Out-of-Plane Performance of Strengthened Unreinforced Brick Wall of Historic Buildings

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ABSTRACT :

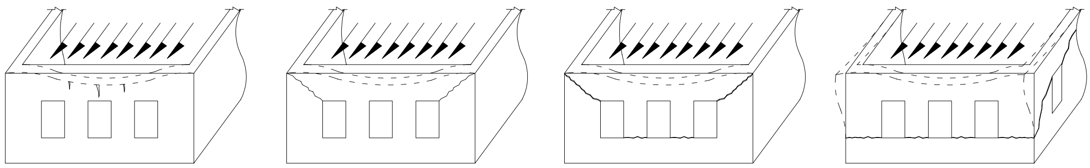
The investigation concentrates at the out-of-plane damage behavior and its strengthening methods for the brick walls of historic buildings. The walls are constrained in the two vertical edges and lower edge. The strengthening methods adopted in this study can be divided in three categories. The first category applies confine member along the upper edge of the wall. The confine member includes steel plate and U shape steel cover beam. The second category applies horizontal band of carbon fiber, glass fiber, and stainless wire mesh to strengthen the upper edge of the brick wall. The third category uses both of horizontal and vertical bands to strengthen the wall in two directions. Totally, there are 9 brick specimens (215cmx154cmx11cm) are made and tested under statically horizontal load.

According to the experiment, the damage mode of the unreinforced specimen is formed by following stages: (1) a major central vertical crack occurred; (2) two inclined cracks extending from the central crack to the corner of wall specimen; (3) finally, an U-shape crack near the three constrained edges is observed. In the three strengthening categories, the specimens strengthened by confine members have shown an increase of 100% for ultimate load. The specimens strengthened by horizontal bands have the increase of 40%~100%, depending on the band materials used. For the specimens strengthened by horizontal bands associated with vertical bands, an ultimate load that increases 90~200% is obtained.

KEYWORDS: out-of-plane; brick wall; historic building; retrofit

1. INTRODUCTION

Most of the historic buildings in Taiwan rely on brick walls to resist lateral force during earthquakes. Thus in addition to the in-plane wall strength, the out-of-plane wall strength of these brick walls also needs to be well considered during conservation. Fig. 1 shows the four damage modes of unreinforced brick wall often observed in historic buildings. Based on these damage modes, obviously, improving the strength and stiffness of the upper wall edge is most critical.



(a) (b) (c) (d)

Figure 1 Out-of-plane damage modes

2. EXPERIMENTAL PROGRAM

2.1. Wall specimens

Nine specimens were constructed and tested in this study. As shown in Fig. 2, the dimension of the specimen is 215x154x11cm (W x H x t). All of the specimens were constructed with cemented mortar (1:2) and Taiwan standard bricks (23x11x6cm, L x W x H) in stretcher bond. `

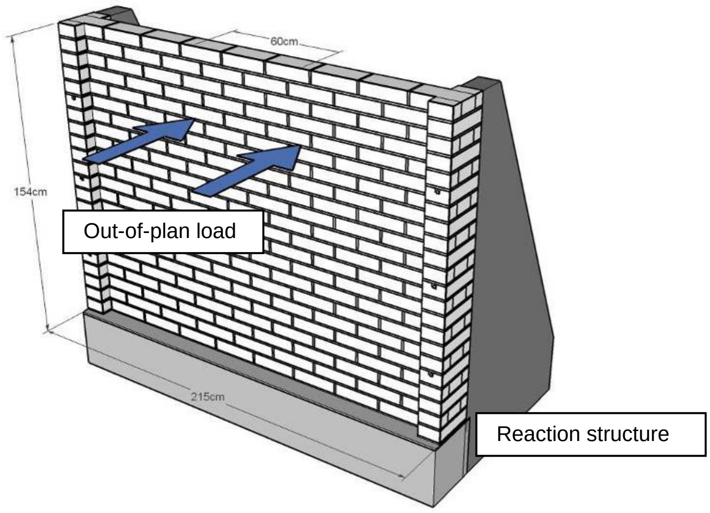
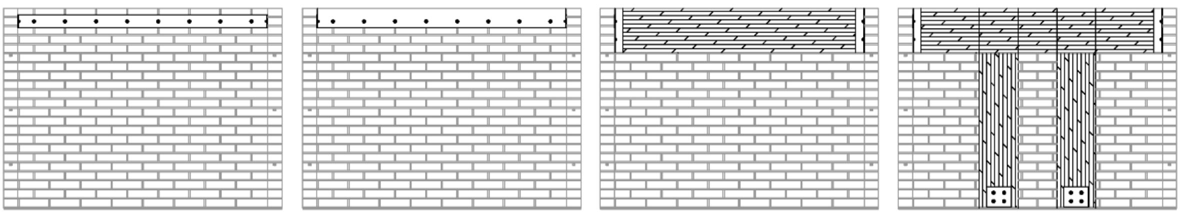


Figure 2 Unreinforced specimen W9 and loading position

The specimens labeled as W1 to W9 could be divided into three categories by the methods of strengthening as shown in Table 1. The first category (specimen W1~W3) has the wall strengthened with confine member along the upper edge of the wall. Specimen W1 and W2 were both applied steel plate(10x0.6cm, W x t) on tensile side and fastened with adhesive bolts, and additional epoxy grouting in the interface of brick and steel plate were applied to specimen W2 (Fig.3(a)). Specimen W3 were applied U shape steel cover beam (15cm in depth) on the top edge of the wall and then Fastened with bolts (Fig.3(b)). The second category (specimen W4~W6) applies horizontal band (35cm in width) of carbon fiber sheet, glass fiber sheet, and stainless wire mesh for strengthening the upper edge of the brick wall. In Specimen W4 and W5 which strengthened with fiber sheet, epoxy was used to be the adhesive, and specimen W6 were plastered with cement mortar on stainless wire mesh (Fig.3(c)). The third category (specimen W7~W8) applies not only horizontal band, but also two vertical bands from tensile side to the back(Fig.3(d)). In table 1, the non-strengthening specimen W9 is used for the comparison with specimen W1~W8.

Table 1 Details of the brick specimens

Specimen	Strengthening method		Annotation
W1	Category 1	Steel plate	Fastened with adhesive anchor bolts
W2		Steel plate	Fastened with adhesive anchor bolts, epoxy grouting in the interface of brick and steel plate
W3		U shape steel cover beam	Fastened with bolts
W4	Category 2	Carbon fiber sheet	Adhered with epoxy
W5		Glass fiber sheet	Adhered with epoxy
W6		stainless wire mesh	Covered up with cement mortar
W7	Category 3	Carbon fiber sheet	Adhered with epoxy
W8		Glass fiber sheet	Adhered with epoxy
W9	non-strengthening specimen		

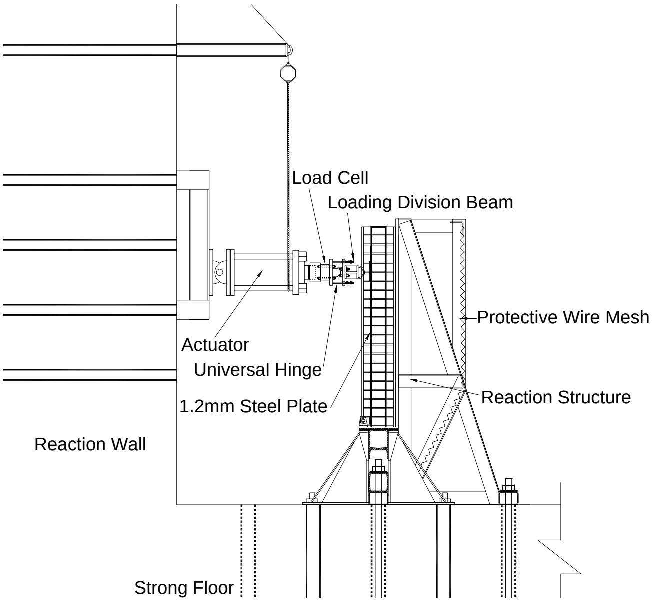


(a) W1,W2 (b) W3 (c) W4,W5,W6 (d) W7,W8

Figure 3 Strengthened specimens

2.2. *Test setup*

Fig.4 illustrates the test setup. Specimens were fixed both left and right edge to the lateral supporting structure, and fixed bottom of the wall to the base structure. The out-of-plane loading was applied through the actuator, and divided into two concentrated load by a loading division beam. The loading was measured by the load cell on the actuator, and the middle point deflection on the top of the specimen was measured using a displacement transducer.



(a)

(b)

Figure 4 Test Setup

2.3. *Loading setup*

During test, the wall specimen was subjected to two concentrated lateral loads which were 120cm height above the bottom edge, and 30cm from the center line of the wall as shown in Fig.2. Loading was applied gradually until serious damage occurred in the specimen.

3. EXPERIMENT RESULTS AND DISCUSSION

3.1 Material properties

Table 2 gives fundamental properties of the wall specimens.

Table 2 Tested material properties

Property	Strength (kgf/cm^2)
Compressive strength of brick	428.7
Compressive strength of mortar	301.9
Shear strength of interface between brick and mortar	5.33
Tensile strength of interface between brick and mortar	4.05
Tensile strength of carbon fiber	288.2
Tensile strength of glass fiber	115.5

3.2 Behavior of unreinforced specimen W9

Fig.5 shows the crack sequence of specimen W9, and Table 3 shows the relationship between damage sequence, load, and drift. The first crack occurred near central area of the upper edge, and extended down at the drift of 0.0016. When loading was continued to be added, this vertical crack became extending to both bottoms corners of the specimen. Then a horizontal crack appeared on the bottom of the specimen, and brick surface crushed in some area near this crack was observed. The horizontal crack also appeared near the load-adding position as a result of local failure by high stress. Finally, an U-shape crack near the three constrained edges was observed.

Fig. 6 shows the force-drift relationship of this test. The specimen is elastic before the first crack occurred. The first vertical crack appears at the drift of 0.0016, and the corresponding load is 1587kgf. After the first crack occurred the drift rises much faster than elastic stage, and some horizontal cracks developed. Finally, the U-shape crack mode appears at 0.023 drift. The recorded ultimate load of the unreinforced specimen is 2076kgf.

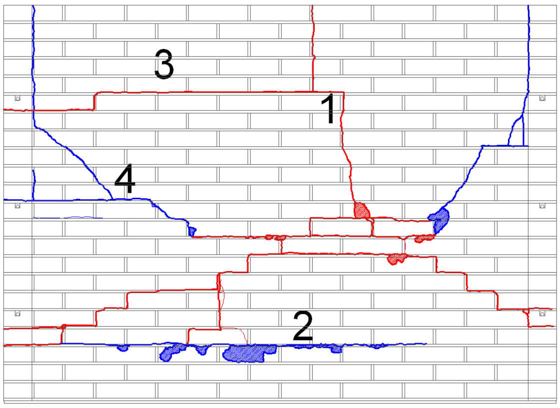


Figure 5 Crack record of specimen W9

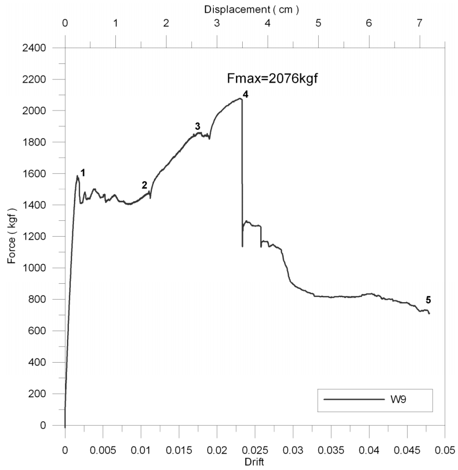


Figure 6 Load-drift curve of specimen W9

Table 3 Relationship between damage sequence and loading

W9	Damage sequence	1	3	4	
	Crack description	Vertical crack	Upper horizontal crack	U-shape crack	**Ultimate load**
	Loading （kgf）	1587	1851	2076	**2076**
	Drift	0.0016	0.0176	0.023	**0.023**

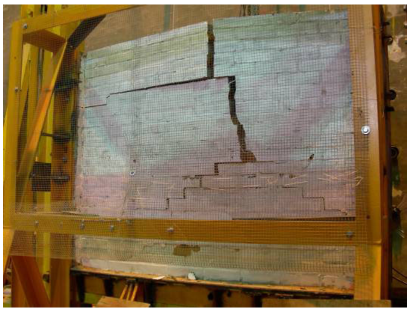


Figure 7 Specimen W9 after test

Figure 8 U-shape crack

3.3 Behavior of the specimen strengthened by confine member

Specimen W1 and W2 were both strengthened by steel plate reinforcement, but epoxy grout was added in the interface of W2. The damage sequence of specimen W1 is similar to that of unreinforced specimen W9, while Specimen W2 performed differently. The main reason is because of the adhesion for the wall-steel interface. The adhesion constrained the specimen to deform, and changed the U-shape damage mode to local punching failure as shown in Fig. 9(b).

Specimen W3, strengthened by cover beam with channel cross-section at the upper edge, behaved similar to specimen W1, but some details of the crack sequence had changed (Fig.9(c)).

Generally, the specimens strengthened with confine member reveal the improvement both in the stiffness and the strength. The load-drift curves of these three specimens are shown in Fig. 10. The ultimate load of these three specimens are about twice of specimen W9, while the corresponding drifts are less than 0.0057, which is much smaller than specimen W9.

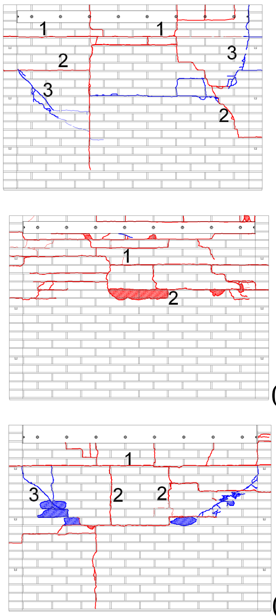


Figure 9 Crack record of specimens

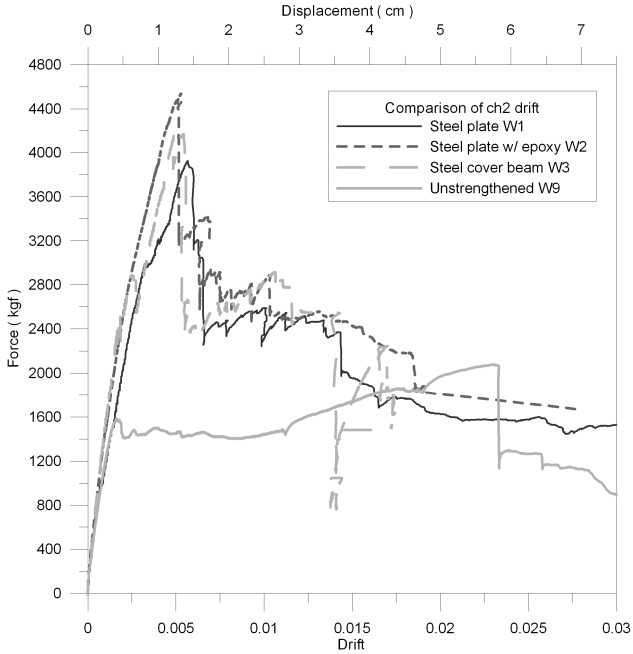


Figure 10 Load-drift curve of category1 method

Table 4 Relationship between damage sequence and loading (Category1)

W1	Damage sequence	1	2	3	
	Crack description	Vertical crack	Upper horizontal crack	U-shape crack	**Ultimate load**
	Loading（kgf）	2986	3215	3924	**3924**
	Drift	0.0033	0.004	0.0057	**0.0057**
W2	Damage sequence	1			
	Crack description	Upper horizontal crack			**Ultimate load**
	Loading（kgf）	4535			**4535**
	Drift	0.0053			**0.0053**
W3	Damage sequence	1	2	3	
	Crack description	Upper horizontal crack	Vertical crack	U-shape crack	**Ultimate load**
	Loading（kgf）	2563	2882	4163	**4163**
	Drift	0.0018	0.0025	0.0054	**0.0054**

Figure 11 W1 after test

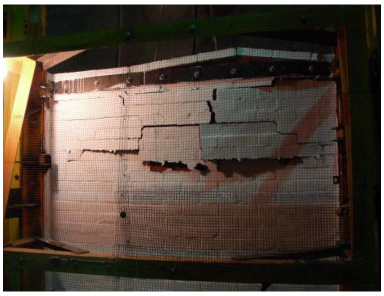


Figure 12 W2 after test

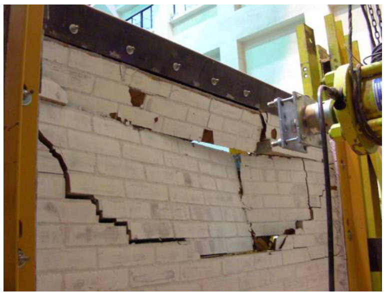


Figure 13 W3 after test

3.4 Behavior of the specimen strengthened by horizontal band

Fig. 14(a) shows the crack of specimen W4 that applied carbon fiber sheet for strengthening. Approximately, the damage sequence follows the steps described previously for W9. The interface between carbon fiber and brick were peeled off gradually while coming to reach the ultimate load. The value of ultimate load was controlled by interface adhesion. The damage mode of specimen W6 strengthened by stainless wire mesh, is analogous to that of W4, and the ultimate load is also controlled by the interface between cement mortar and brick. A special phenomenon worth to be mentioned is the plaster layer of specimen W6 revealed many cracks along the major central vertical crack as shown in Fig. 14(c). It indicates that higher tensile stress have concentrated in this area. However, the damage mode of specimen W5 shows differently from that of above two specimens. Due to the tensile strength of glass fiber is weaker than interface adhesion, the glass fiber broke down when the ultimate load is reaching.

Fig. 15 shows the load-drift relationship of these tree specimens. The slope of load-drift curve of three is very close before drift 0.002. Specimen W5, W6, and W4 reach the ultimate load at the drift 0.0035, 0.0057, and 0.022. The corresponding ultimate loads are 2952kgf, 3406kgf, and 4285kgf, respectively. Comparing the force-drift curve of these specimens, the curve of specimen W4 shows visible different in shape, which drops down at drift 0.004 (3100kgf) and then rises gradually until the ultimate load is reached (4285kgf).

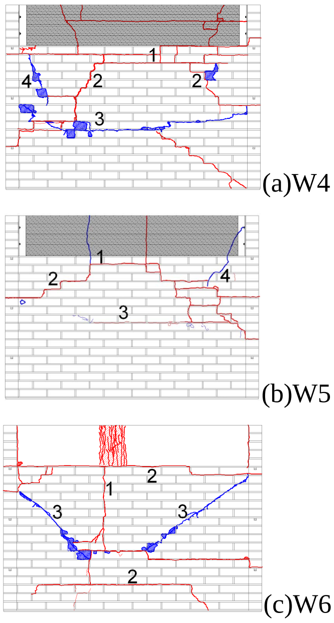


Figure 14 Crack record of specimens

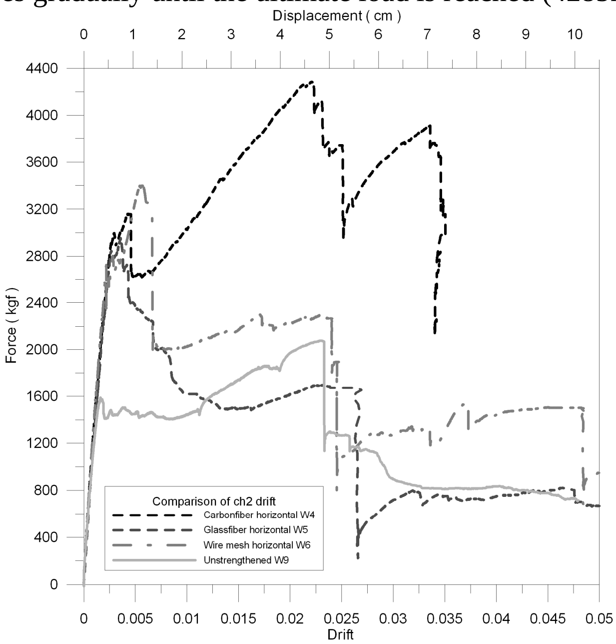


Figure 15 Load-drift curve of category2 method

Table 5 Relationship between damage sequence and loading (Category 2)

W4	Damage sequence	1	2	3	
	Crack description	Vertical crack	inclined cracks	U-shape crack	**Ultimate load**
	Loading (kgf)	2997	3160	4285	**4285**
	Drift	0.003	0.0044	0.022	**0.022**
W5	Damage sequence	1	2		
	Crack description	Vertical crack	U-shape crack		**Ultimate load**
	Loading (kgf)	2840	2952		**2952**
	Drift	0.0026	0.0035		**0.0035**
W6	Damage sequence	1	2	3	
	Crack description	Vertical crack	inclined cracks	U-shape crack	**Ultimate load**
	Loading (kgf)	2722	2802	3406	**3406**
	Drift	0.0022	0.0028	0.0057	**0.0057**

Figure 16 W4 after test

Figure 17 W5 after test

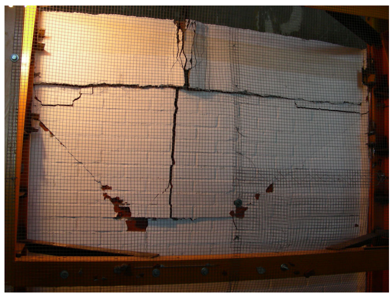
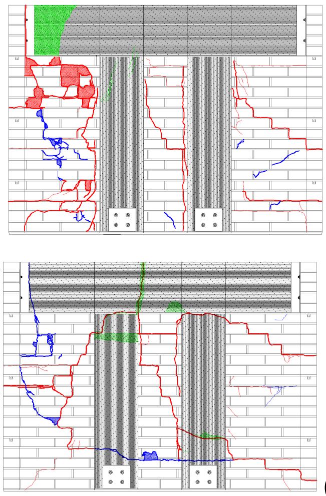


Figure 18 W6 after test

3.5 Behavior of the specimen strengthened by horizontal and vertical bands

The test result of two specimens (W7 and W8) showed strengthening method category 3 has made the specimens more homogeneous. Even the same damages such as vertical cracks and inclined cracks still appeared but diffused in nonstrengthening areas (Fig. 19). Material properties also controlled the damage modes just like specimen W4 and W5. It is found that carbon fiber sheet interface peeled off near the anchor area. Glass fiber was cut off at the middle area of horizontal band and near the bottom area of both vertical bands.

The load-drift curve showed that additional vertical bands improved the performance of strength and ductility. The comparison of specimens between added vertical bands or not is shown in Fig.20. The strength of W7 that strengthened by carbon fiber had about 60% higher than that of W4, and the ultimate drift extended from 0.002 to 0.045. The glass fiber specimen W8 also improved 30% in strength, and the ultimate drift changed from 0.0035 to 0.001.



(a)W7

(b)W8

Figure 19 Crack record of specimen

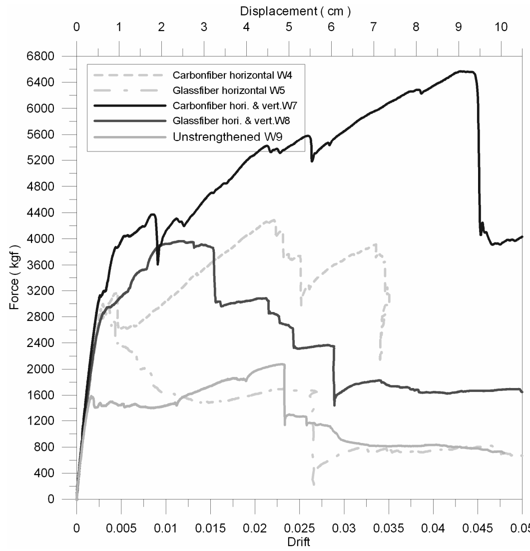


Figure 20 Load-drift curve of category3 method

Table 6 Relationship between damage sequence and loading (Category 3)

W7	Damage sequence	1	2	3	
	Crack description	Vertical crack	inclined cracks	U-shape crack	**Ultimate load**
	Loading (kgf)	4359	5576	6561	**6561**
	Drift	0.0085	0.026	0.043	**0.043**
W8	Damage sequence	1	2	3	
	Crack description	Vertical crack	inclined cracks	U-shape crack	**Ultimate load**
	Loading (kgf)	2952	3528	3966	**3966**
	Drift	0.0035	0.0074	0.012	**0.012**

Figure 21 W7 after test

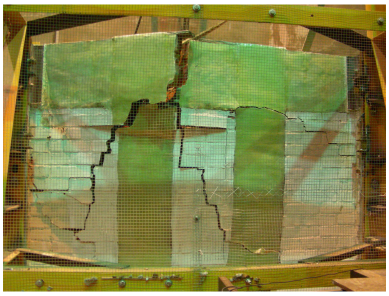


Figure 22 W8 after test

3.6 Comparison of the three categories of strengthen method

Fig. 23 shows the comparison of specimen W2(which is representing the category1 method) and the other specimens strengthened by fiber sheets and wire mesh. All of these three categories obtain increase of ultimate load but revealed different performances: category1 only improves stiffness, but the other categories increase both strength and ductility. The cover area of force-drift curve for W4(category2) or W7(category3) is much greater than that of W2. Thus from the aspect of energy-absorption, it comes that fiber strengthening method or wire mesh strengthening has better performance than that of steel plate strengthening method. However, from test it is also observed that in the stage of low drift (before 0.005), the wall strengthened with steel plate can obtain a much high strength. For historic building, keeping the brick walls from cracking or deforming seriously is much important than that performing well in energy-absorption during earthquake excitation. Thus, during conservation design, the strengthening method to be adopted should be well considered.

The vertical bands strengthening method tested in this study has shown the improvement of wall stiffness in horizontal direction of long shape wall, and avoid wall collapse occurred. This strengthening method may be adopted for the building case with long masonry wall, such as historic ceremony hall.

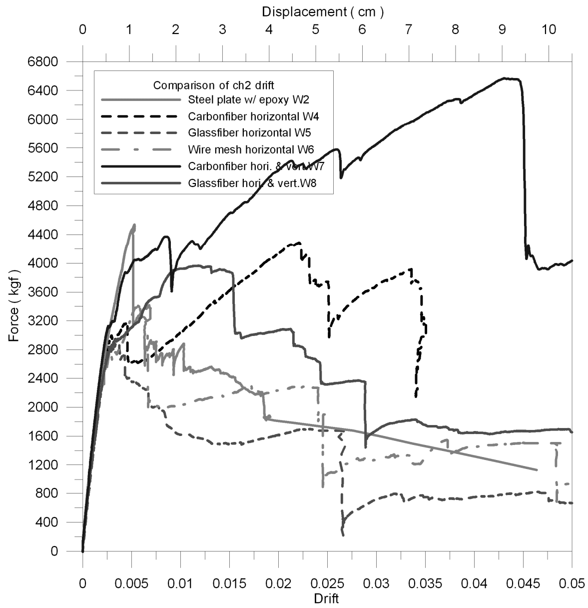


Figure 23 Load-drift curve of comparison by different strengthening method

4. CONCLUSION

In this experimental study, followings can be summarized:

1. The brick wall strengthened with steel plate confine members at the free upper wall edge can obtain an increase of 100% for ultimate load.
2. Comparing to the specimens strengthened with steel plate confine members, the specimen strengthened with horizontal bands obtain an lower increase in the ultimate load(about40%~100%). The value depends on the band material used.
3. The specimen strengthened with fiber in both horizontal and vertical direction performs better energy absorption than any other strengthening method.
4. For historic building, steel plate strengthening method can obtain high strength in low drift (<0.005), which is benefit in preventing serious cracking occurred in the historic building during earthquake.

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