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Compressive Strengthening of Damaged Historic Masonry Walls Repaired with GFRP

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Abstract The purpose of this research is to determine the mechanical properties of damaged historic masonry walls retrofitted with Glass Fiber Reinforced Polymer (GFRP) under axial load through experimental method. Five masonry wall specimens were tested under axial load acted at the top surface. One wall specimen was served as reference without retrofitting. Two walls were retrofitted with GFRP before damage. Other two walls were repaired using epoxy injection and GFRP sheets after predefined damage. The results show that the bearing capacity of historic masonry walls was completely restored and even exceeded the original capacity.

Keywords: Historic masonry wall, repair, retrofit, glass fiber reinforced polymer, axial load

Introduction

In Thailand, many historic buildings have been designated by UNESCO as a World Heritage Site due to their cultural value in Buddhism. Most of them were made of bricks. Earthquakes, soil settlements, strength degradation of materials due to wind and weather are high risk factors for the architectural heritage. Time shows that many historical constructions have collapsed. In recent years, Bureau of Archeology and Museums in Thailand has paid more attention on restoration of these historic structures. Some traditional retrofit methods were ever used, such as repair with external layer of reinforced concrete or cement paste, external un-bond steel wire. However, there was report after report of failure after restorations (Suddchai 2000, Kriangsak 1996). This research work conducted with aiming of finding a new retrofitting method based on experimental and theoretical investigations.

In recent years, many researches have shown that using fiber reinforced polymers (FRP) is a feasible solution to increase strength and ductility of masonry walls (Hernan et al. 2006, Amir Fam 2002, L Binda 2004). This is due to the well-known advantages of FRP composites including good resistance, high strength and ease for site handling due to their light weight. However, most of the researches have focus on strengthening of undamaged masonry walls (Triantafillou 1998, Liu Jifu 2007, Miha,et al. 2009).

The objective of this study is to examine the performance of a severely damaged and repaired historic masonry walls using GFRP sheets, applied on one side of the walls. This experiment is more practical for repair of existing historic masonry walls which are normally damaged before repair.

Design of Test Specimens

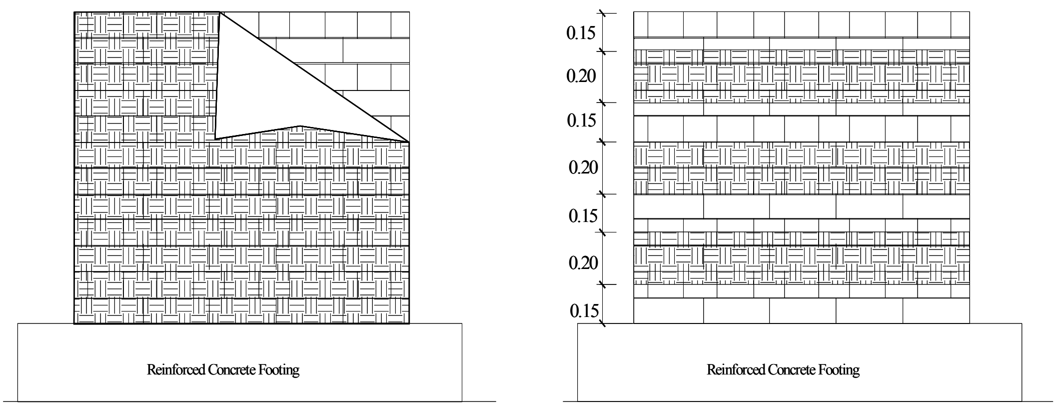
Five wall specimens were constructed in the stretcher as English bond with a mortar joint of 10 mm thickness. The nominal dimensions of these walls are 1200 mm height, 1500 mm length, and 630 mm width (Fig.1)

Material's Properties The test walls are representative of a typical un-reinforced historic masonry wall built 300 to 400 years ago at Ban Lum Plee, Ayutthaya, Thailand. At Ban Lum Plee, a great number of fallen bricks of historic buildings were collected to test their material properties (Suddichai 2000). So the bricks were selected such that test specimens would reflect structural characteristics of an ancient masonry wall. The brick unit is 300×150×50 mm, with compressive strength of 4 MPa and elastic modulus of 3.103 GPa. The ancient cement mortar was specially prepared according to original method which involved soaking raw lime in water for at least 60 days before mixing it with white cement and coarse sand at 1:2:9 ratio. The mortar has compressive strength of 1.06 MPa and elastic modulus of 1.406 GPa.

GRFP sheets and epoxy resin were come from Thai company. Nominal tensile strength of it is 1,700 MPa and elastic modulus of 72 GPa. The epoxy resin has tensile strength of 55Mpa and elastic modulus 3.3 Gpa.

Figure 1: *Sizes of five specimens*

Repairing Method and Retrofitting schemes Specimen MD-1 was un-reinforced as reference wall. Other four specimens were retrofitted in different modes before or after defined damaged (shown in Fig.2). Specimen MD-2 was fully reinforced with GFRP sheets on only one face of the wall before loading. Specimen MD-3 was reinforced with three GFRP stripes of 20cm width at spacing of 35cm on center on only one face of the wall before loading.



(a) Specimen MD-2 and MD-4 (b) Specimen MD-3 and MD-5

Figure 2: *Retrofitting schemes of specimens*

For specimen MD-4 and MD-5, at first step they were subjected to vertical axial load applied on the top surface until its ultimate compressive strength of 85 ton and 45 ton, respectively. Then GFRP repair scheme was applied as following. All loose particles were removed and the wall was readjusted to vertical position. The missing parts of the bricks as well as the mortar joints were patched with new mortar after being wetted and allowed to dry. All cracks were patched using epoxy. Quick-setting hydro cement, dried with a heat gun, was used to stop epoxy leaks from the surface. Later, the cement and epoxy patches were removed from the surface using hammers and grinder. After these processes, the cracks were closed tightly by the epoxy grout. Then, specimen MD-4 and MD-5 were strengthened with GFRP sheets in the same modes as specimen MD-2 and MD-3, respectively. The GFRP repair system was left to cure for at least one week.

Test Process and Performance of Test Specimens

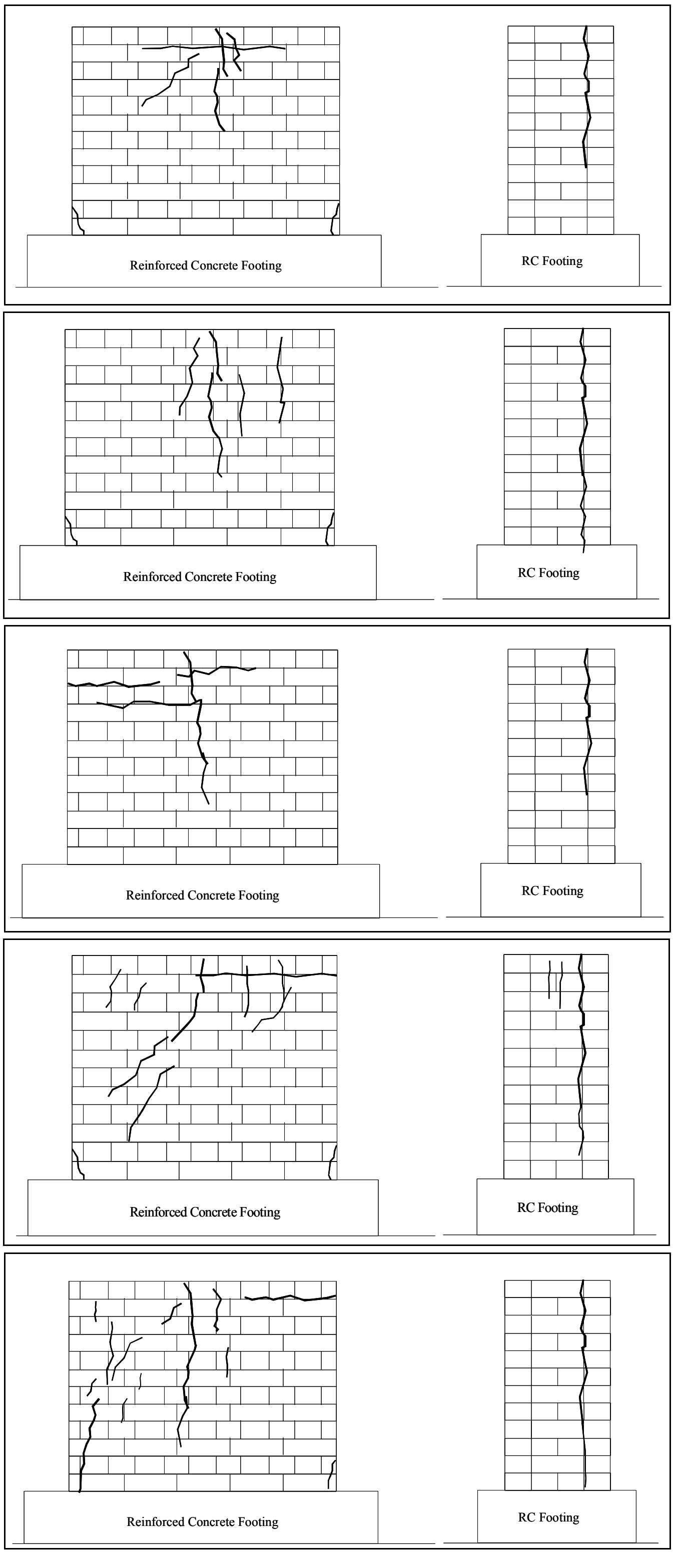
The vertical axial load was transferred through steel distribution beam to the top of the wall uniformly and increased gradually until specimen failure. Four LDVT (Linear Variable Differential Transformer) were erected at top surface and mid-height of the wall to control in-plane vertical and out-plane lateral displacements. Six strain gauges were pasted on the face of the brick and the GFRP sheets at mid-height to monitor the strain development, as shown in Fig. 3.

Figure 3: *Test set-up and instruments*

Un-retrofitted Wall MD-1. When the load of 48.96 ton was applied and the vertical deformation 2.72 mm, cracks began to appear at the vertical mortar joints at the top center of wall length. When the wall was loaded to 60 ton, the main crack is extended to 17 cm long and 0.20 mm wide. The vertical displacement of 3.28 mm was measured. At vertical displacement 4.06 mm, the measured load was 70 ton. Crack appeared in the first horizontal mortar joint from the top, extend from center of the wall length to left and right of about 20 cm. At the ultimate load of 84.27 ton, horizontal crack developed to both side faces. At the same time, cracks up to 1.6 mm wide with 74 cm long and 0.3 mm with 37 cm long respectively throughout the vertical mortar joints at the side face were observed. The vertical displacement is 4.61 mm. The crack pattern of wall MD-1 is shown in Fig. 4 (a).

Retrofitted by Full GFRP before Damaged, **Wall MD-2**. At the load of 71.42 ton, vertical cracks appeared on one of the side face of the wall and extend about 48.5 cm long from the top. Vertical deformation of 3.90 mm was measured. At the load of 79.62 ton, vertical cracks initiated on the other side face, extend 58 cm long from the top. Some vertical cracks throughout several layer of mortar and bricks appeared only on the face of the wall without GFRP sheets. Vertical displacement was 4.7 mm. Due to the constraints effect of GFRP sheets, no cracks were observed on the face pasted with GFRP until wall failure. With the load increasing, the constraint roles of GFRP sheets delay the emergence of new cracks. Finally, compared with MD-1, the ultimate compressive strength of specimen MD-2 was improved at about 50% to 125 ton. Crack on the side face up to 2 mm was observed and vertical displacement 7.20 mm. The crack pattern is shown in Fig.4 (b).

Retrofitted by Three Strips GFRP before Damaged, Wall MD-3. When the load reached 113 ton, transverse strain began increased rapidly with the appearance of initial vertical and horizontal cracks at top center of the wall. With the load increasing, vertical crack developed downward through may layers, about 80 cm long. At the load of 120 ton, vertical cracks opened on both side face and more horizontal cracks initiated on the wall face. Finally, when compressive load reached its ultimate value of 125 ton, the width of cracks on both side faces reached 2.00 mm, which denoted the failure of the wall. Nevertheless, on the wall face with GFRP strips, no crack appeared and no peel-off of GFRP is observed (Fig.4 (c)). Compared with MD-1, the ultimate compressive strength was improved 50%.



(a) Specimen MD-1

(b) Specimen MD-2

(c) Specimen MD-3

(d) Specimen MD-4

(e) Specimen MD-5

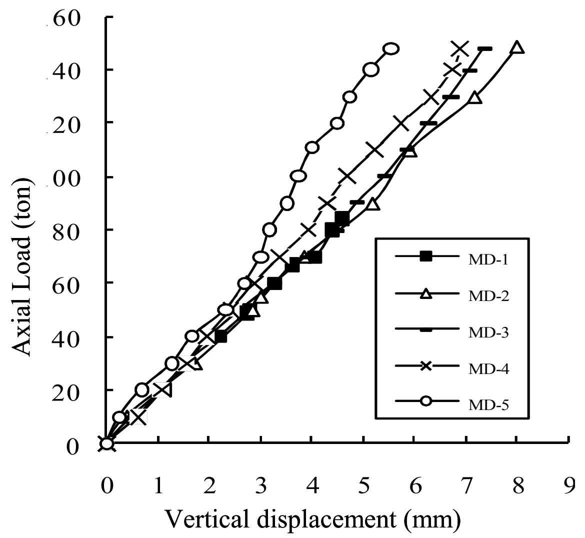
Figure 4: Crack pattern of five walls

Damaged, Repaired and Retrofitted with Full GFRP, MD-4. After repaired with epoxy and pasted with GFRP, specimen MD-4 was retested using the same test setup and the vertical loading was increased gradually until specimen failure. At early loading stages, about 83.5% of its original ultimate strength before damage, some vertical cracks began to open at the top center on the wall face without GFRP sheets. At the load of 77.05 ton, horizontal crack appeared also on the face in the mortar of top layer. At the load of 77 ton, vertical crack opened on one side face, 52.5 cm long and 0.7 mm wide. It was noticed that, all the cracks appeared at new positions which were different from the damaged cracks before repair. It revealed that a new pattern of cracks developed and that the old cracks did not open. The crack development is shown in Fig.4 (d). It was observed that at failure point, the cracks densely covered almost the whole wall face. However, no crack was observed on the face with GFRP sheets. It should also be noted that the compressive strength of the repaired wall even exceeded the strength of MD-1 and MD-2 to 129 ton.

Damaged, Repaired and Retrofitted with Three GFRP Strips, MD-5. Specimen MD-5 was also retested after repaired under vertical loading until failure. When the load reached 60% of original ultimate strength of wall MD-3, initial cracks appeared at top center on the wall face without GFRP strips. Vertical crack on the side face was observed at load of 42 ton and 59.4 ton, respectively. It is same to specimen MD-4 that, a new crack pattern developed. With the increasing of load, more new cracks appeared and the initial cracks opened downward continuously. At the load of 101 ton, cracks emerged on the wall face between top and middle GFRP strips and opened to the bricks under top GFRP strips. When the load reached 124 ton, these cracks developed downward through the middle strips to the top edge of the bottom strips. Finally, when peak load of 125 ton was reached, no crack is observed under bottom GFRP strips and no GFRP sheets peel-off happened (Fig.4 (e)).

Test Data Analysis

The load-vertical displacement responses of five specimen walls are described in Fig.5. The vertical displacements of all five test walls show linear direct proportion with axial loading increasing, which means that GFRP retrofitting don't change the elastic properties of masonry walls. Ultimate displacements of specimen MD-4 and MD-5 are obviously smaller than that of specimen MD-2 and MD-3, which indicates that the stiffness or the elastic modulus of MD-4 and MD-5 were increased due to repairing of epoxy resin.



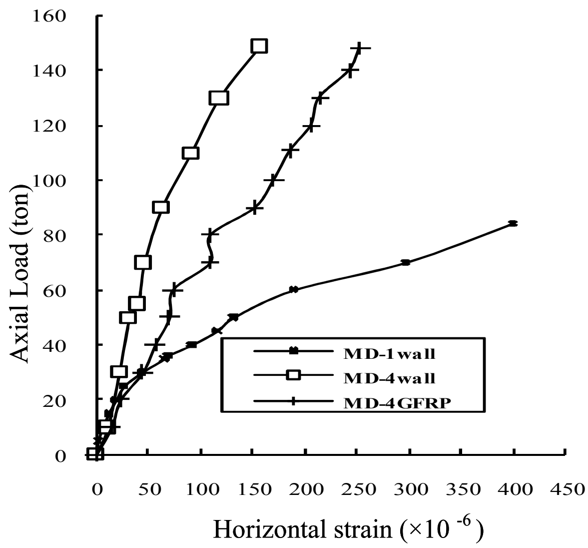


Figure 5: *Load –vertical displacement response Figure 6: Strain developments in GFRP sheets and wall surface*

Fig. 6 describes the load-horizontal strain responses in wall surface of reference specimen MD-1 and in wall surface and GFRP sheets of repaired specimen MD-4. Due to constraints of GFRP sheets, at the same load level, horizontal strain in wall surface of MD-4 is obviously smaller than that of MD-1. Most of tensile force was resisted by GFRP sheets. After the load reached to about 25% of its ultimate load, tensile strain of GFRP sheets increases quickly and much bigger than that in wall at the same position on the other surface.

Conclusions

Five test walls were subjected to vertical axial until failure. Within the scope of this study, the following preliminary conclusions can be made:

• This test confirms that the compressive strength of the historic masonry wall was obviously improved by 50 percent after retrofitted with GFRP sheets. Due to the constraints of GFRP sheets, the cracks densely covered the wall surface before failure.

• After repaired with GFRP sheets, the bearing capacity of damaged historic masonry wall was completely restored and even exceeded the original capacity. A new crack pattern developed and the old cracks didn't open after repair. Different retrofitting mode effect little on the compressive strength of historic masonry walls.

• This study also confirmed that retrofitted with GFRP after damage or before damage have the similar function. The laboratory test investigation on masonry wall strengthened with GFRP before damaged can present the practical results of repair with GFRP on damaged historic masonry walls on site.

• Further research should be focus on the repair technique at the joint on the side face and the parameters to decide the suited retrofitting schemes for historic masonry walls in different damage level.

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