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Retrofit Historical Masonry Walls with GFRP under Seismic Loading

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Abstract

Restoration of historical structures is a durative and arduous work in many countries. This research determines the seismic behavior of historical masonry walls in Thailand retrofitted by glass fiber reinforced polymer (GFRP) through the experimental method. Five masonry wall specimens were built in the traditional method in Thailand and tested under horizontal cyclic loading without vertical axial load. One wall served as reference specimen without retrofitting. Three walls were retrofitted with GFRP in different modes before loading. One wall was repaired after predefined damage and retrofitted with GFRP before secondary loading. The failure mechanism, shear strength, ductility and energy dissipation of walls were studied in detail. The results show that the shear strength and energy dissipation capacity of the historical masonry walls were distinctly improved after GFRP strengthening.

Keywords: Historical masonry wall, seismic performance, cyclic loading, retrofitting, glass fiber reinforced polymer (GFRP)

Introduction

In Thailand, many historical buildings have been designated by UNESCO as World Heritage sites, due to their cultural value in Buddhism. Most of them were made of bricks around the eleventh and the twelfth Buddhist centuries. Earthquakes, soil settlements, and strength degradation of materials, due to wind and weather, are high risk factors for these architectural heritages. Many historical constructions have collapsed. In recent years, the Bureau of Archeology and Museums in Thailand has paid more attention to the restoration of these historic structures. Some traditional retrofit methods were used, such as repairing with an external layer of reinforced concrete or cement paste and external un-bond steel wire. However, there were multiple reports of failure after these restorations [1,2].

Figure 1 Historical masonry walls in Thailand.

In recent years, a large survey of research has shown that using fiber reinforced polymers (FRP) is a feasible solution to increase the strength and ductility of masonry walls. Nigel *et al*. [3] performed a test that used glass fiber reinforced polymer (GFRP) sheets to increase the flexural capacity and energy absorption characteristics of plain and reinforced concrete block walls. Many researchers [4-6] conducted in-plane tests of damaged masonry walls repaired with carbon fiber reinforced polymer (CFRP). In Europe, especially in Italy and Greece, some research works focused on the repair and strengthening of historic masonry building in seismic areas [7,8]. In the study of Catherin *et al*. [9], an application of a new structural material, namely textile-reinforced mortar (TRM), as a means of increasing the load carrying capacity and deformability of unreinforced masonry walls subjected to cyclic in-plane loading was experimentally investigated. Chuang *et al*. [10] presented the experimental results of 3 CFRP retrofitted masonry walls under combined constant gravity load and in-plane lateral displacement reversals. Two different CFRP configurations were used for the test. Hernan *et al*. [11] also used CFRP laminate and sheets to strengthen masonry wall panels. They found that external CFRP reinforcement decreased the thickness of the cracks and increased the shear strength and stiffness of the panels.

This research is conducted with aiming of finding a new retrofitting method for historic masonry walls in Thailand in order to avoid damage during earthquakes. Since GFRP has similar properties to that of CFRP, it is more suitable for historic masonry wall strengthening due to its light color, which avoids obfuscation or destruction of the cultural paintings inside those buildings. Considering the special size of, and large amount of weak mortar joints in, historic masonry walls in Thailand, it is necessary to undertake some experimental research on the seismic performance of historical masonry walls retrofitted with GFRP sheets. This paper reports a detailed program and the results of those tests.

Experimental program

Five wall specimens were constructed with mortar joint of 10 mm thickness. All specimens were chosen with an aspect ratio of 1.0 to ensure that most of the walls would exhibit shear-induced damage. The nominal dimension of the wall was 1500 mm wide × 1500 mm high × 600 mm thick (**Figure 2**). They were representative of a typical un-reinforced historical masonry wall, built 300 to 400 years ago at Ban Lum Plee, Ayutthaya, Thailand.

Material properties

New bricks, 300×150×50 mm in size, were produced, according to the properties of the old bricks [1]. The ancient cement mortar was specially prepared according to an original method which involved soaking raw lime in water for at least 60 days, before mixing it with white cement and coarse sand at a ratio of 1:2:9. **Table 1** displays the properties of the materials.

Table 1 Properties of materials.

Materials	Unit Weight [g/cm^3]	Strength [MPa]	Elastic Modulus [MPa]
Brick	1.373	4.012 (Compressive)	3103.3
Mortar	1.924	1.06 (Compressive)	1460.5
GFRP	0.005	1700 (tensile)	72000
Epoxy resin	-	55 (tensile)	3300

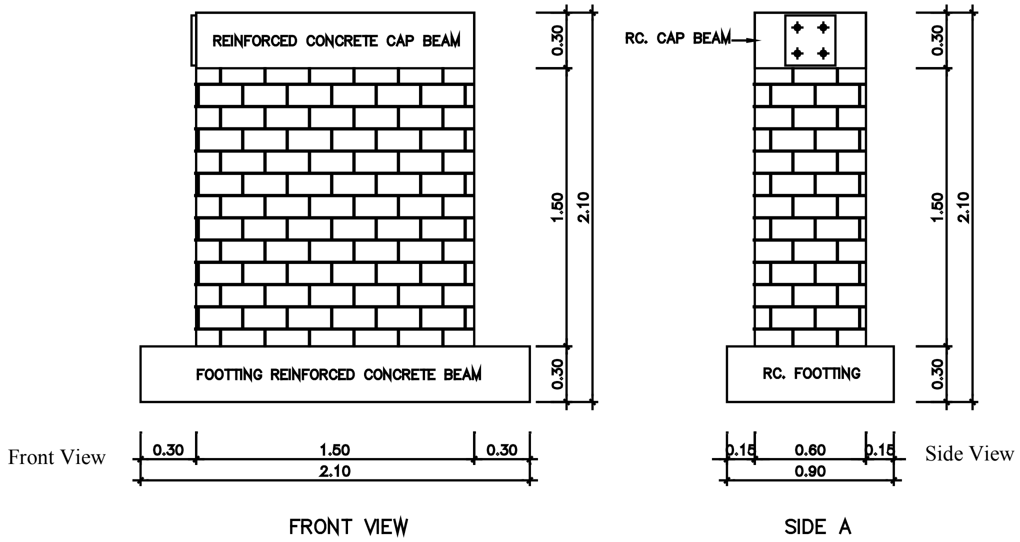
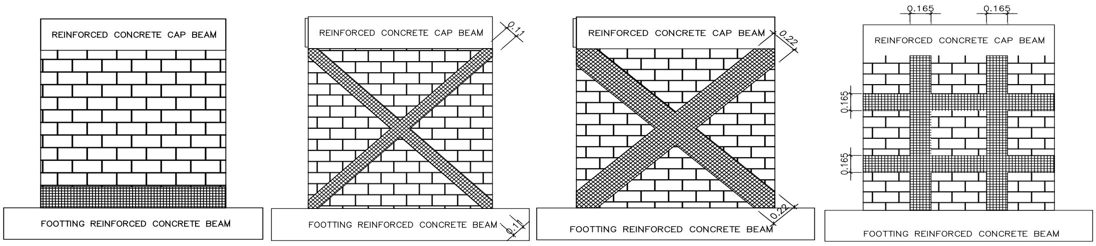


Figure 2 Dimensions of specimen walls.

Retrofitting patterns of GFRP

Specimen AMW01 was un-reinforced, as a reference wall. After failure, all cracks of AMW01 were patched with epoxy. One 200 mm-wide GFRP stripe was then pasted in a horizontal direction along cracks on each side of the wall. The specimen was then taken as specimen AMW02 (**Figure 3a**) and cured for at least one week before being subjected to the secondary loading test. Three different GFRP retrofitting patterns with the same GFRP strengthening ratio in area (= area of GFRP sheets/area of wall face) of 0.40 were used for the other 3 specimens before testing (**Figures 3b - 3d**). Specimen AMW03 was reinforced with 2 110 mm-wide GFRP stripes diagonally on both sides. Specimen AMW04 was reinforced with 2 220 mm-wide GFRP stripes diagonally on just one side of the wall. Specimen AMW05 was reinforced with 4 165 mm-wide GFRP stripes orthogonally on just one side of the wall.



(a) AMW02 (b) AMW03 (c) AMW04 (d) AMW05

Figure 3 Retrofitting patterns of specimens.

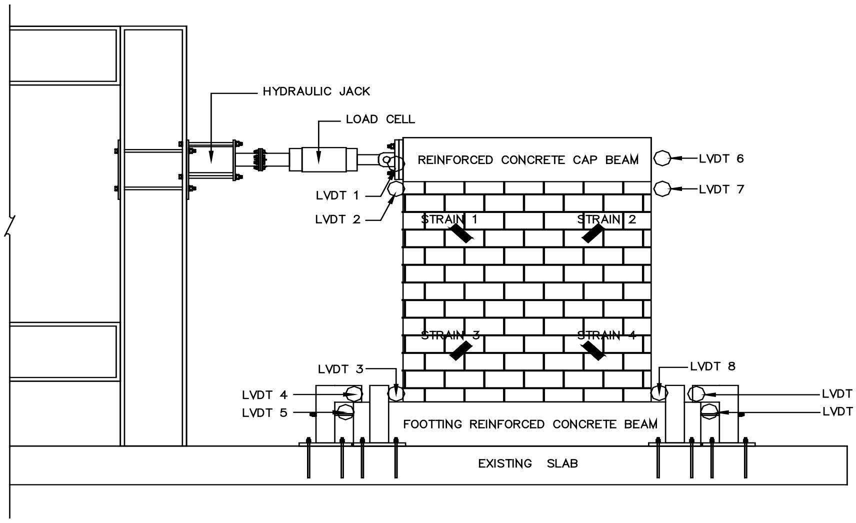


Figure 4 Test set-up.

Test set-up and load history

In this test, no external axial compression was applied due to the inadequacies of the laboratory. The horizontal cyclic load was transferred through a cap beam to the wall. Ten LDVTs (Linear Variable Differential Transformers) were erected to control the lateral displacements of the wall and footing beam. Four strain gauges were glued onto the bricks and the GFRP sheets to monitor the strain development (**Figure 4**). In this quasi-static test, a force controlled scheme was followed until the first cracking of the wall, in increments of 2 kN. Then, a displacement controlled scheme was used to the point of failure, in increments of 1 mm. Each loading step performed one fully reversed cycle. It was defined as the failure point when the applied load reduced to 80 % of the maximum strength previously recorded.

Test results and failure modes

As a reference specimen, wall AMW01 began to crack at the third course of mortar joints when the lateral load reached 8.3 kN. With the load increased, cracks developed along the mortar joints and throughout the whole cross section at the end. The failure mode presented was shear slide failure (**Figure 5a**). For AMW02, because GFRP stripes were well pasted along the cracked mortar joint in the specimen AMW01, the shear strength of the wall was significantly increased. The appearance of the first crack was delayed until the loading stage of 16 kN, equal to the maximum value of the lateral load which could be resisted by AMW01. The old cracks along the third course of mortar in specimen AMW01 opened again.

No new cracks were observed outside this region. At failure point, the GFRP stripes were peeled off at many positions. At the 2 ends of the third course of mortar joints, GFRP sheets were torn apart due to the wide cracks, as shown in **Figure 5b**.

(a) AMW01 (b) AMW02

(c) AMW03 (d) AMW04

(e) AMW05

Figure 5 Failure modes of five specimens.

For AMW03, the first cracking occurred at the bricks near the bottom corner when the lateral load reached 26 kN. Then more cracks appeared in several courses of mortar above the base joint and developed upward along the diagonal direction. The crack pattern is shown in **Figure 5c**. For AMW04, the first cracking started in the second course of mortar near the bottom corner of the wall when the load reached 26 kN. With the load increased, more horizontal shear sliding cracks developed at several courses of mortar joint near the base. Some cracks further extended towards the diagonal direction. The failure mode of AMW04 behaved as a combination of bricks crashing near the bottom corner and sliding, as shown in **Figure 5d**. When the lateral load of 18 kN was applied on wall AMW05, a slight crack was observed at the third course. Then, some horizontal cracks appeared in several courses of mortar near the base. The failure mode presented was shear slide failure (**Figure 5e**).

Test data analysis

Shear bearing capacity

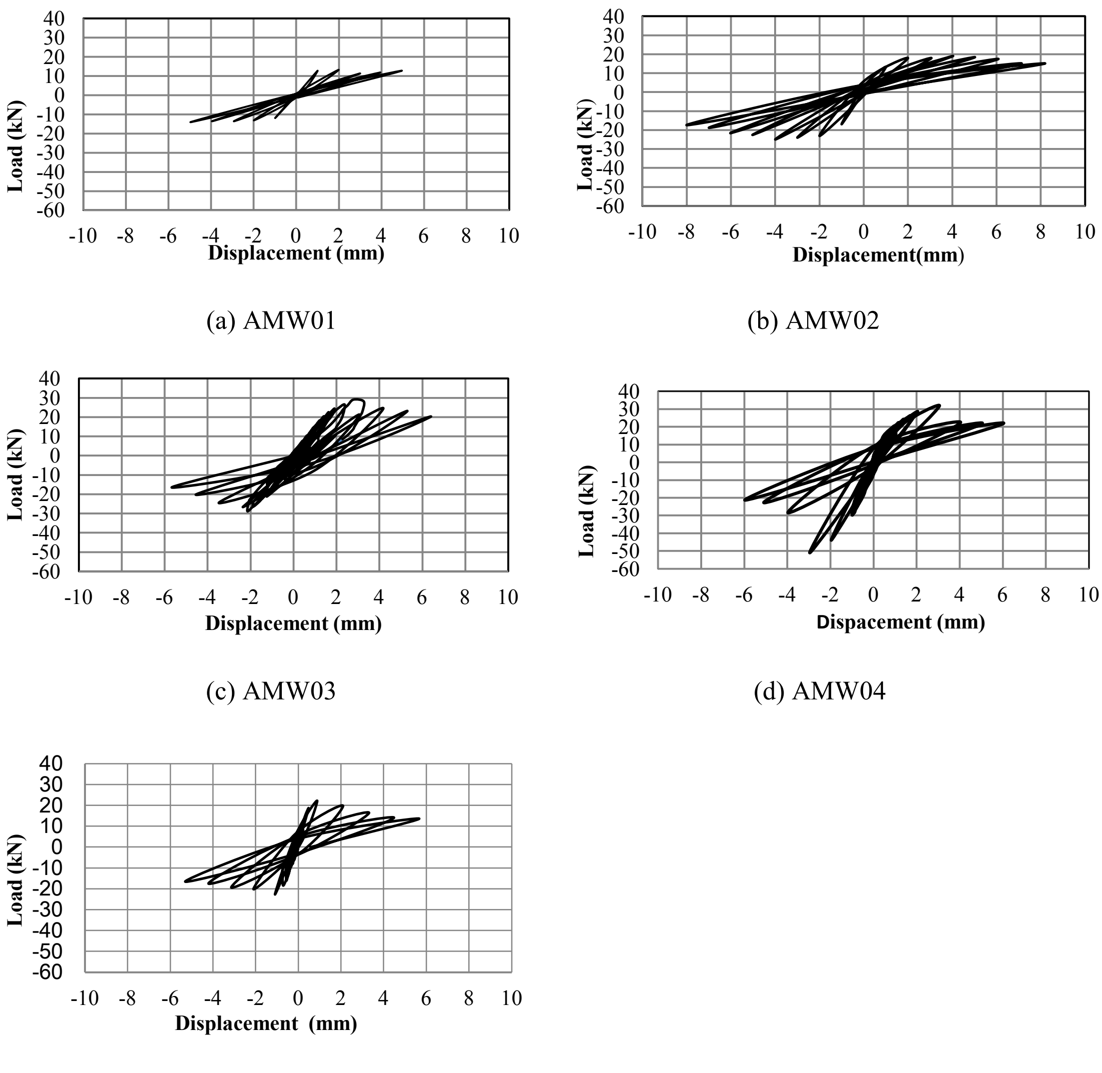
Test results are summarized in **Table 2**. GFRP stripes retrofitted to historic masonry walls are effective in significantly increasing their shear bearing capacity. Although only one horizontal GFRP stripe was pasted at the cracking positions on each side after simple repairing, wall AMW02 achieved a significant increase of 93 and 38 % in the cracking load and the shear strength, compared to AMW01. The GFRP stripe effectively strengthened the tensile strength of the mortar joints covered by it. Compared to wall AMW01, the increment in the cracking load of retrofitted walls AMW03, AMW04, and AMW05 was 2.13, 2.13, and 1.2 times, respectively. The maximum shear strength of AMW03, AMW04, and AMW05 increased 73, 100, and 38 %, respectively. The results indicated that diagonal reinforcement is more effective in terms of shear strength and ductility than orthogonal cross reinforcement. Compared to the wall AMW05, the wall AMW03 and AMW04 showed more densely spread cracks and larger displacement before failure. Because the orthogonal cross GFRP stripes were pasted outside the corner zone and the course joints where slide cracking normally occurred in un-reinforced wall AMW01, the improvement of shear bearing capacity and deformation capacity of AMW05 were limited. As the thickness of historic masonry wall in Thailand is very large, up to 600 mm, no out-of-plane bending occurred whether GFRP stripes were pasted on one side or both sides of the wall. Using the same strengthening ratio to paste GFRP sheets, specimen AMW03 and AMW04 exhibited similar improvement in deformation and shear capacity.

Table 2 Experimental test results.

Samples	First cracking		Maximum		Failure		Ductility ratio $\mu = \Delta_u / \Delta_c$
	Cracking load P_c [kN]	Displacement Δ_c [mm]	Maximum load P_m [kN]	Displacement Δ_m [mm]	Failure load P_u [kN]	Displacement Δ_u [mm]	
AMW01	8.3	0.50	16	2	14.13	4.98	9.96
AMW02	16	0.65	22	4.04	17.43	6.09	9.36
AMW03	26	1.98	27.6	2.57	20.25	6.40	3.23
AMW04	26	1.09	32	3.06	22.14	6.04	5.54
AMW05	18	0.83	22.14	1.09	17	5.30	6.38

Hysteretic behavior of walls

The hysteretic relationships of all wall specimens are presented in **Figure 6**. All the hysteresis loops showed a pinching phenomenon, which is the effect of shear deformation caused by slip. The hysteresis loop area gradually increased, showing a certain energy dissipation capacity. The hysteresis loops of reinforced walls were much fuller than that of un-reinforced walls, indicating a stronger energy dissipation capacity for resisting earthquakes.



(a) AMW01

(b) AMW02

(c) AMW03

(d) AMW04

(e) AMW05

Figure 6 Hysteresis loops of 5 specimen walls.

Envelope curves

The lateral load-displacement envelopes are displayed in **Figure 7**. As can be seen from the envelope curves, shear strength of reinforced walls was increased. The inflection points did not appear in the curve at the cracking point and the strengthened section after cracking was small. For un-reinforced specimen walls, the envelope curve steeply descended after reaching the maximum capacity, indicating the load bearing capacity decreased rapidly with little lateral deformation. For reinforced walls, the envelope curve slowly descended after reaching the maximum capacity, showing a better deformation capacity. The GFRP retrofitted walls can absorb more earthquake energy.

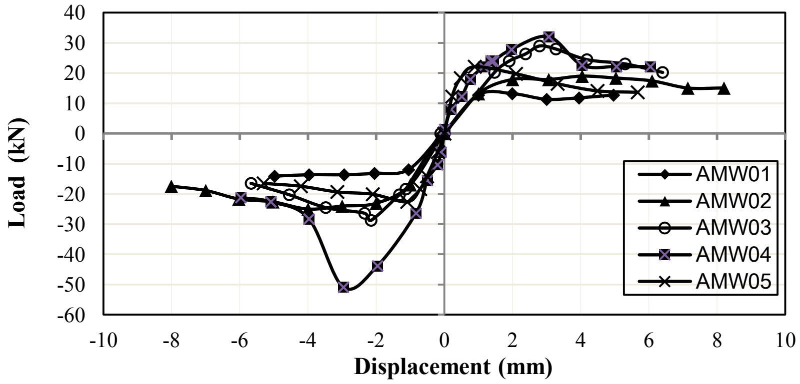


Figure 7 Envelope curves of 5 specimen walls.

The 5 walls showed broadly consistent stiffness degradation trends. After first cracking, the stiffness of the wall decreased rapidly, with an increase of displacement, which is due to the repeated opening and closing of cracks under cyclic loading and the expansion of cracks.

Energy dissipation capacity

The energy dissipation capacity, expressed as the equivalent viscous damping ratio, was calculated as: $\xi_{eq} = A_n / 2\pi A_E$, in which A_n represents the hysteretic damping or energy loss per cycle for one complete idealized load-displacement hysteresis loop, and A_E represents the elastic strain energy stored in the equivalent linear elastic systerm under static conditions with effective stiffness [12]. The values of the equivalent viscous damping ratios for the specimens are plotted in **Figure 8**.

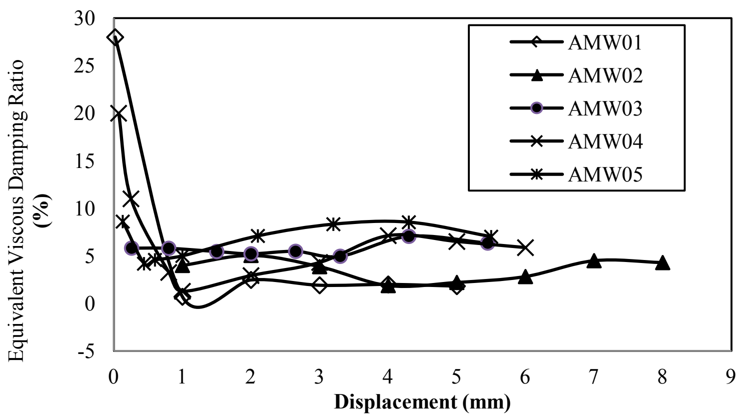


Figure 8 Equivalent viscous damping ratios at various displacement levels.

After the wall cracked, the equivalent viscous damping ratios gradually increased with a corresponding increase in lateral deformation of the walls. This was because the appearance and development of cracks and the friction at the brick-mortar interface dissipated large amounts of energy. At a given displacement level, the equivalent damping ratio of the reinforced wall was larger than in the unreinforced wall. The GFRP stripes obviously contributed to improving the energy dissipation capacity of the piles. This confirms the qualitative observations based on the shape of the hysteresis curves. Since the specimen AMW02 was only simply repaired, the energy dissipation capacity did not show a big difference.

Conclusions

This paper presents the test results of historic masonry walls retrofitted with GFRP in different configurations under lateral cyclic loading. The following preliminary conclusions can be made:

1) Considerable improvement in shear strength and energy absorbtion can be obtained through using GFRP sheet rehabilitation of partially damaged walls or straight strengthening of such walls in seismic zones.

2) After being repaired with GFRP sheets along cracking positions, the bearing capacity and ductility of damaged historic masonry wall were completely restored, and even exceeded the original capacity. More suitable repair technology needs to be used to avoid re-occurrence of cracking at the repaired zone.

3) Using the same strengthening ratio, compared with orthogenal cross retrofitting mode, diagonal GFRP stripe retrofitted walls showed better energy dissipation capacity and more dense and adequate cracking development. Failure mode was a combination of crashing near the bottom corner and shear sliding.

4) Due to the large thickness of walls, there were similar effect on the improvement of shear strength and ductility of walls when GFRP stripes were pasted, whether on one side or on both side. So, one side retrofitting mode can be used for this type of wall ,for construction convenience and aesthetic reasons.

5) In order to establish the formula for shear strength of historic masonry walls retrofitted by GFRP sheets, further research should focus on the influence of aspect ratio, vertical load, and openings in the walls.

Acknowledgements

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