen strengthened with 1 ply PBO presented an excellent behavior in term of ductility and energy dissipation. The energy dissipation for this specimen was improved by 55% compared to that of 2 ply PBO without anchorage and 80 % compared to that of the control specimen. The same specimen presented gradual and slow degradation of stiffness compared to the corresponding control specimen. The initial stiffness of strengthened specimen is greater than that of its corresponding control specimen by 45 to 75 % depending on the type of fiber used. The stiffness of the control specimen was decreased by 30% within first cycles. Failure of strengthened specimens initiates with yielding of reinforcing steel followed by fiber slippage or debonding at the fiber/bonding mortar interface. After failure at the strengthening system, the masonry walls showed similar behavior to that of the unstrengthened walls with yielded steel.

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