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Behaviors of Historic Masonry Walls Retrofitted with GFRP under Axial Load

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Abstract The purpose of this research is to determine the mechanical properties of historic masonry walls retrofitted with Glass Fiber Reinforced Polymer (GFRP) under axial load through experimental method. Four ancient masonry wall specimens were tested under axial load acted at the top surface. Two wall specimens were served as reference without retrofitting. The third wall was retrofitted with GFRP on full surface before loading. The forth wall was strengthened with three GFRP strips before loading. The behaviors of historic masonry walls in Thailand were particular because of their special bond manner and dimension. The tested results demonstrated that the bearing capacity of historic masonry walls was distinctly improved after GFRP strengthening.

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

Introduction

In Thailand, there are many historic structures which were built around the eleventh and the twelfth Buddhist centuries. Most of them were made of bricks. Being fruitful archeological information about Thai heritage, restorations of such Thai historic structures are always an engineering challenge and are now taken charged by Bureau of Archeology and Museums, Thailand. Most restorations were executed in traditional engineering manners. There was report after report of failure both prior to and after restorations. This research work conducted with aiming of finding a new retrofitting method based on experimental and theoretical investigations.

FRP (Fiber Reinforced Polymer) laminates or fabric sheets used as a feasible material for retrofit reinforced concrete (RC) structures have been studied and applied in practice in the last few years. It is proved that FRP retrofitting can distinctly improve RC member's strength capacity and seismic capacity. But only until recent years, some reported researches have focused on strengthening of masonry walls. 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. The continuous reduction in the material cost of FRP composites has also contributed to their popularity.

A large survey of research related to rehabilitation of masonry structures has been reported by Musiker (Musiler 2002）. In Canada, Nigel G. et al (Nigel et al. 2001) performed the test that using Glass FRP (GFRP) sheets to increase the flexural capacity and energy absorption characteristics of plain and reinforced concrete block walls. In USA, Amir Fam et al. (Amir et al. 2002, Hernan et al. 2006) conducted in-plane test of damaged masonry wall repaired with FRP. In Europe, especially in Italy and Greece, some research works were focus on repair and strengthening of historic masonry building in seismic area (Thanasis et al. 1997, Binda et al. 2004). In Thailand, the research about retrofitting historical building using FRP has also been executed in analytical program (Suddchai 2000). However experimental research and more insight analysis are much needed.

In this study, test investigation was processed to study the behavior of historic masonry wall retrofitted with GFRP.

Experimental Program

Brick and Mortar A great number of fallen bricks of historic buildings in Ayutthaya province, which has been designated by UNESCO as a World Heritage Site, more than 400 years as capital of Thailand, were collected to test their material properties. Then new bricks were produced according to these material properties to built specimen walls. The dimension of brick is 15×30×5 cm. 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 ratios. Table 1 shows the properties of bricks and mortar.

Table 1: Properties of bricks and mortar

Material	*Unit weight* [g/cm^2]	*Compressive strength* [MPa]	*Elastic modulus* [MPa]
Brick	1.373	4.012	3103.3
Mortar	1.924	1.06	1460.5

GRFP sheets and epoxy resin were come from company in Thailand. GFRP sheet has weight of 50g/m^2 with 0.5 mm thickness and 1000 mm width. 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.

Dimension and Retrofitting Mode of Specimen Walls Four specimen walls were built as that of the history masonry wall at Ban Lum Plee, Ayutthaya. The bricks must be laid in the stretcher as per the English bond, as shown in Fig. 1. The joint must be constructed as the flush joint. A string line and spirit level must be used to ensure that bricks are laid on an even plane. The joint between each brick layer is 1cm.

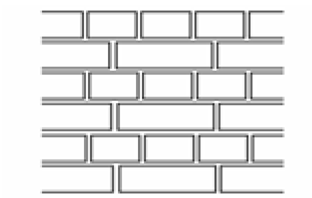


Figure 1: *English bond*

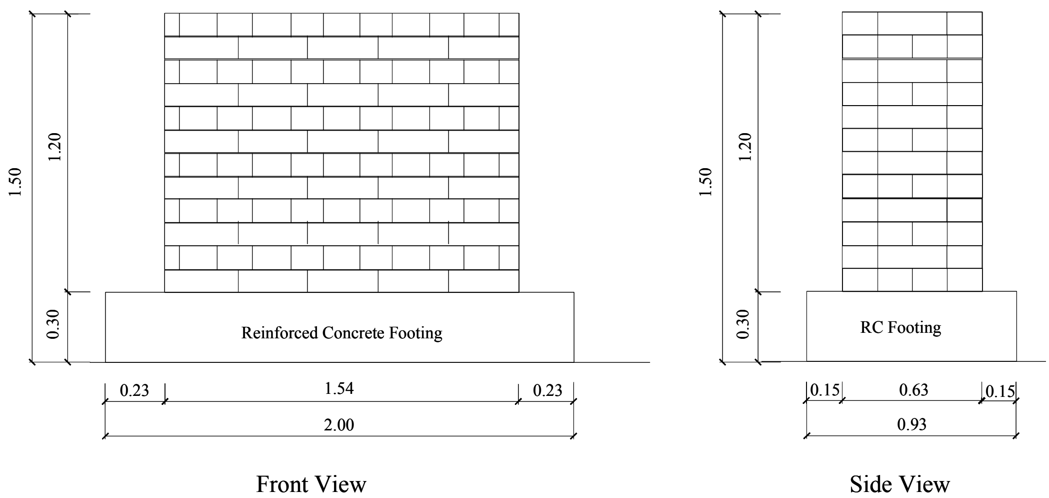
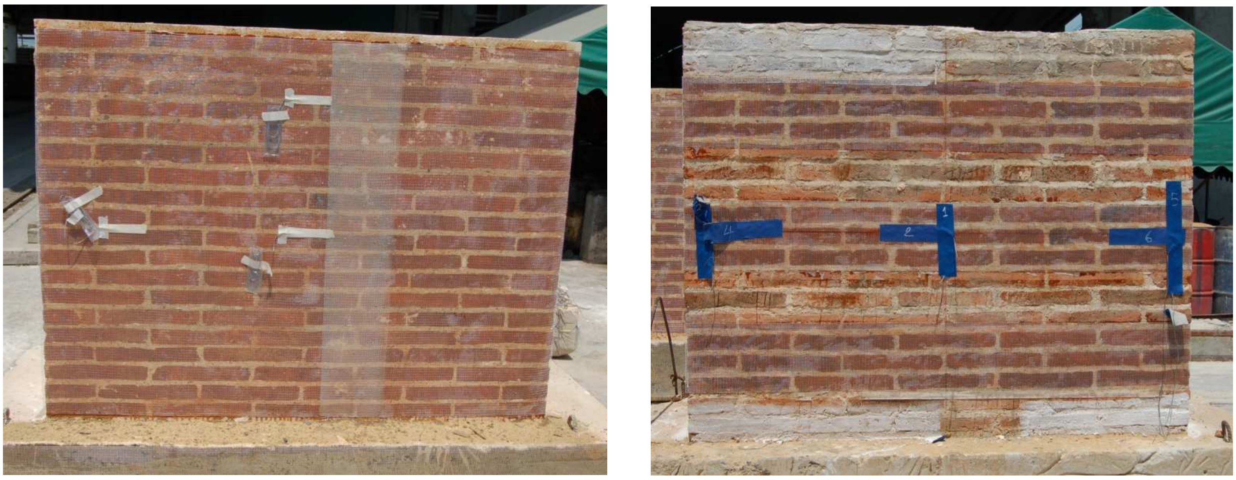


Figure 2: *Dimension of walls* (m)

Four walls are in the same dimension, as shown in Fig.2. The thickness of the walls is 600 mm, as the ancient wall in Ayutthaya, Thailand. Specimen N-1 and N-2 are used as reference wall without any retrofitting. Specimen N-3 was fully reinforced with GFRP sheets on only one face of the wall. Specimen N-4 was reinforced with three GFRP stripes of 20cm width at spacing of 35cm on center on only one face of the wall. Fig.3 shows the different retrofit scheme.



(a) Specimen N-3 (b) Specimen N-4

Figure 3: *Different retrofit scheme*

Test Set-up and Instruments Steel structure frame was fabricated and fixed, and hydraulic jack were installed to apply vertical load on the top of the wall through distribution steel beam. 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. 4

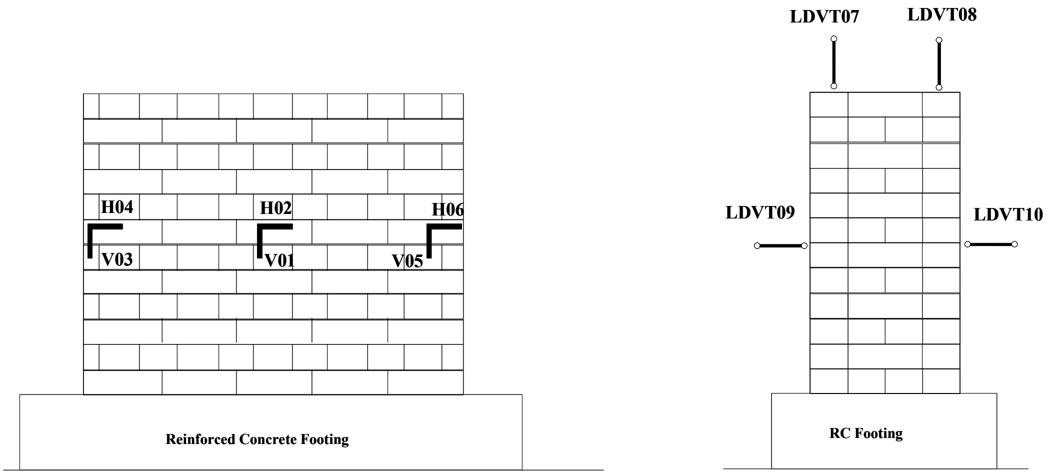


Figure 4: *Test instruments*

Test Process and Results The vertical loading was increased gradually with increment of approximately 3 tons until specimen failure.

For Specimen N-1, when the load is applied to 77% of its ultimate load, 36.14 ton, vertical cracks began to appear at the top center position, run through the mortar joints and some layer of bricks. The main crack is 42.5 cm long and 0.30 mm wide. With the load continued to increase, previous vertical cracks gradually opened and developed downwards and new vertical cracks were initiated. At the load of 45 tons, crack appeared throughout the first horizontal mortar joint, which has the distance of one layer from the top edge of the wall. It is about 120 cm long and 1.6 mm wide. At the same time, cracks opened throughout the vertical mortar joints at the side face, 17cm long from the top edge and 0.1 mm wide on one side face and 34 cm long and 0.7 mm wide on the other side face. At end the wall was fail at the load of 47 ton.

For Specimen N-2, when the load is applied to 58% of its ultimate load, 48.96 ton, vertical cracks began to appear at the top center position, run through the mortar joints and some layer of bricks. The main crack is 17 cm long and 0.20 mm wide. With the load continued to increase, previous vertical cracks gradually opened and new cracks initiated. At the load of 70 tons, crack appeared throughout the first horizontal mortar joint, extend from center of the wall length to about 20 cm. At the ultimate load of 84.27 ton, first appeared horizontal crack developed to both side faces. At the same time, cracks opened throughout the vertical mortar joints at the side face, 74cm long and 1.6 mm wide on one side face and 37 cm long and 0.3mm wide on the other side face.

For Specimen N-3, GFRP sheet was pasted on the full surface. When the load reached 71.42 ton, 48% of the ultimate load, vertical crack appeared on one side face with length of 48.5 cm. At the load of 79.62 ton, vertical cracks also appeared on the other side face with 58 cm long from the top edge. At the same time, some vertical cracks opened on the face of the wall without GFRP sheets. However, no cracks appeared on the face with GFRP sheets until wall failure. Finally, the wall was fail at the load of 148 ton due to cracks on the side face of more than 2mm wide. It is observed that the color of some local parts in GRFP sheets changed, and pop cracking voice can be heard clearly. This can be taken as the peeling-off of GFRP from wall surface. Thanks to the good quality of paste work, only few local peeling-off happened.

For specimen N-4, three strips were pasted on the surface. Its load-displacement response was similar to wall N-3. When the load reached 113 ton, vertical crack appeared at the top center position of the face of the wall without GFRP sheets. At the load of 120 ton, vertical cracks also appeared on the side face with 32 cm long from the top edge. At this load level, 35cm long horizontal crack of emerged through mortar at 18 cm distance from the top edge of the wall. However, no cracks appeared on the face with GFRP sheets until wall failure. Finally, the wall was fail at the load of 125 ton due to cracks on the side face of more than 2mm wide.

Discussion of Test Results

The load-deformation responses of four walls are shown in Fig.5 and Fig.6. All of four specimen walls show linear behaviors in both vertical and lateral direction under axial in-plane vertical load. Ignoring the unordinary behavior of wall N-1 due to weak mortar joints at the first top layer, the elastic properties of un-strengthened wall N-2 and strengthened wall N-3 and N-4 are almost the same. Compared wall N-2, the ultimate compressive strength and peak deformation of specimen N-3 were improved at about 50%. Similarly, the ultimate load of wall N-4 with three GFRP strips also is higher than un-strengthened wall N-2, about 1.5 times.

Fig.7 shows the strain developments in vertical and transverse directions on the masonry surface. In vertical direction, they are compressive strain due to the axial vertical load. In transverse direction, they are tensile strain due to the horizontal tensile force in the perpendicular direction of loading. It can be seen from the diagram that, load-strain developments of reference wall N-2 and strengthened wall N-3 and N-4 are the same, which indicates that constraints effect of GFRP sheets didn’t play in vertical direction. In transverse direction, the axial vertical compressive stress suffered by specimen wall was smaller in the initial loading stage, and the corresponding transverse stain was very small. So it can be seen that transverse strain in un-strengthened wall N-2 and strengthened wall N-3 and N-4 are almost the same until load of 30 ton, which means that the constraints effect of GFRP still didn't played. With the increase of load, transverse strain began increased rapidly with the appearance of initial cracks. However, Fig.7 shows clearly that increasing of transverse strain in GFRP strengthened wall N-3 and N-4 are obviously slower than that in un-strengthened wall N-2. It demonstrates that most of transverse tensile force was resisted by GFRP sheets. Tensile force subjected by masonry wall was reduced obviously. So the widths of cracks were reduced and even the emergences of cracks were avoided.

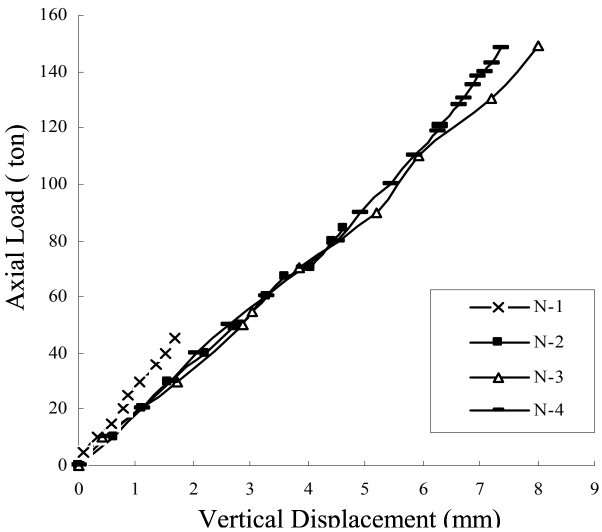


Figure 5: Load –vertical deformation responses of specimens

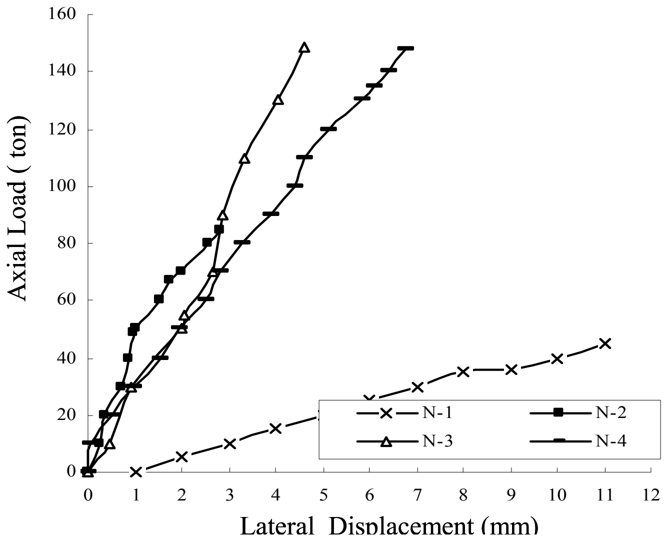


Figure 6: Load-lateral deformation responses of specimens

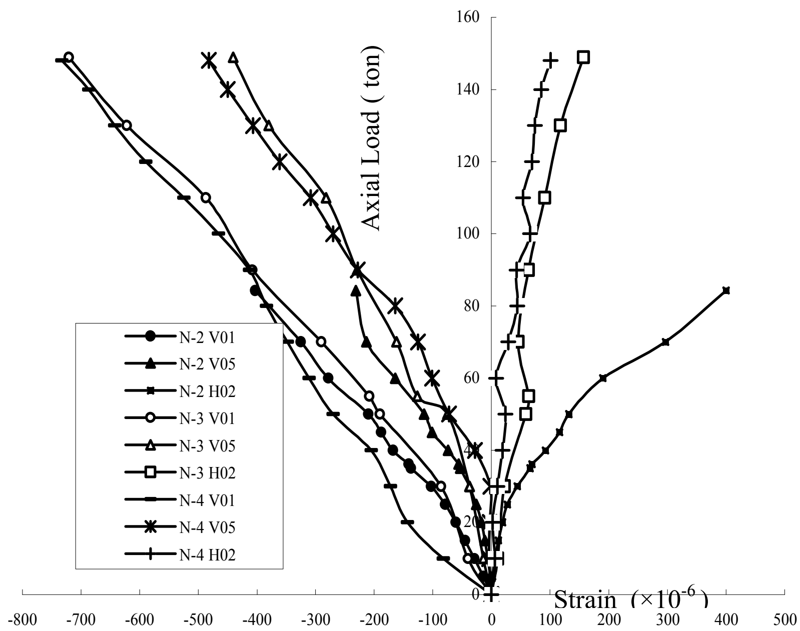


Figure 7: *Strain developments on the masonry surface of specimens*

Conclusions

Historic masonry walls in Thailand are particular due to their special English bond and big thickness. Through test it can be observed that the crack and failure modes of them under axial vertical loading are different from that of some historic masonry walls in other districts described in published research reports. More experimental tests and theoretical study are needed about their mechanical behaviors.

The compressive strength of the historic masonry wall was obviously improved by 50 percent after retrofitted with GFRP sheets. The constrain role of GFRP sheets delay or even prevent the emergence of cracks.

Different retrofitting schemes have little effect on the compressive strength of the historic masonry wall. Considering the economical and labor reasons, it is more practical to strengthened historic masonry walls with GFRP stripes instead of full face GFRP sheets.

Further research is needed about the relationship between material properties and the retrofitting effects of historic masonry wall.

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