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CFRP STRENGTHENED SANDSTONE WALLS UNDER CYCLIC LOADS

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ABSTRACT:

Many investigations have been carried out for the purpose of preserving unreinforced masonry walls URM structures against seismic events during the last decades in many countries where earthquakes are likely to take place. Saudi Arabia possesses many unique historical buildings constructed mostly with URM. An efficient strengthening and retrofitting technique for such URM construction is the use of CFRP (Carbon Fiber Reinforced Polymers) in restoration of such structures. The work presented in this paper include cyclic load tests for three sandstone block walls; as built URM wall, damaged wall retrofitted with CFRP and undamaged wall strengthened with CFRP. These walls were subjected to in-plane lateral load applied in a cyclic mode under a constant axial load. Parameters of the tested specimens including strength, energy dissipation, and failure mode are discussed in order to verify the effectiveness of using CFRP in preserving such structures.

1 INTRODUCTION

Heritage URM structures including castles, palaces, monumental buildings, religious places of worship, etc. attract tourists from all over the world therefore countries like Spain, Italy, Egypt, Greece and Turkey consider these structures as one of the main sources of their income budget. However, these valuable structures suffer from a severe damage when subjected to earthquakes due to weak energy dissipation, deficient flexural and shear strength and inadequate ductility and in-plane stiffness. Consequently, several strategies of seismic retrofitting of such structures have been proposed and applied in seismically active zones including Egypt, Turkey, Iran, Mexico, Japan and the United States. According to Saudi Geological Survey (2006), most of the historical buildings constructed mainly of URM walls are located in regions prone to seismic activity in Saudi Arabia. Therefore, efforts are being made by private and governmental sectors to strengthen these significant heritage buildings in order to avoid destruction of national heritage. Many investigations in the area of preservation and maintenance of URM structures against seismic events have been conducted during the last two decades. Using CFRP (Carbon Fiber Reinforced Polymers) is one of the common FRP materials in reinforcing and retrofitting

URM structures. The parameters that govern the behavior of the URM wall system have been experimentally investigated before and after retrofitting process (Chuang et al., 2003, Santa Maria et al., 2011, Mosallam et al., 2011). The test panels were subjected to lateral load incrementally increased in reversal mode under constant gravity load. Applying CFRP as a retrofitting material has been found to significantly increase the performance of the URM walls in terms of strength and ductility. Nevertheless, few efforts have been made on experimental investigation of the seismic retrofitting features of masonry walls constructed mainly of stones since most research investigations were focused on concrete or clay-block masonry walls.

Marcari et al. (2007) investigated the in-plane behavior of full-scale tuff masonry walls with variable FRP retrofitting strategies in terms of FRP's type including CFRP, FRP's density and FRP's configuration under monotonic shear-compression loading in quasi-static test set-up. Tuff rocks were largely used in Italy, Turkey, Japan and North America due to its feasible properties. They reported that the retrofitted wall with FRP exhibits significantly improved shear strength. Moreover, they noted that the original failure mode of the strengthened wall altered its failure mode because of the large effective axial stiffness of the FRP strips. Also, they proved that the elastic stiffness of FRP retrofitted walls as well as the inelastic deformation was not greatly modified by the external retrofitting.

Demir (2012) carried out a research on the response of walls which resembles the walls used in the monumental structures in Istanbul under cyclic loading. In his investigation, he studied the effect of cyclic loading on a multi-leaf masonry wall used in the heritage Bayezid II Mosque located in Istanbul. He has observed different types of failure of the walls consistent with the level of exerted axial load. He noticed that the walls are likely to be stiffer as the axial stress becomes higher.

Algohi (2013) carried out an experimental investigation on sandstone masonry wall, which has been widely used in the heritage structures in Riyadh in Saudi Arabia. Algohi examined the CFRP effectiveness on the masonry walls when subjected to a combination of axial and horizontal loading. He showed that using CFRP, considering the bonding strength between CFRP and masonry wall, boosted the lateral strength as well as lateral stiffness of the wall. In addition, the author noticed that CFRP aids to prevent premature rocking failure of the wall and allows for the mobilization of the wall as a one body which contributes to the resistance against the applied forces.

This research paper aims to fully understand the behavior of sandstone block wall retrofitted and strengthened with CFRP before and after damage when subjected to cyclic loading. Three sandstone block masonry walls were tested under cyclic loading to get data for the investigated parameters; one of them being un-strengthened while the second one retrofitted with CFRP after damage and the last one is strengthened before damage. Additionally, a finite element model of the walls has been developed using ABAQUS software in order to fully understand the behavior of the masonry walls under cyclic loads.

2 EXPERIMENTAL PROGRAM

Three full-scale sandstone block masonry walls was investigated in this research (1) un-strengthened sandstone wall as control specimen (2) sandstone wall retrofitted with CFRP sheet after damage and (3) Sandstone wall strengthened before damage with CFRP. These walls were subjected to in-plane cyclic lateral load applied incrementally under a constant axial load.

2.1 Specimens

The sandstone block masonry wall specimens constructed for the cyclic test were intended to represent the typical sandstone masonry wall of heritage buildings located in Diriyah, Northwest of Riyadh. Two typical sizes of sandstone blocks have been used. The larger block had a dimension of 300x100x200mm while the smaller one had a dimension of 150x100x200mm with compressive and tensile strength of 47.21 and 2.64MPa, respectively. The lime mortar had a thickness of 10mm with compressive and tensile strength of 1.8 and 0.24MPa, respectively. The mixture procedure was directed to simulate approximately the behavior of the real mortar used in such buildings. Three sandstone masonry wall specimens (1 m long × 1m high), were built at Reaction Floor Lab at KFUPM. These specimens were single-wythe sandstone masonry consisting of 9 courses of 20cm thickness with an aspect ratio (ratio of height to length) close to one in order to ensure that the shear behavior of the tested specimen under cyclic loading will be dominated. After constructing these specimens, they were continuously cured with water for 28 days.

2.2 Applying CFRP Composites to the Specimens

Two masonry specimens were strengthened using non-prestressed CFRP (SikaWrap Hex 230C) and 2-part epoxy adhesive (Sika-Dur 300). A diagonal pattern (X-shape) configuration was adopted as shown in Figure 1.

Prior to applying the CFRP sheets, the specimen surface was prepared by removing projections by manual saw as well as fine dust and loose mortar by air compressor. Next the CFRP sheets were cut into strips of required length of 20 cm bandwidth. After that, a 2-part epoxy resin (Sika-Dur 300) was applied to the targeted surface following the manufacturer's instructions regarding the mixing and applying procedure [Sikadur, 2005]. Then the strips of one layer were applied on both sides of the specimen by hand in the targeted area. The strips were pressed by the epoxy saturated roller in order to insure a full distribution of the epoxy through fibers. Lastly, a steel roller was used to press and remove any air bubbles created during the application process.

2.3 Test Setup and Loading System

The setup used in this research program consisted mainly of a steel frame which was constructed on the reaction floor laboratory. The sandstone wall specimen was bolted on a built-up steel section connected firmly to the reaction floor inside the loading frame. This loading frame was used to exert the axial as well as lateral load on the specimen. The axial load was exerted on the specimen using Enerpac hydraulic jack while the lateral load was exerted on the specimen using hydraulic jack connected to the strong vertical reaction wall. The vertical as well as horizontal forces were exerted on the wall through a stiff concrete beam connected firmly to the top of the wall. The configuration of the whole setup is shown in Figure 2.

(a) Strengthening of Undamaged Wall (b) Retrofitting of Damaged Wall

Figure 1 CFRP Configuration Used in Strengthening of Sandstone Walls

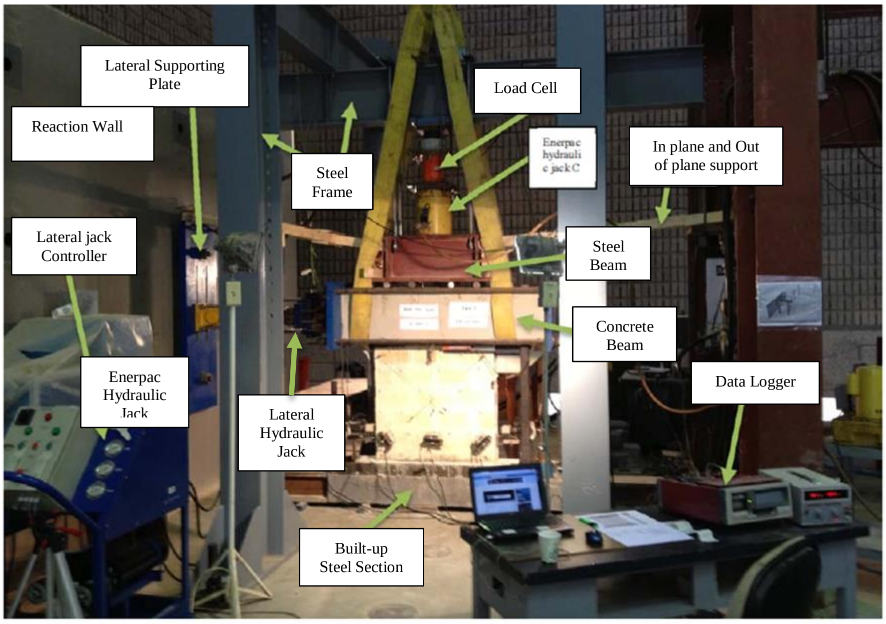


Figure 2. Cyclic Test Setup of Control wall

2.4 Testing Procedure

The sandstone wall specimens were subjected to lateral load increasing incrementally under constant axial load. The axial stress exerted in all specimens was 2 MPa except for the retrofitted one which was 2.5MPa.

In the cyclic test carried out on the specimens, first the axial load was exerted slowly with a rate of 1.0 KN/s until it reached the required axial stress and it was kept constant during the test. The wall was then subjected to a lateral load in a reversal mode (push then pull at each displacement level as illustrated in Figure 3) using displacement control load with a loading rate of 0.05 mm/s. The horizontal displacement load was controlled by means of the horizontal CDP LVDT-100 connected to the top middle of the specimen. It can be noted that the test is stopped before the final failure due the limitation of the hydraulic jack used. However, the results gained from the test are reasonably appealing.

Several sensors including strain gauges, load cells, LVDT' s and Patriot displacement transducers was used to capture the response of the walls and record all the experimental readings through data logger. Axial as well as lateral loading were recorded using load cells. Transducer (CDP LVDT-100) was the main instrument for measuring the lateral displacement.

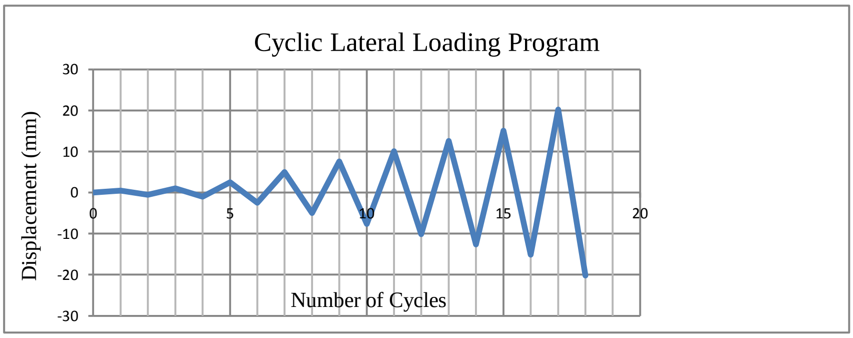


Figure 3. Cyclic Lateral Loading Program

3 BEHAVIOR OF TEST SPECIMENS

Observed behavior of the cyclic test specimens regarding lateral strength, energy dissipation, cracking pattern and failure mode are summarized in the following subsections. In addition, hysteresis-loop diagrams of the lateral force-deformation curve for the test specimens are presented.

3.1 As-built (Control) Specimen

In control specimen that was subjected to cyclic loading it can be noted that the first cracks started at the bottom left and right corner introducing the rocking failure in loop 3 (Figure 4a&4b). Therefore, the whole lower course was wrapped with CFRP in order to prevent the specimen to overturn or slide and the test was continued. As a result, the crack pattern took another form and started to initiate within the specimen body in the head and bed joint and the sandstone units itself as well (Figure 4c). As the exerted lateral drift was increased up to 10.2mm, new cracks arose and the existing cracks got wider. As a result, the failure mode can be considered as a combination of rocking and staggered head and bed joint failure. Also, it can be observed that the lateral force-deformation curve was increasing linearly up to 98kN at drift of 2.4mm confirming that there is a negligible permanent deformation at the first three loops as shown in Figure 5. After that, the lateral strength was noticed to increase slowly compared with the last loops as the exerted lateral displacement was increased up to 10.2mm. As a result, the specimen started to behave nonlinearly and permanent deformation became visible reaching to 2.9mm. Also, lateral force-deformation curve shows that the specimen attained high energy dissipation especially after loop 3 which indicates that the cracks started to initiate from that point. Finally, it can be recognized that the as-built specimen suffers from the stiffness degradation, energy dissipation and combined failure mode when subjected to cyclic loading.

(a) (b) (c)

Figure 4. Cracking and failure mode of control specimen

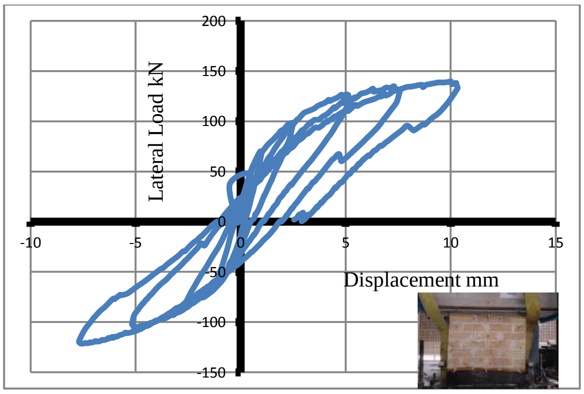
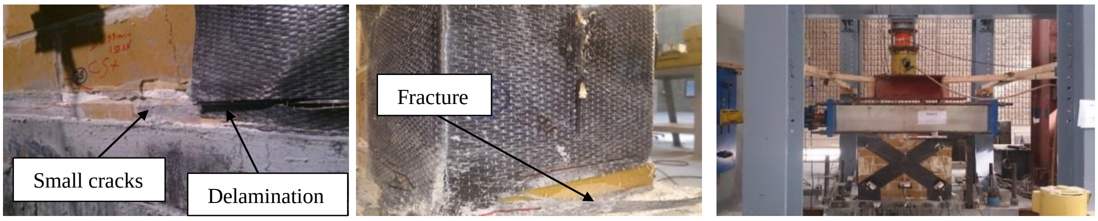


Figure 5. Lateral force-deformation hysteresis loop Diagram for Control specimen

3.2 Strengthened with CFRP

This specimen was strengthened by a single layer of CFRP on both sides forming X-shape, and then it was subjected to cyclic load to evaluate the enhancement gained from this strengthening technique. Apart from the small cracks, which occurred along the lower course of the specimen (Figure 5a) due to the excessive rocking behavior during the test, no other cracks were detected within the whole specimen. Also, it was noted that no delamination happened between CFRP and the specimen and also no fracture of CFRP except at the bottom corners (Figures 6a&6b). Furthermore, it can be seen from Figure 7 that the lateral force-deformation curve developed in a stiffer manner up to as compared to the control one. However, the specimen experienced a permanent deformation of 5mm as the lateral load increased to 166kN due to the tendency of the specimen to overturn as a single body. Also, the maximum lateral strength attained during the test was 18.7% more which confirms the primary purpose of the CFRP strengthening technique. Finally, less energy was dissipated due to the absence of pronounced cracking initiation within the specimen body.



(a) (b) (c)

Figure 6. Some cracking patterns of undamaged specimen strengthened with CFRP

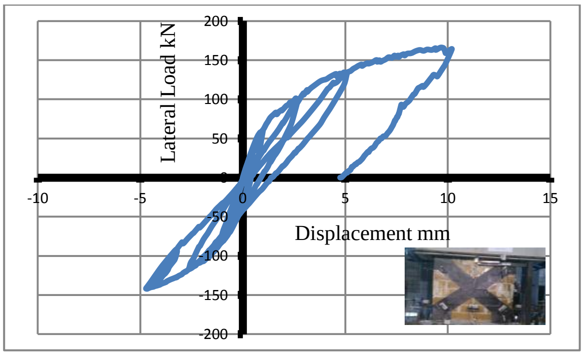


Figure 7. Lateral force-deformation hysteresis loop diagram for strengthened specimen

3.3 Damaged Wall Retrofitted by CFRP

After conducting the cyclic test on the as-built specimen and getting the required damage, the damaged wall was retrofitted by a single layer of CFRP on both sides forming X-shape, and then it was subjected to cyclic load to evaluate the enhancement gained from this retrofitting technique and compared with the strengthened specimen. It was noted that no visible cracks initiated during the cyclic test except a tiny hair fracture on CFRP, which occurred at the left bottom corner in contrast to the strengthened specimen, maybe because the lower course was completely wrapped with CFRP, which reduced the rocking influence significantly as shown in Figure 8. Regarding the lateral-force deformation curve development, it was stiffer than strengthened specimen and increased in a constant rate as shown in Figure 9. Also, this specimen did not experience pronounced permanent deformation during all cycles. It was reported that the maximum lateral strength attained during the test was 45.3% more than the as-built specimen and 21.7% more than the strengthened specimen. This notable increase in the lateral strength was attributed also to the CFRP confinement of the whole lower course. As a result, no significant reduction in the lateral strength occurred due to the rocking behavior. Finally, it can be observed from Figure 8 that the dissipated energy was a little more compared to the strengthened specimen.

Figure 8. Cracking patterns of retrofitted specimen

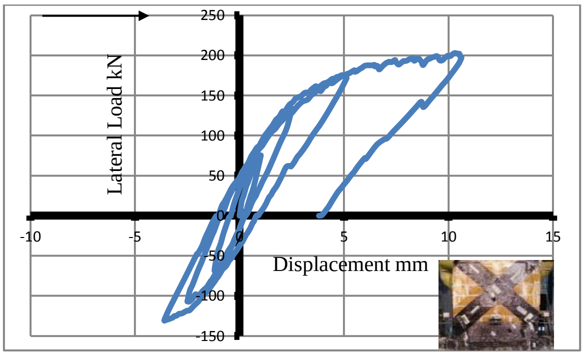


Figure 9. Lateral force-deformation hysteresis loop diagram for retofitted specimen

4 PRELIMINARY RESULTS OF FE MODELING OF MASONRY SPECIMENS

FE analysis of the wall was carried out using the software ABAQUS and damage plasticity model to validate the experimental results (Al-Gohi et al., 2014). The force-displacement curve obtained from the FE simulation under monotonic loading compared very well with envelop of the cyclic hysteresis loop obtained in the experimental test as shown in Figure 10.

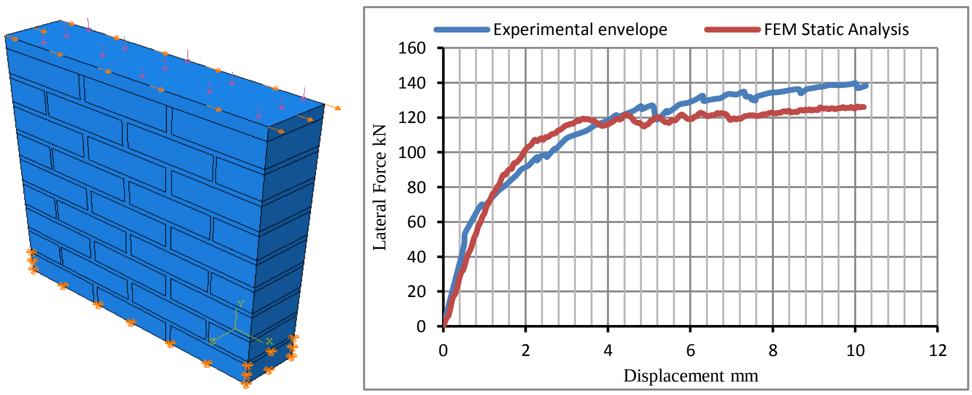


Figure 10 Preliminary Results of As-built Specimens.

5 CONCLUSIONS

The cyclic behavior of full scale sandstone masonry wall specimens strengthened and retrofitted with CFRP has been experimentally investigated. Following conclusions can be drawn based on the present research:

- It was clearly noted that the unstrengthened specimen experienced deficient cyclic load behavior in terms of stiffness decay, higher energy dissipation and appearance of pronounced cracking causing failure in combined patterns.
- For CFRP strengthened undamaged specimen, an increase in lateral strength was evident in comparison to the unstrengthened one. In addition, less energy was dissipated which conforms that no pronounced cracks arose during the test. Finally, the combined failure modes were prevented due the integral behavior as a one body gained from the CFRP strengthening technique.
- CFRP strengthening at the base is highly recommended as it provides significant enhancement of lateral load resistance under cyclic loading.
- It was observed that no debonding occurred between CFRP and the test specimens during the cyclic loading except at the bottom corners due to high stresses concentrated there and lack of suitable anchorage.
- It can be concluded that using CFRP as a strengthening material enhances the the lateral strength and cracking prevention. Consequently, it is proved that CFRP strengthening is a reliable and effective option in rehabilitation and strengthening the masonry structures prone to seismic load.

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