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PERFORMANCE OF REINFORCED MASONRY WALLS STRENGTHENED WITH FRP COMPOSITE EXPOSED TO COMBINED ENVIRONMENTAL CONDITIONS

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ABSTRACT

Fiber reinforced polymer (FRP) composite have been used effectively to strengthen reinforced masonry and concrete structures. However, the performance of FRP composite strengthening systems is still of great concern especially when it's exposed to harsh environmental conditions. In this study, an effort was made to investigate the flexural behavior of reinforced masonry walls strengthened with near surface mounted (NSM) FRP bars and exposed to different weathering actions. The walls performance was investigated by exposing the specimens to 350 different environmental cycles through a computer-controlled environmental chamber. These cycles are proposed to simulate 20 years of the typical in-situ weather conditions of the Central US. Seven reinforced masonry walls were built for this study. An identical reinforced masonry walls in its unstrengthened form are used as control specimens. Constant reinforcement ratio (ρ) for mild steel was used. Two sets of three specimens strengthened using NSM with different types of FRP bars (glass and carbon) and carbon strip were tested. The first set was tested after at least 28 days as a curing period of laboratory conditions, while the other set was tested after 72 days of exposure to combined environmental conditions. The walls tested in four-point bending under cyclic load with loading rate 1.27 mm/min. In term of flexural capacity, the specimen strengthened with CFRP bar was affected by weathering condition more than the specimens strengthened with CFRP strip or GFRP bar. Different modes of failure occurred in the strengthened reinforced walls, including a punching shear failure through the concrete block, as well as debonding of FRP reinforcement from the masonry substrate.

KEYWORDS: *reinforced, masonry, FRP, NSM, environment*

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INTRODUCTION

Strengthening of masonry walls with fiber reinforced polymer FRP as near surface mounted NSM has become a popular technique in the last years. NSM has been considered to increase the flexural capacity for both unreinforced and reinforced masonry walls [1-4]. The existing research on strengthening using FRP in term of durability focuses on environmental degradations factors individually. The temperature action is one of the main environmental degradation factors that can affect the behavior of strengthened reinforced concrete structures[5]. Cubic and slab specimens strengthened with NSM carbon fiber reinforced polymer (CFRP) strips was used to study durability performance of the near-surface mounted (NSM) strengthening technique. These specimens were submitted to thermal cycles and tested up to failure using four point bending and pullout direct test for slab and cubic specimens respectively. The results indicate that the slabs capacity and damage mechanism were not affected by thermal cycles range of -15°C to 60°C. Nevertheless, the bond strength increased with the number of thermal cycles. Flexural performance of NSM carbon/vinylester FRP tape strengthened concrete slabs at low temperatures was investigated[6]. The effects of adhesive type (cementitious or epoxy) and groove width are discussed at both room (21°C) and low (-26°C) temperature. The results show no discernable negative impacts on the performance of any of the strengthened members using epoxy or cementitious grout adhesives at low temperature. Effects of elevated temperature on NSM FRP strengthening systems for reinforced concrete slabs was conducted [7]. Under sustained service loads, the strengthened slabs were capable of withstanding over 40 min at 100°C but less than 10 min at 200°C. NSM technique fails at elevated temperature by debonding at the adhesive-concrete interface. A significant losses in bond resistance at elevated temperature, since the experimental tests occurred at temperatures exceeding the glass transition temperature (T_g) of the epoxy adhesive.

Moisture has been observed to be another important deteriorating agent for the specimen strengthened with advanced composite. Moisture effects on the pull-off bond strength of FRP-masonry elements was evaluated[8]. The specimens have been exposed to constant moisture level of 100% R.H. at 23 C for eight weeks. The degradation in the bond performance has been investigated on the conditioned specimens after four and eight weeks of exposure. The percent of bond strength reduction was observed in the exposed specimens 15% and 23% for the specimens immersed in water for 4 and 8 weeks, respectively. The results of this study showed that moisture can reduce the bond strength of the FRP-masonry elements largely within a two months period of exposure. The bond failure for specimens exposed to accelerated wet/dry cycling always occurred at the primer-to concrete interface and not within the concrete substrate. In contrast the specimens not exposed to wet/dry cycling bond failure always occurred in a very thin mortar layer of the concrete[9].

The glass transition temperature for the polymeric matrix in FRP composites is decreased due to moisture exposure[10]. These studies present the need for evaluating the performance of composite durability under combined environmental exposure to simulate the natural weathering conditions. There is a lack of long-term and durability performance of strengthened masonry walls considering structural aspect under combined environmental exposure. This research focused on effect of combined environmental cycles on flexural behavior of reinforced masonry walls strengthened with NSM FRP technique. The behavior evaluated in term of initial stiffness, ultimate capacity, ultimate deflection and mode of failure.

RESEARCH SIGNIFICANCE

Reinforced masonry walls strengthened with NSM FRP are exposed to combined environmental conditions that may cause a change in design flexural capacity or expected failure mechanism.

Seven reinforced masonry walls were built for this study. Two sets of three specimens strengthened using NSM with different types of FRP (glass and carbon) in addition to control specimen were tested. The first set was tested after at least 28 days of a laboratory condition, while the other set was tested after 72 days of exposure to 350 different environmental cycles of freeze-thaw, relative humidity and high temperature cycles. These cycles are proposed to simulate 20 years of the typical in-situ weather conditions of the Central US. So this study investigated how the combination of different environmental cycles can affect the long-term behavior of the strengthened walls. Since, the effects of the single environmental factors were investigated in previous studies; this study allows evaluating the combined effect which is more representative of structural applications.

EXPERIMENTAL INVESTIGATION

This experimental program investigates the resistance of NSM technique for the out- of- plane strengthening of reinforced masonry walls exposed to different weathering action. Seven reinforced masonry walls were tested; the specimens strengthened by NSM technique using carbon and glass fiber with epoxy as adhesive agent. These specimens divided in two sets, the first one consist from control specimen and three strengthened masonry walls in addition to three masonry units. All these specimens subjected to laboratory conditions before test. The second set includes three strengthened specimen and three masonry units subjected to environmental cycles before test.

Testing Specimens

The test specimens were intended to represent structures built in California (high seismic zone). Reinforced masonry walls for all specimens have the same overall dimensions and longitudinal main reinforcement. Each wall constructed using standard masonry blocks 152.5 mm (6 in.) in running and stack pattern and type S mortar. The nominal dimensions of these walls were 1220 mm (48 in.) length by 610 mm (24 in.) width. They were grouted four days after construction to ensure stability during the vibration process. The reinforcement ratio (ρ) for mild steel was constant for all specimens (2#4) steel bars. These control and strengthened wall configuration, in addition to cross section of block unit are shown Figure 1.

Test Matrix and Wall Specimen Designation

The specimen ID consist of two parts as shown in table 1: the first part consist of three characters represent FRP information (type, shape and size). The first character identified the FRP type: namely “C” for carbon FRP and “G” for glass FRP. The second character referenced the bars cross section; an ‘‘S’’ represented a rectangular strip, and a ‘‘B’’ represented a circular bar. The third character represented the FRP size. The second part identified the exposure condition: namely “L” for laboratory conditions and “EN” for environmental chamber exposure.

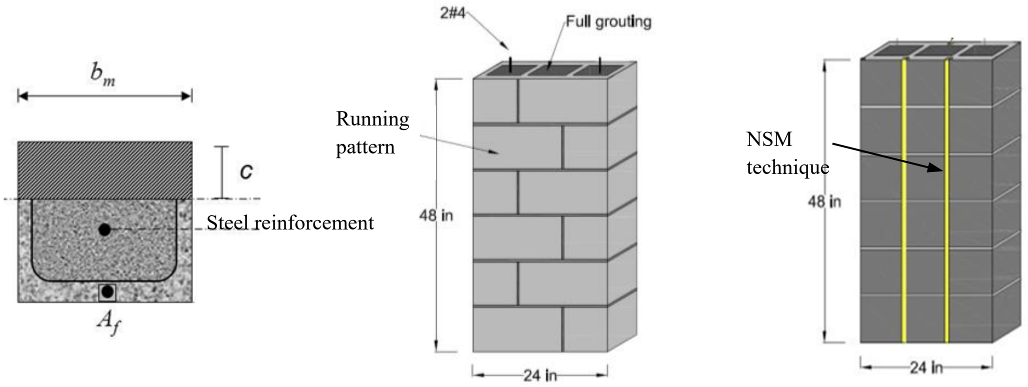


Figure 1: Cross Section and Reinforced Wall Configuration

Table 1: Experimental Test Matrix

Wall	Specimen Designations	FRP Type	Number of bars	Groove dimension (mm*mm)
1	Control-R	-	-	-
2	CS3-L	carbon	-	17.8*25.5
3	CB3-L	carbon	1	19*19
4	GB3-L	glass	1	19*19
5	CS3-EN	carbon	1	17.8*25.5
6	CB3-EN	carbon	1	19*19
7	GB3-EN	glass	1	19*19

Materials Characterization

A series of tests were performed to determine each material’s mechanical properties. The properties of the materials that were used to construct the specimens are summarized in table 2. The manufacturing properties of FRP and its epoxy adhesive are presented in table 3.

Table 2: Results of the Material Properties

Item	Properties (MPa)	Values	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 Bar	Yield Strength	471	ASTM A370-13
	Modulus of Elasticity	203000	

Note: 1.0 MPa = 145 psi.

Table 3: Mechanical Properties of FRP and Bonding Adhesive

Type of FRP	Dimension (mm)	Ultimate tensile strength (MPa)	Elongation at break %	Tensile modulus (GPa)
Aslan 500 CFRP Strip	4.5x16	1965	1.5	124
Aslan 200 CFRP bar	10	2172	1.75	124
Aslan 100 GFRP bar	10	827	1.79	46
Epoxy	-	27.6	1	-

Note : 1.0 GPa = 145.03 ksi; 1.0 MPa = 0.145 ksi; 1.0 mm/mm = 1.0 in./in.; 1.0 mm = 0.039 in.

NSM Strengthening Procedure

For the NSM there is no surface preparation needed. The NSM FRP installation process involves inserting FRP bar into a groove cut at the tension surface of the wall. A special concrete saw was used to cut the grooves with a dimension double the diameter of the bar to avoid splitting failure of the epoxy cover[11]. The FRP bars are deformed by a helical wrap with a sand coating to improve the bond between the bars and epoxy. The epoxy was pressure injected into the grooves to cover 2/3 of the groove height. The FRP bar was placed in the grooves and lightly pressed to force the bonding agent to flow around the bar and ensure completely bond between the bar and the sides. The groove is then filled with more epoxy and the surface leveled. Construction of masonry walls and installation of FRP in groove are shown in Figure 2.

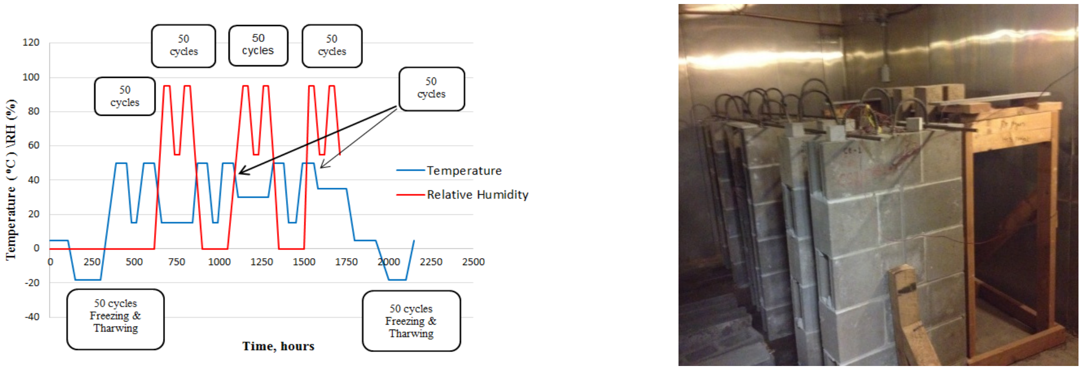
(a) (b)

Figure 2: Experimental Program: (a) Construct Walls and (b) Installation of FRP in Grooves

Exposure Cycles

The exposure cycle consisted of a combination of sever freeze-thaw cycles, extreme temperature cycles, high relative humidity cycles and indirect ultra-violet radiation exposure. The exposure regime was selected to simulate the seasonal changes in an environment such as Midwest, US in an accelerated manner. A computer-controlled environmental chamber is used to simulate 350 different environmental cycles. This regimen consisted of 100 freeze-thaw cycles that simulated the effects of the winter season. Each freeze-thaw cycle consisted of freezing at -17.8ºC (0ºF) for

50 minutes and thawing at 4.4ºC (40ºF) for 50 minutes. The transition period between freezing and thawing was 30 minutes. To simulate the summer season effects, 150 alternating cycles of extreme temperature from 27 to 50°C (80 to 120°F) is used. Extreme temperature cycle consisted of temperature variation between 27ºC (80ºF) for 25 minutes and 50ºC (120ºF) for 25 minutes. The transition period between high and low temperature was 20 minutes. Relative humidity cycles were carried out between 60% and 100% and maintained for 20 minutes each, transition period between 100% and 60% humidities was 30 minutes. Relative humidity cycles were carried out at constant temperatures of 15.5ºC (60oF) and 26.7ºC (80ºF). The order of cycling was 50 freeze-thaw cycles, 20 RH cycles at constant temperature of 15.5ºC (60ºF), first set of 40 extreme temperature cycles, 20 RH cycles at constant temperature of 26.7ºC (80ºF), second set of 40 extreme temperature cycles, 20 RH cycles at constant temperature of 15.5ºC (60ºF) and third set of 40 extreme temperature cycles. The exposure regime and specimens in environmental chamber are shown in figure 3.

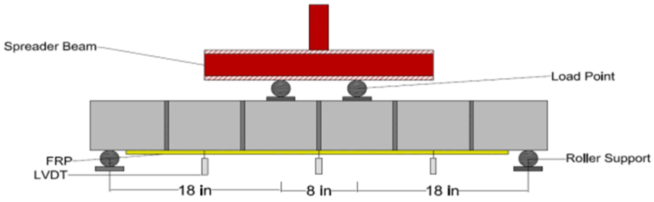


(a) (b)

Figure 3: Environmental cycles: (a) Exposure Regime (b) Specimens in Environmental Chamber

Test Setup and Loading Rate

Four-point line loading can be used to conduct out-of-plane testing on reinforced masonry walls. The strengthened reinforced masonry specimens used in this study will be tested with simply supported boundaries under cyclic load as shown in Figure 4. An MTS double-acting hydraulic jack with a push-pull capacity of 965 MPa (140 kips) will be used to apply a vertical load on the wall panel. This load is transferred to the masonry specimen by means of continuous steel plates and bars along the full width of the external face of the reinforced walls to provide two equal line loads. A piece of thick rubber sheet is inserted at all of the interfaces between the steel plate and masonry wall. The rubber sheet distributes the load evenly and minimizes any stress concentration due to unevenness of the wall surface. The distance between these two lines is 200 mm (8 in.). The load will be applied in cycles of loading and unloading, as a displacement control, at a rate of 1.27 mm/min (0.05 in. /min) through an MTS computer control station up to the load peak value. 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 5. For the lab conditions specimens, the specimens were ramp loaded after FRP failure happened. Deflections at the mid and third spans were measured using three Linear Variable Displacement Transducers (LVDTs) at each side. In addition, strain gauges will be placed on the steel and fiber to record their strains during loading.



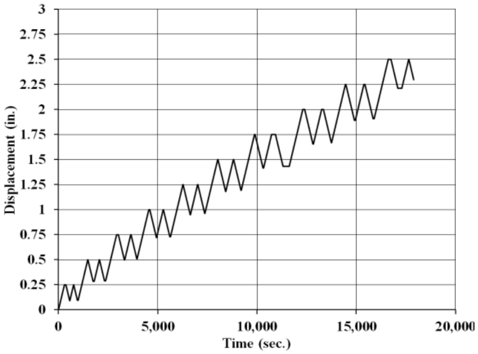


Figure 4: Four Point Load Setup

Figure 5: Loading Protocol

TEST RESULT AND DISCUSSION

In order to study the effect of sever environmental conditions on strengthened reinforced masonry walls; the individual components (epoxy adhesive, masonry unit and FRP bars) and strengthened masonry walls should be evaluated before and after exposure.

Epoxy Adhesive

The mode of failure for both sets is controlled by the masonry unit property and the debonding failure surface is in the masonry material and not in adhesive layer or at the FRP- adhesive interface. As a result, the effect of environmental cycles on epoxy adhesive didn’t considered since this component didn’t affect the structural behavior or mode of failure. In general the mechanical properties of the epoxy adhesive subjected to thermal cycles were improved. Regardless of the epoxy adhesive properties have improved, this advantage didn’t affect the structural member response when the failure mode was controlled by concrete properties[5].

Compressive Strength of Masonry Unit

Three individual concrete masonry units were tested for compressive strength according to ASTM C140/C140M-16 before and after environmental conditions. A fibrous composite laminated cap was used to distribute the load over the top and bottom of masonry unit. A rigid 24 x 12 x 2 in. (610 x 305 x 51 mm) steel loading plate was used to apply the loads Figure 6. The maximum stress was averaged of three samples for each set. The result showed that the compressive strength of conditioned masonry unit was reduced by 10 %. This reduction in strength attributed to microcracks due to increasing internal voids pressure that generated after freezing the absorbed water.

Tensile Test of FRP Bars

Tensile tests, according to provisions of ACI 440[12] were conducted by [13] to study the change in longitudinal mechanical properties of FRP. The tensile strength of GFRP bars and CFRP strip subjected to the environmental cycles did not reduced showed a good durability resistance comparing with control bar. Carbon bars showed a degradation in tensile strength by approximately 5%[13]. The results of the effect of environmental cycles on individual components are illustrated in Figure 7.

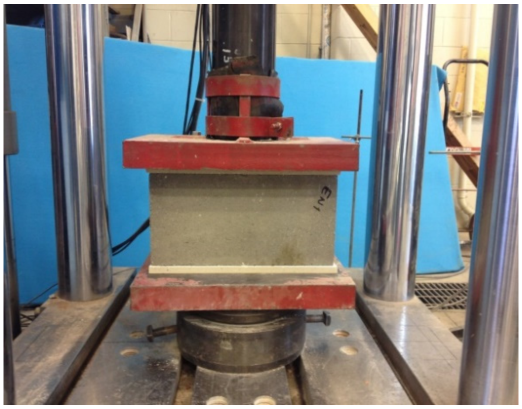


Figure 6: Compressive strength test setup

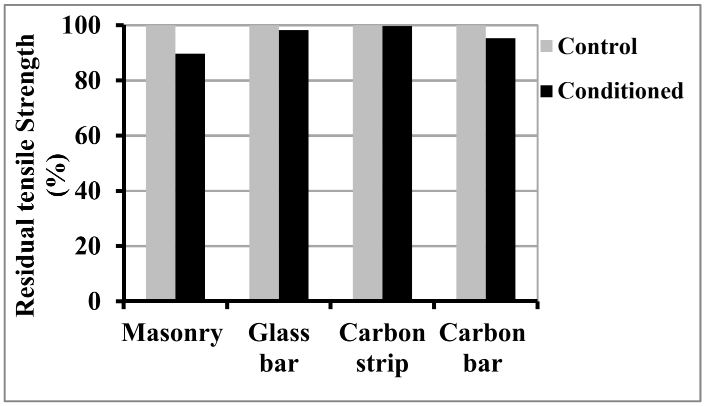


Figure 7: Residual tensile strength (FRP result[13])

Strengthened Masonry Walls Specimens

The load versus deflection curve for both sets is illustrated in Figure 8. The results were expected since the debonding failure surface is in substrate and mechanical properties of FRP bars were not affected by environmental cycles so the main affected factor is masonry unit. The general behavior of walls strengthened with FRP system for both sets (laboratory and environmental conditions) is still the same. The behavior can be divided into three segments. The first portion of the envelope is pre-crack phase which is varies linearly with a small deflection up to the first mortar crack. Insignificant effect of FRP bars on stiffness of this segment and only a little effect on cracking load were observed. The second segment of envelope is pre-yielding stage. This phase is recognized through the change of the slope and its ends with yielding of the steel reinforcement. The third part of the load-deflection envelope is the post-yielding segment. It begins with the yielding of steel and ends with failure of FRP bars, regardless of the type of failure.

For the conditioned specimens, the ultimate flexural capacity and stiffness of the wall strengthened with carbon strip and glass fiber didn’t significantly change comparing with the wall strengthened with carbon bar. The reduction of ultimate capacity of specimen strengthened with one carbon bar was 17%. The reason behind that could be attributed to the reduction of both tensile strength of CFRP bar and compressive strength of masonry unit. The effect of combined environmental cycles led to change the mode of failure from shear (sudden failure mode) to debonding failure (gradual failure). The results of the ultimate load, deflection, and stiffness reduction percent for conditioned specimens are presented in Table 4.

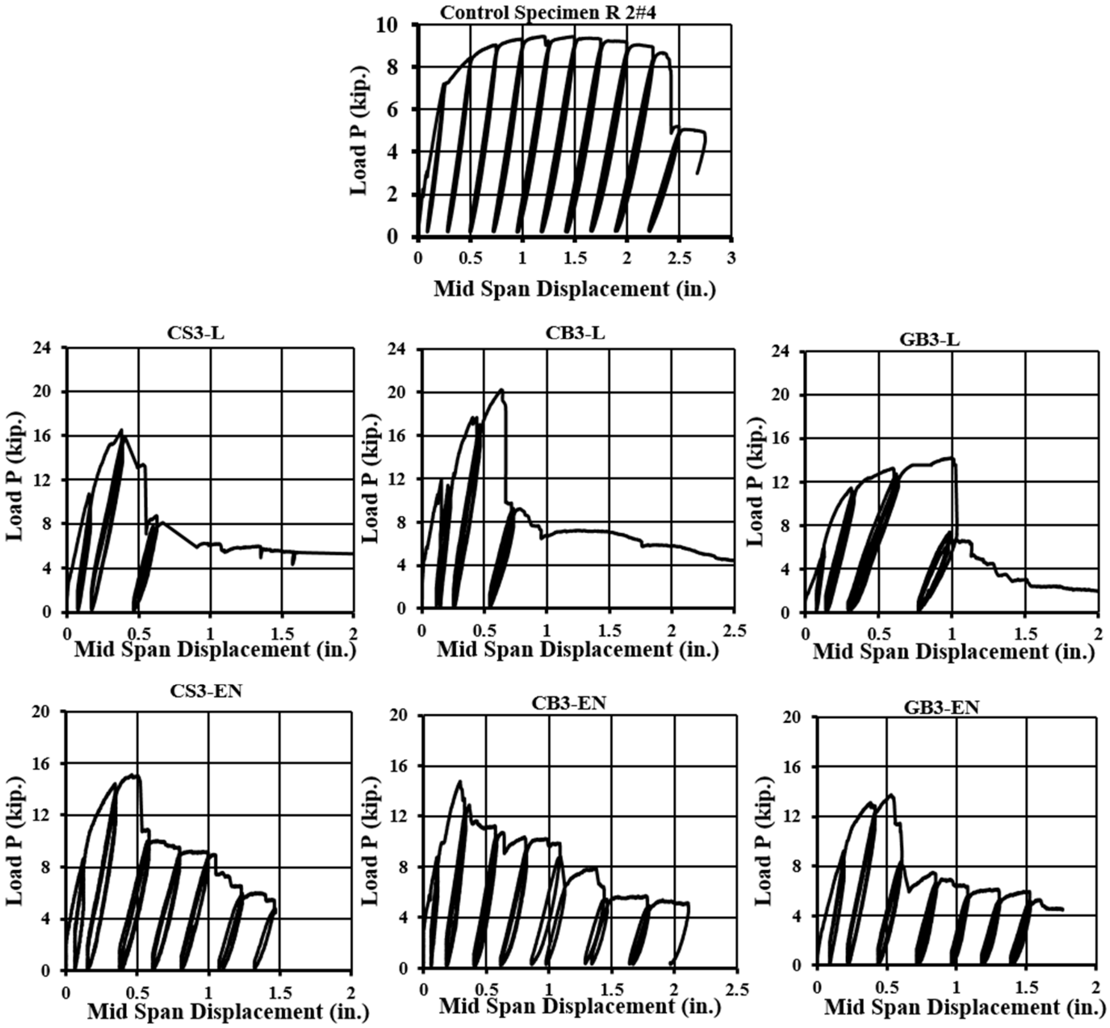


Figure 8: Load Deflection Curve

Table 4: Percentage of Reduction for Strengthened Specimens Exposed to Environmental Action

Specimen	Capacity	Deflection	Stiffness
CS3-EN	8.6 %	1.8 %	7 %
CB3-EN	27.2%	0%	17 %
GB3-EN	3.3 %	39 %	4.8 %

Cracks during Test and Modes of Failure

Same cracks generated during the test of both sets of specimens. The first flexural tensile crack was hair crack initiated at the block mortar in the maximum moment region. Within the increasing in loading, these cracks were developed at other bed joints. Further flexural tensile cracks developed when the specimen loaded at level beyond the cracking load / moment (Mcr). The FRP reinforcement that was encapsulated with an epoxy material caused cracks to propagate in the masonry units.

The masonry cracks were oriented at 45°. These cracks extended along the grooves sides as the load increased. They developed in the CMU as a result of the epoxy's high tensile strength (when compared to the block unit's tensile strength). All these cracks are shown in Figure 9.

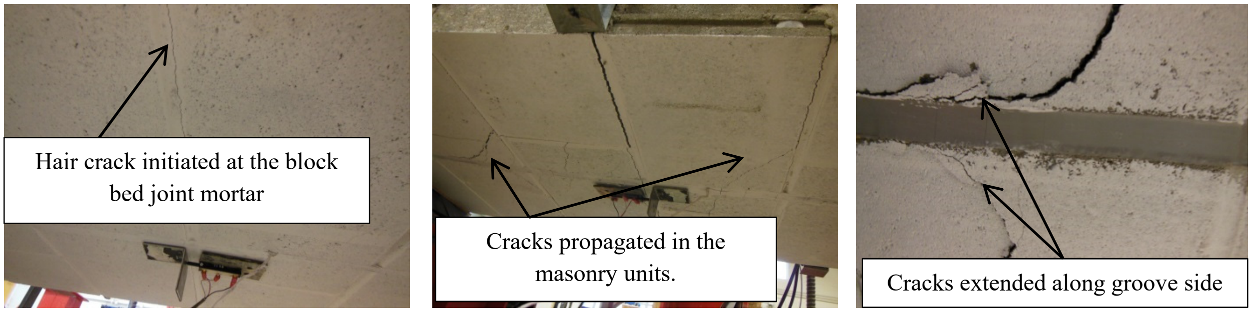


Figure 9: Cracks Developed During Loading

The general mode of failure that controls the behavior of reinforced masonry walls strengthened with FRP is debonding failure. The mode of failure for the specimens strengthened with CFRP strip or GFRP bar before and after environmental cycles was debonding. The specimen under laboratory condition and strengthened with CFRP bar was failed by shear, while it's failed by debonding when it's subjected to environmental action as shown in Figure 10.

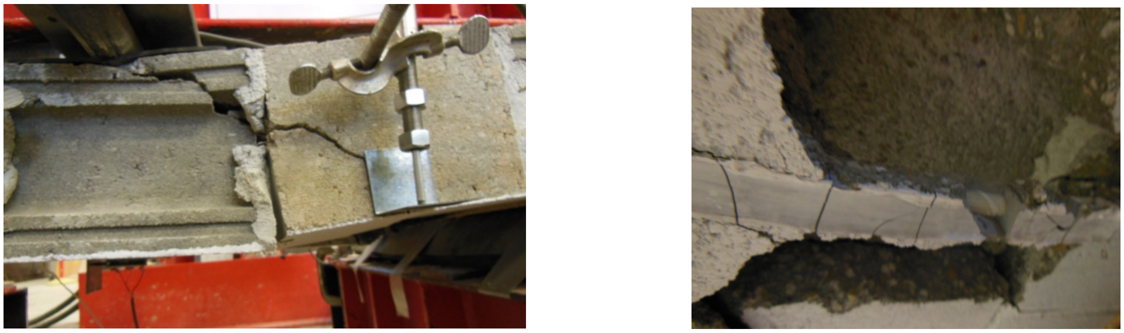


Figure 10: Observed Modes of Failure

CONCLUSION

An experimental program was implemented to study the effect of combined environmental cycles on flexural behavior of reinforced masonry walls strengthened with NSM FRP technique. For specimen strengthened with carbon bar, environmental conditioning significantly reduced the ultimate capacity and stiffness of pre-yield stage by 27% and 17 % respectively. The reason behind that could be attributed to the reduction of both tensile strength of CFRP bar and compressive strength of masonry unit. The conditioned specimens strengthened with carbon strip or glass bar exhibited insignificant change in term of stiffness and ultimate strength as compared to laboratory conditioned specimens. The mode of failure was debonding for the specimens strengthened with carbon strip or glass bar before and after environmental cycles. The specimen under lab condition and strengthened with CFRP bar was failed by shear, while it's failed by debonding when it's exposed to environmental cycles.

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