Structural Engineering and Mechanics, Vol. 25, No. 6 (2007) 675-690
DOI: http://dx.doi.org/10.12989/sem.2007.25.6.675

Experimental study of masonry walls strengthened with CFRP

Chang-Qin Wei†

School of Civil Engineering, Yantai University, Yantai 264005, P. R. China

Xin-Gang Zhou‡

School of Civil Engineering, Yantai University, Yantai 264005, P. R. China
Department of Civil Engineering, Tsinghua University, Beijing 100084, P. R. China

Lie-Ping Ye‡†

Department of Civil Engineering, Tsinghua University, Beijing 100084, P. R. China

(Received September 30, 2005, Accepted October 11, 2006)

Abstract. In order to study the ductility and the lateral load carrying capacity of the masonry walls strengthened with CFRPs (Carbon Fiber Reinforced Polymer sheets), three pieces of masonry walls subjected to cyclic loads with low frequency and vertical load of constant amplitude have been tested. Two different strengthening methods have been used. The strengthening efficiency is affected by the strengthening method. A simplified calculation approach has been introduced based on the experimental test results, and the theoretical results agree reasonably well with the experimental results. It is found that the critical loads, the critical displacements, the ultimate loads, the ultimate displacements and the ductile coefficients of the masonry walls strengthened with CFRPs improve remarkably (6%~57%). Therefore, the masonry structures strengthened with CFRPs are of better ductility and of better lateral load carrying capacity than the masonry structures without any strengthening measurements.

Keywords: CFRPs (Carbon Fiber Reinforced Polymer sheet); masonry walls; strengthening method; lateral load carrying capacity.

1. Introduction

As shown in the literature (Thanasis 1998), the FRP (Fiber Reinforced Polymer) strengthening technique has been widely used in engineering practice. Many researchers did some research works in concrete structures strengthened with FRP and some theories have been proposed and put into practice (Thanasis 1998, Amir and Hamid 1998). To date, the strengthening technique develops

† Postgraduate, E-mail: weichangqin@126.com
‡ Professor, Corresponding author, E-mail: xzhou@ytu.edu.cn
‡† Professor, E-mail: ylp@tsinghua.edu.cn

rapidly and it has been used very widely in the field of concrete structures. It can also be used in the fields of masonry structures and steel structures (Thanasis 1998, Amir and Hamid 1998, Seible and Hegemier 1990, Schwegler 1995, Seible 1995, Ehsani and Saadatm 1997, Triantafillou 1998, Van Zijl and De Vries 2005, Ehsani 1995, Triantafillou 1998, Gilstrap and Dolan 1998, Hamilton *et al.* 1999, Albert *et al.* 2001, Kiss and Kollar 2002, Tumialan *et al.* 2003, Ghobarah and Galal 2004, Hall *et al.* 2002).

In the early stage, researchers ever attempted to use different kinds of FRP, including CFRP (Carbon Fiber Reinforced Polymer), GFRP (Glass Fiber Reinforced Polymer) and AFRP (Aramid Fiber Reinforced Polymer) to strengthen concrete structures. CFRP was paid more attention than the others because of its fine properties, such as good physical and mechanical properties, and for the fact that it is less sensitive to environmental effects. Furthermore, CFRP has good toughness and strong capacity to resist deformation. CFRP is always in the linear elastic stage before it reaches the ultimate strain and it has no obvious yield point. It is also easy to be glued to various curving surfaces and arbitrary irregular surfaces of structures. Designers can cut out CFRP when necessary in order to obtain due design strength in a certain direction (Amir and Hamid 1998). Therefore, the latest CFRP strengthening technique becomes a mainstream of the young strengthening methods in recent years. CFRP is made by Carbon Fiber soaked with epoxy resin, and it is glued to tensile sections of structures with glue materials made of transformed epoxy resin. When the resin coagulates after a certain time, CFRP and the original structures become a new composite structure to sustain external loads. The collaboration between CFRP and the original structures improves the loading carrying capacity. Additionally, the CFRP strengthening technique can be applied to strengthen columns, walls, beams and plates in order to resist the impact of the earthquakes. CFRP also has light weight, high strength and strong resistance to corrosion.

Generally, there are several conventional methods in strengthening structures, such as the method of increasing thickness with reinforced concrete, the method of increasing pre-volumes, the method of wrapping structures with steel, the strengthening method with thin sheets or plates materials and the method to reduce earthquakes acting on structures such as active damping system, etc. Compared with these methods, the CFRP strengthening technique has many advantages such as not increasing the weight and the dimensions of the initial structures, high strength, high efficiency, wide application fields, fine durability, strong resistance to corrosion and simple configuration. CFRP can also be used in multiple layers in order to satisfy the strengthening requirements completely. As for a young technique, the CFRP strengthening technique is still in a primary stage with limited analytical models or design guidelines. Compared to concrete the characterization studies related to masonry structures strengthened with FRP are limited. The first successful application of the CFRP-strengthening-technology to a five-storey model masonry structure was operated by Seible and Hegemier (1990) who conducted a set of tests and many research works about the mechanical performance of masonry structures strengthened with FRP. All the tests and research works on the strengthening technique applied to masonry structures can be divided into two groups. One group is the experimental studies of masonry walls strengthened with FRP for resistance to in-plane action (shear, tension) and the other one is the experimental studies of masonry walls strengthened with FRP for resistance to out-of-plane action (bending).

In the first group, Schwegler (1995) did some experiments to test the resistance to in-plane shear of masonry walls strengthened with CFRP. In his study, the CFRPs were glued in diagonal direction and anchored with mechanical measures. The test results indicate that the masonry walls strengthened with CFRP lie in elastic stage when the applied loads are less than 70% of the ultimate loads. Besides, the crack-width of the test walls is relatively small. Seible (1995) did another experiment to simulate response to the earthquake loads using a full size masonry wall strengthened with CFRPs. The test proves that the CFRP–strengthening-technology can improve the strength, reduce the shear deformation and improve the ductility of masonry structures with high efficiency. Ehsani and Saadatm (1997) did some experiments of masonry walls strengthened with FRP under static loads to test the resistance to shearing. During the test, factors such as the strength of FRP, the directions to glue FRP, the anchoring length for FRP etc. were in consideration. The test results indicate that the strength and the ductility of masonry walls strengthened with FRP improve greatly. The directions to glue FRP will affect the rigidity of masonry walls but will not affect the ultimate loads. Triantafilio (1998) studied masonry walls strengthened with FRP under short-term linear loads in detail in order to test the mechanical performance of the masonry wall. According to the results, the resistance to in-plane shear of the masonry walls strengthened with FRP is still very strong although the vertical loads are very small. Van zijl and De Vries (2005) studied the in-plane resistance to restrained shrinkage of masonry structures by externally applied CFRP reinforcement. The masonry wall was strengthened only on one side and the other side without any strengthening measures. The research results indicate that crack control can be stated as being successful with CFRP reinforcement (i.e. crack widths on the reinforced side were three times of that on the unreinforced side and remained within acceptable levels for a large differential temperature range). In the second group, experimental studies (Ehsani 1995, Triantafillou 1998, Gilstrap and Dolan 1998, Hamilton *et al.* 1999, Albert *et al.* 2001, Kiss and Kollar 2002, Tumialan *et al.* 2003, Ghobarah and Galal 2004, Hall *et al.* 2002) of masonry walls strengthened with FRP for resistance to out-of-plane bending indicate that FRP can increase the capacity of carrying bending movement significantly and it can also improve the ductility of masonry structures remarkably. According to the research results (Tumialan *et al*. 2003), along with the increasing use of FRP in engineering practice, the masonry walls strengthened with FRP subjected to out-of-plane load exhibits three modes of failure: 1) debonding of the FRP from the masonry substrate; 2) flexural failure: wall fails either by rupture of the FRP or masonry crushing; 3) shear failure: either flexural-shear failure or sliding shear failure. Of the three failure modes, the first one is mostly the controlling mode. Furthermore, some measures are taken to avoid shear failure in design guidelines for masonry structures subjected to out-of-plane loads. For example, the reinforcement index $(\omega_f = \rho_f E_f / f'_m (h/t_m))$ should not exceed an upper limit in the masonry etc. Researchers in China have also done some experiments to test the performance of masonry walls strengthened with FRP in recent years. Different kinds of FRP including CFRP, GFRP etc. were used for strengthening masonry walls. The test results indicate that both CFRP and GFRP can control cracking and can prevent unstable growth to large widths and lengths and improve the capacity of masonry walls strengthened with FRP to resist earthquakes effectively, especially when the low-strength mortar is used for masonry structures.

As stated before, the application of CFRPs to masonry structures is still in primary stage. There are not mature and perfect theories as guidance at present. In other words, more research works are still required in the field of masonry structures strengthened with CFRPs. In this paper the responses of three pieces of masonry walls subjected to cyclic loads and vertical constant amplitude loads are reported. These tests were performed in order to study the ductility and the lateral load carrying capacity of the masonry walls strengthened with CFRPs. As known, masonry walls $(h/l \le 1)$ without any strengthening measures under vertical load of constant amplitude and variational lateral loads tend to be of very low load carrying capacity and of bad ductility. They usually produce shear cracks along diagonal directions of the walls. However, the vertical load can play a positive role to a certain extent to improve the lateral load carrying capacity of the walls. Therefore, effective strengthening methods should be considered in order to get a high strengthening efficiency. In the paper, two different strengthening methods have been employed. Theoretically, if CFRPs are glued in the direction of tension stress in masonry walls, it will prevent the cracks from unstable propagation. The point provides us with a strengthening method for cyclic diagonal tensile action (seen in Fig. 3) where some CFRPs are arranged at an angle of 45° with the horizontal line, and other CFRPs at an angle of 135° with the horizontal line. It should be stated that the concept was applied by Schwegler (Schwegler 2000) in both directions for in-plane reinforcement to earthquake action and the strengthening efficiency of the method in masonry structures was proved well. This is one of the two strengthening methods which not only can prevent the cracks from widening but also can increase a part of the vertical load acting on masonry walls due to its confinement action. The other method (seen in Fig. 2) is that the CFRPs are glued vertically onto the masonry wall, which can add more vertical confining load acting on the masonry walls compared with the diagonal reinforcement method. Additionally, all the CFRPs are glued onto the masonry walls with the structural adhesive which has very high strength to avoid the failure to initiate at the sections between the masonry walls and the structural adhesive (debonding). Both strengthening methods have been derived through careful consideration of experimental observation and theoretical analysis. They are tested in the experiment and the test results in different methods are analyzed in the paper. The load-controlling system is also introduced in the paper. In addition, a simplified calculation approach for calculating the lateral load carrying capacity of masonry walls strengthened with CFRP has been introduced based on the results of the test.

2. Experimental tests

2.1 Test specimens

In the experimental tests, mortar and clay brick with axial compressive strength 2.5 MPa (M2.5 Grade) and 10 MPa (MU10 Grade) respectively are used. The CFRPs used in the experiment are made in German of the brand HAUFLER. The dimension of the brick is 240 mm × 115 mm × 53 mm.

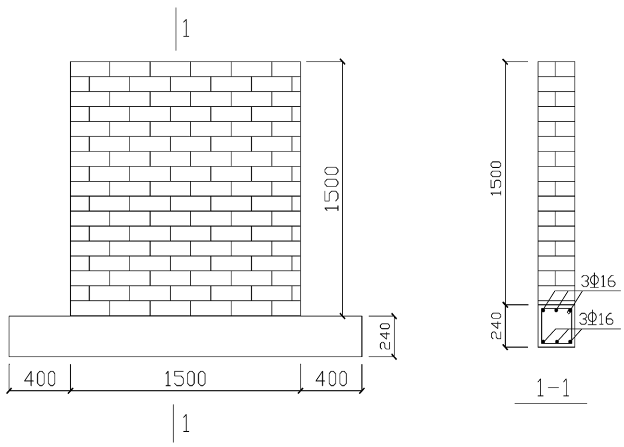


Fig. 1 Initial masonry wall not strengthened with CFRPs (S0)

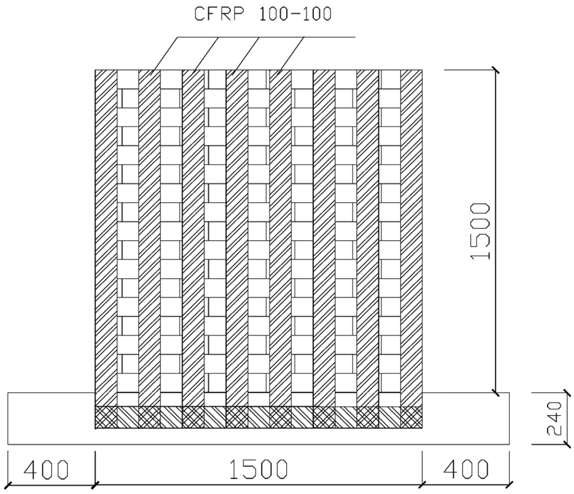


Fig. 2 Masonry wall strengthened with CFRPs in the first method (S1)

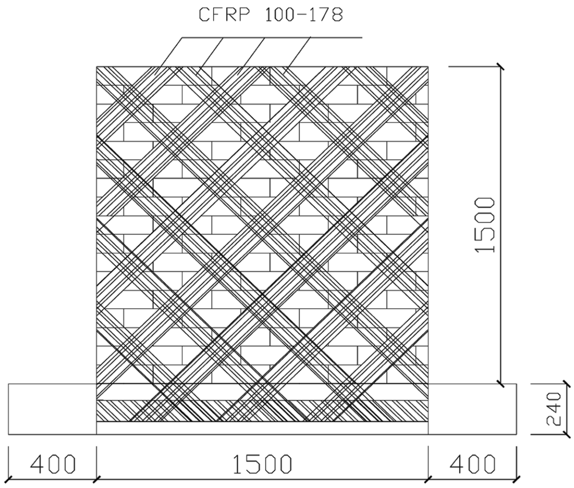


Fig. 3 Masonry wall strengthened with CFRPs in the second method (S2)

Table 1 Properties of the CFRPs

Style	Density g/m^2	Thickness mm	Tensile strength MPa	Elastic modulus MPa	Elongation %
UD-CS200	200	0.111	≥3000 (4347)	≥2.1 × 10^5 (2.4 × 10^5)	≥1.5

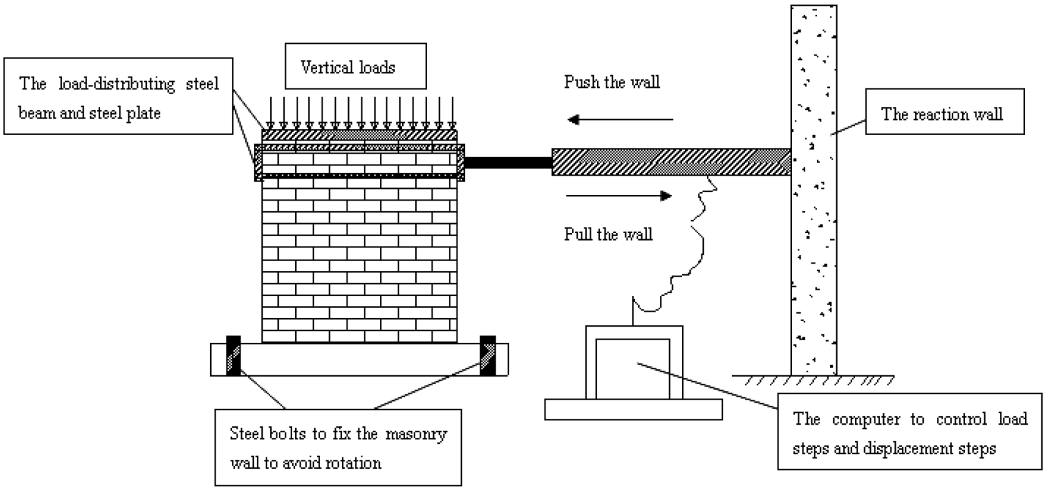
NOTE: The values in the brackets are the actual values of the properties of the CFRP used in the experiments according to the test report.

The sizes of the masonry walls and different strengthening methods chosen for the tests are showed in Figs. 1~3 (The measurements in Figs. 1~3 are all given in mm). In the first strengthening method, the CFRPs are glued vertically onto the masonry wall as shown in Fig. 2. In the second strengthening method, some CFRPs are arranged at 45° and 135° with the horizontal line respectively. Therefore, the CFRPs are intersecting perpendicularly as shown in Fig. 3. In order to conduct the experiments expediently, the masonry walls are fixed upon concrete beams with mortar in advance as shown in Figs. 2 and 3. The grade of the concrete is C25. The properties of the CFRPs are listed in Table 1.

2.2 Load controlling system

According to The Chinese specifications (JGJ101-96) of experimental methods for measuring the capacity of anti-earthquake, the constant amplitude load in vertical direction is applied through two jacks on the top of the wall to simulate gravity loads. The vertical load acted by each of the jack is about 115 kN. Then the total vertical load is about 230 kN. The corresponding stress caused by the vertical loads is denoted as σ_0. So the stress is obtained by dividing the load by the cross-sectional area (1500 mm × 240 mm) of the masonry wall and its value is approximate to be 0.64 MPa. This value is about the same as that of the ground floor supporting walls in masonry residential buildings

(a) The picture of the experimental equipment



(b) The pattern of lateral load

Fig. 4 The system used for applying forces to the masonry wall

with 5-6 stories in China. The lateral loads are applied step by step. The load-controlling method is applied before the first crack appears inside the masonry and the displacement-controlling method is applied after the stage in which the first crack appears inside the masonry. The pattern of the lateral load is shown in Fig. 4(b), in which a positive value of the load means pushing the wall and a negative value means pulling the wall. In the elastic stage, the load-controlling method is applied. The first load step is set to be 20 kN and when the plastic deformation initiates in the masonry wall, the load step is changed to be 10 kN in every two cycle. After the first crack initiates in the masonry, the displacement-controlling method is applied. The first displacement step can be $1\Delta_{cr}$ (Δ_{cr} represents the critical displacement which is defined as the lateral displacement of the masonry wall when the first crack initiates) in every cycle until the lateral load reaches its critical value. Thereafter, the displacement step is changed to be $1\Delta_{cr}$ in every two cycle until the masonry wall fails. In the experimental tests, two hydraulic jacks are used for applying vertical loads to the masonry walls. There are also two rollers between the two steel beams as seen in Fig. 4. The two rollers are used to keep the vertical loads in constant amplitude and also to guarantee that the lateral displacement of the masonry walls is not affected by the vertical loads. The lateral cyclic loads acting on the top side face of the masonry walls are applied by the hydraulic controlling equipment. In Fig. 4, it can be seen that some strain gauges are placed on CFRPs in order to measure the strains of the CFRPs. By measuring and monitoring the strains, the variation and distribution of the stress in the CFRPs can be analyzed, the critical positions of the masonry wall where cracks will initiate can be determined, and the crack's development and distribution can be monitored as well. Since the strengthening function of CFRPs in improving the behavior of masonry walls comes true by restraining the cracks development in the walls, the strain measurement can indicate the effectiveness of the CFRPs, furthermore decide which is the best strengthening method and the corresponding measures concerning different strengthening profile. Therefore, the optimum strengthening measures can be suggested for application. The LOAD-CONTROLLING SYSTEM is shown in Fig. 4.

2.3 Test results

In order to assess the strengthening efficiency, the experimental tests on the masonry wall without any strengthening technique and the masonry walls strengthened by the previously introduced two methods have been carried out. The curves of the hysteresis of the masonry walls in the tests are shown in Figs. 8(a)~8(c). The detailed experimental results are described next.

2.3.1 Original masonry wall (S0) without being strengthened by CFRPs

At the beginning of the test, the load-controlling method is applied and the lateral loads increase gradually. The lateral displacement of the masonry wall is relatively small for lateral load $P < 60$ kN. The deformation of the masonry wall is elastic and the load-displacement curve is approximately in a straight line. As the lateral loads increase in excess of 60 kN, plastic deformation initiates in the masonry wall. When the lateral load arrives to 80 kN, the first crack appears in the left bottom corner of the masonry wall.

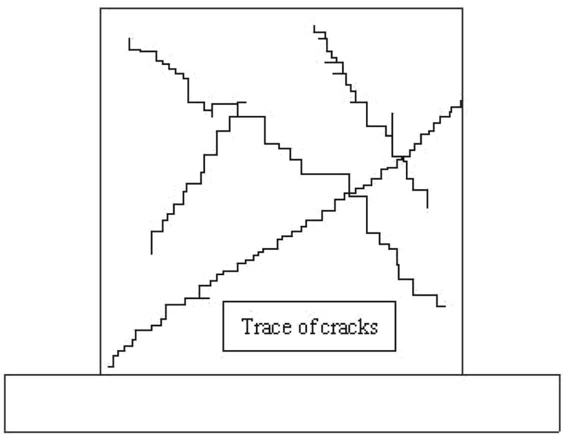


Fig. 5 The failure mode of the initial wall S0

After the first crack appears, the displacement-controlling method is used in the test. As the displacement of the masonry wall increases gradually, additional cracks develop and expand in time. When the lateral displacement of the masonry wall is about $5\Delta_{cr}$, many small cracks form to be run-through cracks. In this stage, the masonry wall is assumed to be in failure, and the maximum observed crack width is approximately 5 mm. The failure mode is seen from Fig. 5.

2.3.2 Masonry wall strengthened with CFRPs in the first method (S1)

In the early stage, the load-controlling method is applied and the lateral load increases gradually. The lateral displacement of the masonry wall is very small for lateral load less than 80 kN. The masonry wall behaves elastically indicated by the straight line load-displacement curve. As the lateral load increases in excess of 80 kN, plastic deformation initiates in the masonry wall. When the lateral load arrives to be 100 kN (P = 100 kN), cracking initiates and develops and the deformation of the masonry wall increases quickly. Then the first bending-crack appears between the masonry wall and the supporting concrete beam.

After the first crack appears, the displacement-controlling method is used in the test. As the displacement of the masonry wall increases, the deformation of the wall gradually turns into shearing deformation. Cracks are formed in the masonry wall along the diagonal direction and then the cracks develop and expand in time. When the lateral displacement of the masonry wall is about $9\Delta_{cr}$, many small cracks form to be run-through cracks. Finally, about 3~4 pieces of the CFRPs are broken and the masonry wall is assumed to be in failure. The maximum observed crack width is approximately 2 mm. The failure mode is seen from Fig. 6.

2.3.3 Masonry wall strengthened with CFRPs in the second method (S2)

In the initial stage, the load-controlling method is applied and the lateral load increases gradually. As for S1, the lateral displacement of the masonry wall is very small for load less than 80 kN. In this range the deformation of the masonry wall is linear elastic. From the readings of the strain gauge, it has been found that CFRPs play important role before crack appear. As the lateral load increases in excess of 80 kN, plastic deformation initiates in the wall. When the lateral load arrives to 115 kN, the deformation of the masonry wall increases apparently and a ringing sound is heard. The CFRP at the lower right corner of the masonry wall is tilted firstly and then the CFRPs anchored on the supporting concrete beam are broken. The first bending-crack appears in the lower right corner of the masonry wall.

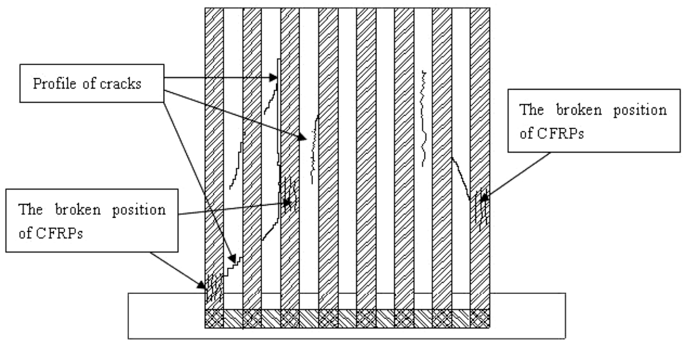
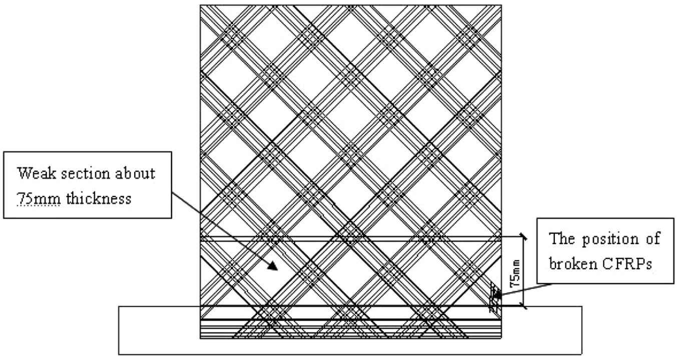
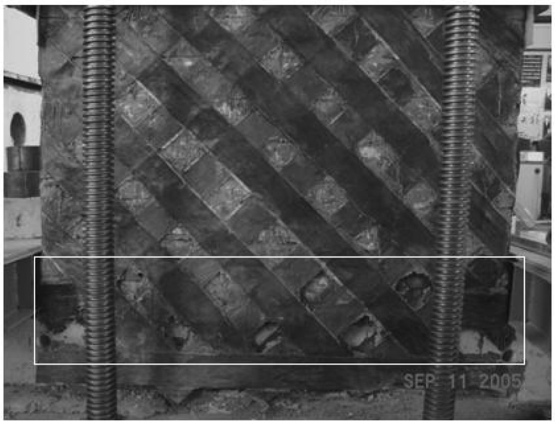


Fig. 6 The failure mode of the initial wall S1



(a) Weak section



(b) Close view of the weak section

Fig. 7 The failure mode of the initial wall S2

After the first crack appears, the displacement-controlling method is used in the test. As the displacement of the masonry wall increases gradually, cracks between the masonry wall and the supporting beam develop and expand continuously from two sides to the center. The clay bricks in the lower left and right corners of the masonry wall are crushed gradually leading to a weak field about 75 mm from the bottom of the masonry wall (See Figs. 7(a)~7(b)). When the lateral displacement of the masonry wall is about $5\Delta_{cr}$, the whole masonry wall has a vibrating movement by the mid-point at the bottom of the masonry wall. At this time, the masonry wall is defined to be in failure mode.

It has been found in the test that some CFRPs have clearly transverse slack. The phenomenon shows that the major tensile stress in the vertical direction of the CFRPs plays a certain role in giving rise to the transverse slack.

Through careful observation of the destroyed sections of the masonry walls strengthened with CFRP, it appears that most of the failure comes from the tearing bricks of the masonry walls or the tearing concrete of the supporting beams (See Fig. 7). The interfaces between the CFRPs and the masonry, the CFRPs and the concrete beam are still good. It indicates that the performance of the structural glue is good.

All the phenomena of the masonry walls tested are listed in Table 2.

Table 2 Test phenomenon

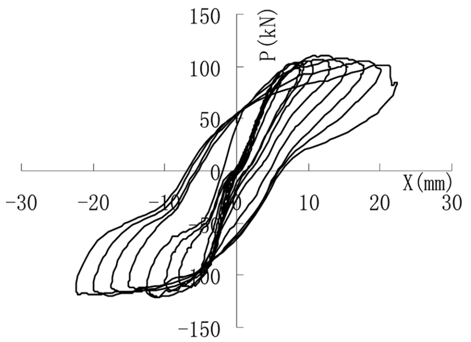
Test object	Elastic state	Elastic-plastic state		
		Before cracks open	From cracks opening to ultimate state	From ultimate state to final failure
	Load-controlling	Load-controlling	Displacement-controlling	Displacement-controlling
S0	P < 60 kN The lateral displacement of the masonry wall is very small.	60 kN < P < 80 kN There are obvious plastic deformation in the masonry wall.	80 kN < P < 105 kN The first crack appears in the lower left corner of the masonry wall when P_{cr} = 80 kN	P_u = 105 kN The biggest width of the cracks is 5 mm
S1	P < 80 kN The lateral displacement of the masonry wall is very small.	80 kN < P < 100 kN There are obvious plastic deformation in the masonry wall.	100 kN < P < 120 kN The first bending-crack appears between the masonry wall and the shoring beam when P_{cr} = 100 kN	P_u = 120 kN The biggest width of the cracks is 2 mm
S2	P < 80 kN The lateral displacement of the masonry wall is very small.	80 kN < P < 115 kN There are obvious plastic deformation in the masonry wall.	115 kN P < 165 kN The first bending-crack appears in the lower right corner of the masonry wall when P_{cr} = 115 kN	P_u = 165 kN There aren't some obvious cracks seen from the surface of the masonry wall.

NOTE: In the above table, P_u represents the ultimate load; P_{cr} represents the critical load, which means the critical lateral load when the first crack initiates in the masonry wall

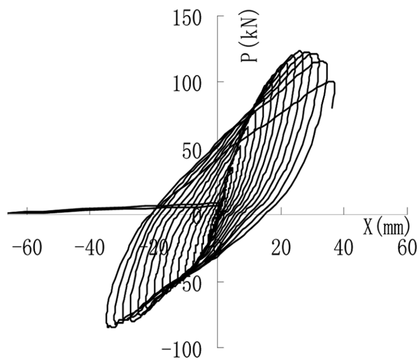
3. Analysis of masonry wall strengthened with CFRP

3.1 Experimental analysis

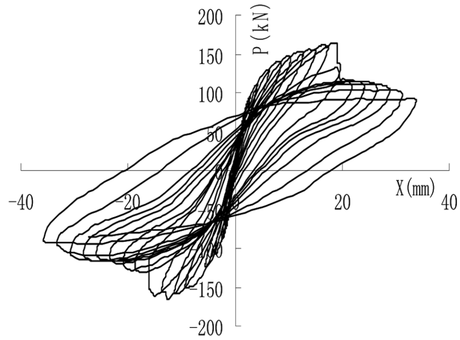
The characteristics of the structure can be derived from the hysteresis curves and the envelope of the hysteresis responses in Fig. 8 and Fig. 9. A more bulgy set of hysteresis curves, i.e. a large area enclosed by the force-displacement graph, indicates a structure with good response. The hysteresis curves (a), (b), (c) represent the performance of the original masonry wall without being strengthened by CFRPs, the strengthened masonry wall in the first method and the strengthened masonry wall respectively in the second method. In the three hysteresis curves, the hysteresis curves (b) and (c) are more bulgy than the hysteresis curve (a), and the areas of the hysteresis loops in the latter two hysteresis curves are larger than that in the hysteresis curve (a). The numerical data of the 1/4 areas of the envelope of the hysteresis responses curves are 785.5 kN·mm (Fig. 8(a)), 1241.8 kN·mm (Fig. 8(b)), 2187.0 kN·mm (Fig. 8(c)) respectively. This indicates that masonry walls strengthened with CFRP are of better capacity of carrying lateral loads and better ductility than the original masonry wall without being strengthened. The reasons can be found through careful analysis. CFRP plays a similar role as the tensile members in a truss in the whole process of the test. The tension in CFRP prevents cracks from developing and improves the mechanical performance of the masonry. As a result, the cooperation between the CFRP and the masonry produces a composite, which has a higher load carrying capacity than masonry itself. In the process



(a) The hysteresis curve of the original masonry wall without being strengthened by CFRPs (S0)



(b) The hysteresis curve of the strengthened masonry wall in the first method (S1)



(c) The hysteresis curve of the strengthened masonry wall in the second method (S2)

Fig. 8 Hysteresis curves

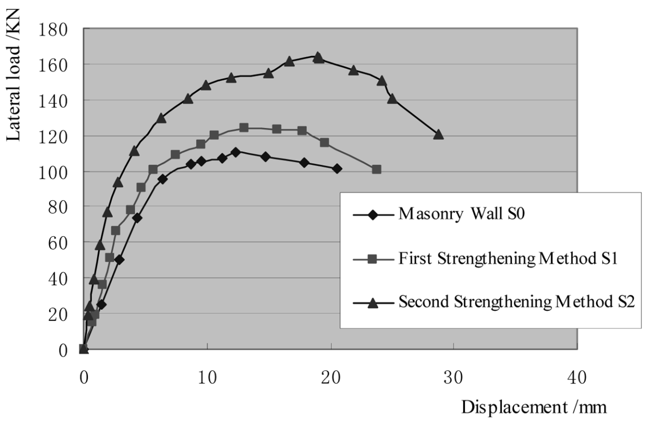


Fig. 9 The envelope of the hysteresis response curves

of load application, the existence of the CFRP makes the hysteresis curves more bulgy and increases the area of the hysteresis loop. In other words, CFRP improves the ductility and the

Table 3 Test results for masonry walls with and without being strengthened by CFRPs

Test object	Critical load		Critical displacement		Ultimate load		Ultimate displacement		Ductile coefficient	
	Test result (kN)	Improvement (%)	Test result (mm)	Improvement (%)	Test result (kN)	Improvement (%)	Test result (mm)	Improvement (%)	Test result	Improvement (%)
S0	80	----	4.35	----	105	----	20	----	4.59	----
S1	100	25%	4.98	14%	120	14.3%	25	25%	5.02	9.4%
S2	115	44%	4.63	6%	165	57.1%	30	50%	6.48	41.2%

Note: The ductile coefficients are calculated by the ratio of the ultimate displacement to the critical displacement

capacity of resisting the deformation of masonry structure. Furthermore, the fact that the dropping section of the envelope of the hysteresis responses becomes smoother indicates that the resistance to earthquakes of the whole masonry walls is improved by CFRP.

According to the experimental tests, both the masonry walls S0 and S1 lose the capacity of sustaining loads in the end due to the shearing failure. Furthermore, the wall S1 fails with many of the CFRPs broken finally. In contrast, the bending failure leads to the final failure of the masonry wall S2. Under the combined axial and bending effect ($\sigma = N/A \pm M/W$), the CFRPs glued in the lower left and right corners of the masonry wall is tilted and peeled off firstly, then, the CFRPs anchored on the supporting concrete beam are broken, and finally, the clay bricks in the lower left and right corners of the masonry wall are crushed gradually leading to a weak layer about 75 mm in the bottom of the masonry wall. At this stage, the deformation of the masonry wall increases visibly until the wall fails finally.

Based on the results tabulated in Table 3, the masonry walls strengthened with CFRPs have improved shear capacity compared with the original masonry wall without any strengthening measures. Besides, the ductility coefficient of the masonry walls strengthened with CFRPS is also improved greatly.

3.2 Theoretical analysis

3.2.1 Original masonry wall (S0) without being strengthened with CFRPS

Masonry walls sustain the lateral shear loads caused by earthquakes and the vertical loads caused by gravity loads simultaneously. The confining pressure σ_0 improves shear resistance, as formulated in Coulomb-friction fashion and used to compute masonry wall resistance to earthquakes by to Chinese design code GB 50011-2001 as follows

$$f_{VE} = \zeta_N \cdot f_V = \sqrt{1 + \frac{\sigma_0}{f_V}} \cdot f_V \tag{1}$$

In Eq. (1), f_{VE} denotes the strength of the masonry of resisting the lateral shear strength caused by earthquakes; ζ_N is an coefficient measured by compressive stress; f_V is the design value of the shear strength of masonry without any strengthening measures; σ_0 is the average compressive stress at the cross sections of the masonry caused by gravity load.

3.2.2 Masonry wall strengthened with CFRPS in the first method

In the first strengthening method, the tensile axial resistance in the vertical CFRPs causes vertical compressive stress the masonry. Therefore, in order to calculate the resistance of masonry strengthened with CFRPs in this method to lateral shear caused by earthquakes, the term σ_{CFRP} should be included in Eq. (1) as follows

$$f_{VE} = \zeta_N \cdot f_V = \sqrt{1 + \frac{\sigma_0 + \sigma_{CFRP}}{f_V}} \cdot f_V \tag{2}$$

where

$$\sigma_{CFRP} = \frac{A_{CFRP} \cdot E\varepsilon}{b\ t} = \frac{A_{CFRP} \cdot \alpha \cdot f_{CFRP}}{b\ t} = \frac{2n \cdot A_{CFRP1} \cdot \alpha \cdot f_{CFRP}}{b\ t}$$

$$= \frac{2\dfrac{b}{s + b_f} \cdot A_{CFRP1} \cdot f_{CFRP}}{b\ t} = \frac{2\alpha \cdot f_{CFRP}}{t}\frac{A_{CFRP1}}{s + b_f} \tag{3}$$

In Eq. (2), b, t are the width and the thickness of the masonry wall respectively; b_f is the width of the CFRPs; s is the closest side distance between two adjacent pieces of CFRPs; A_{CFRP} is the cross section area of CFRPs with only one piece; f_{CFRP} is the tensile strength of CFRPs; α is a reduction coefficient ($0 < \alpha < 1$).

3.2.3 Masonry wall strengthened with CFRPs in the second method

In the second strengthening method, one part of the tensile stress ($\sigma_{CFRP(V)}$) acting in CFRPs causes vertical compressive stress in the masonry and the other part ($\sigma_{CFRP(L)}$) directly resists the lateral shear caused by earthquakes. Therefore, in order to calculate the resistance of masonry strengthened with CFRPs in this method to the lateral shear caused by earthquakes, two terms, $\sigma_{CFRP(V)}$ and $\sigma_{CFRP(L)}$, should be added to Eq. (1) as follows

$$f_{VE} = \zeta_N \cdot f_V + \sigma_{CFRP(L)} = \sqrt{1 + \frac{\sigma_0 + \sigma_{CFRP(V)}}{f_V}} \cdot f_V + \sigma_{CFRP(L)} \tag{4}$$

In Eq. (4), $\sigma_{CFRP(V)}$ and $\sigma_{CFRP(L)}$ are the vertical component and the lateral component of the tensile stress sustained by CFRPs, the relationship between the two terms is defined as follows

$$\sigma_{CFRP(L)} = \sigma_{CFRP(V)} = \sigma_{CFRP}\cos 45^\circ = \frac{A_{CFRP} \cdot \alpha \cdot f_{CFRP}}{b\ t} = \frac{2n \cdot A_{CFRP1} \cdot \alpha \cdot f_{CFRP}}{b\ t}$$

$$= \frac{2\dfrac{\sqrt{b^2 + h^2}}{s + b_f} A_{CFRP1} \cdot \alpha \cdot f_{CFRP}}{b\ t} = \frac{2\sqrt{b^2 + h^2}\alpha \cdot f_{CFRP}}{b\ t} = \frac{A_{CFRP1}}{s + b_f} \tag{5}$$

It should be noted that it is necessary to consider many factors in order to determine the value of α, such as the mutual action between the CFRPs and the masonry, the effect of the anchorage measures, the performance of the structural glue, the masonry resistance to the lateral shear caused by earthquakes, and the techniques of construction, the transverse slack of the CFRPs, etc. In this study, the value of α is taken according to the average strain of the CFRPs. In the first method, when the lateral load reaches the limit, the strain measurement of CFRPs is $\varepsilon_{CFRP} \approx 3500\mu\varepsilon$. The

Table 4 Experimental and theoretical strengths of the masonry to overcome the lateral shear strength caused by earthquakes

Test object	Experimental result $f_{VE}^{/}$/(MPa)	Calculation result f_{VE}/(MPa)	The relative error $\gamma = \frac{\lvert f_{VE}^{/} - f_{VE}\rvert}{f_{VE}^{/}}$
S0	0.291	0.241	17%
S1	0.333	0.291	12%
S2	0.458	0.527	15%

Note: The experimental results are calculated by the ratio of the ultimate loads in Table 3 to the cross section areas of the masonry walls (1500 mm × 240 mm), while the calculation results are calculated with the equations proposed in the paper.

design elastic modulus and tensile strength are 2.1×10^5 MPa and 3000 MPa respectively, therefore, the reduction coefficient α can be calculated, and the value is 0.24. For the second method, the strain measurement of CFRPs is $\varepsilon_{CFRP} \approx 3000\mu\varepsilon$ at the limit lateral load state, so the α is merely 0.21.

As seen from Table 4, the theoretical results of the masonry walls S0, S1, S2 are in good accordance with the test results. According to the test results, the failure of the masonry walls S0 and S1 are in shear, compared with the bending failure of masonry S2. Therefore, the resistance of masonry wall S2 is reduced. It may be concluded that the amount of CFRPs used in the test is too large because when the masonry wall fails, the failure sections initiate at the masonry and not in the CFRPs. In the wall plane, the rigidity is relatively large and generally there are not noticeable cracks except for some parts of the masonry wall peeled off at the bottom. Besides, the strain value of the CFRPs is less than the calculated result. Finally, the whole masonry wall under the mutual action of the vertical load and the lateral loads makes rigid vibrating movement by the mid-point of the masonry wall at the bottom and the wall fails suddenly. Due to the above stated reasons, in the test, the masonry wall strengthened in the second method does not increase its capacity of carrying lateral loads most efficiently. Therefore, more tests should be conducted in the future to improve the strengthening efficiency of masonry strengthened with CFRPs in the second method.

Next, some Equations about the relationship of f_{VE} (The strength of masonry strengthened with CFRPs to overcome the lateral shear strength caused by earthquakes) and $A_{CFRP1}/s + b_f$ are presented. They can give engineers and designers some valuable references for design purpose. As for the best value of $s + b_f$, it is necessary to do additional experiments. According to the results in the test results, $s + b_f = 200$ mm is assumed in the first strengthening method and $s + b_f = 400$ mm is assumed in the second strengthening method ($b_f = 100$ mm is the width of the CFRPs). Although the lateral load carrying capacity and ductility of the masonry strengthened with CFRPs are improved obviously, the strain value of the CFRPs is less than the expectation. In other words, CFRPs do not exert all their potential. Many other factors are necessary to be considered in order to determine the best value of $s + b_f$.

4. Conclusions

In this study, a young strengthening technique, namely CFRP strengthening technique, has been used to strengthen masonry structures. In the tests, three pieces of masonry walls subjected to cyclic loads with low frequency and vertical load of constant amplitude have been tested. A simplified calculation approach has been introduced based on the experimental test results, and the theoretical results agree reasonably well with the experimental results. According to the test results, CFRPs play an important role in improving the critical load, the ultimate load, the ultimate displacement and the ductility coefficient of the masonry. Therefore, masonry walls strengthened with CFRPs have good ductility and good capacity of carrying lateral load. It is recommended that careful measures should be taken to stick CFRPs at the bottom of masonry to improve the strengthening efficiency. Finally, because of the limited number of masonry walls strengthened with CFRP in the tests, there may be some other factors affecting the calculation equations of the results in the tests. More experimental tests should be conducted in the future in order to allow derivation of more accurate relationships between the various factors and thus to apply CFRP to masonry structures more widely.

References

Albert, M.L., Elwi, A.E. and Cheng, J.J.R. (2001), "Strengthening of unreinforced masonry walls using FRPs", *J. Compos. Constr.*, **5**(2), 76-84.

Amir, M.M. and Hamid, S.M. (1998), "Ultimate shear capacity of reinforced concrete beams strengthened with web bonded fiber reinforced plastic plates", *ACI Struct. J.,* 391-399.

Ehsani, M.R. (1995), "Strengthening of earthquake damaged masonry structures with composite materials", *Non-metalllic (FRP) Reinforcement Concrete Struct.* RILEM. 680-687.

Ehsani, M.R. and Saadatm, A.H. (1997), "AL-Saidy A. Shear behavior of URM retrofitted with FRP overlays", *J. Compos. Constr.,* **1**(1), 17-25.

Ghobarah, A. and Galal, K.E.M. (2004), "Out-of plane strengthening of unreinforced masonry walls with opening", *J. Compos. Constr.,* **8**(4), 298-305.

Gilstrap, J.M. and Dolan, C.W. (1998), "Out of plane bending of FRP reinforced masonry walls", *Compos. Sci. Technol.*, **58**(8), 1277-1284.

Hall, J.D., Schuman, P.M. and Hamilton, H.R. (2002), "Ductile anchorage for connecting FPR strengthening of under-reinforced masonry buildings", *J. Compos. Constr.*, **6**(1), 2097-2112.

Hamilton, H.R., Holberg, A. and Caspersen, J. (1999), "Strengthening concrete masonry with fiber reinforced polymers", *Fourth International Symposium on Fiber Reinforced Polymers*. Baltimore, Maryland. 1103-1115.

Kiss, R.M. and Kollar, L.P. (2002), "Masonry strengthened with FRP subjected to combined bending and compression, Part II-tests and model predictions", *J. Compos. Mater.*, **36**(9), 1049-1063.

Schwegler, G. (1995), "Masonry construction strengthened with fiber composite in seismically endangered zones", *Proc. of the Tenth European Conf. on Earthquake Engineering*. Rotterdam, Netherlands, 2299-2303.

Schwegler, G. (2000), "Maintenance and restrengthening of materials and structures", *Brick and Brickwork*, Aedificatio Publishers (edt Wittmann FH), Freiburg, 105-110.

Seible, F. (1995), "Repair and seismic retest of a full-scale reinforced masonry research building", *Proc. of the 6th Int. Conf. on Structural Faults and Repair,* **3**, 229-236.

Seible, F. and Hegemier, N. (1990), "Priestley G. Preliminary results from the TCCMAR 5-story full-scale reinforced masonry research building test", *The Masonry Soc. J.,* **12**(1), 53-60.

Thanasis, C.T. (1998), "Shear strengthening of reinforced concrete beams using epoxy bonded FRP composites", *ACI Struct. J.*, 107-115.

Triantafillou, T.C. (1998), "Strengthening of masonry structures using epoxy-bonded FRP laminates", *J. Compos. Constr.,* **2**(2), 96-103.

Triantafillou, T.C. (1998), "Strengthening of masonry structures using epoxy-bonded FRP laminates", *J. Compos. Constr.,* **2**(2), 96-103.

Tumialan, G., Galati, N. and Nanni, A. (2003), “FRP strengthening of URM walls subject to out-of-plane loads”, *ACI Struct. J.*, **100**(3), 321-329.

Van Zijl, G.P.A.G. and De Vries, P.A. (2005), “Masonry wall crack control with carbon fiber reinforced polymer”, *J. Compos. Constr.,* **12**(1), 84-89.