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# PERFORMANCE EVALUATION OF MASONRY SHEAR WALLS STRENGTHENING BY TWO DIFFERENT FRPs

M.A. RAHMAN<sup>1\*</sup> and T. UEDA<sup>2</sup>

<sup>1</sup>*JSPS RONPAKU Fellow, Department of Civil Engineering, KUET, Bangladesh*

<sup>2</sup>*Graduate School of Engineering, Hokkaido University, Japan*

## ABSTRACT

This paper investigates strengthening masonry shear walls using two types fiber reinforced polymer (FRP) sheets. An experimental research program is undertaken. Masonry wall made from wire-cut clay brick specimens are tested strengthening by PET (Polyethylene Terephthalate) and CFRP (Carbon fiber reinforced polymer) sheets. Strengthening is considered on both side of the wall to ensure uniformity and symmetrical stiffness of the wall. Static tests are carried out on seven masonry panels, under a combination of vertical preloading, and in-plane horizontal shear loading. The mechanisms by which load was carried were observed, varying from the initial, uncracked state, to the final, fully cracked state. The results demonstrate that a significant increase of the in-plane shear capacity of masonry can be achieved by bonding with PET and CFRP sheets to the surface of masonry walls. The experimental data were used to assess the effectiveness of the strengthening of one FRP over the other and also the percent of gross area covered by the FRP sheets. Subsequently suggestions are made to allow the test results to be a reasonable source of guideline in the design of strengthening for masonry structures.

**Keywords:** Brick; Masonry; Shear wall; FRP sheets; Static Shear tests.

## 1. INTRODUCTION

Externally bonded Polyethylene Terephthalate (PET) fiber with a large fracture strain is one of the retrofitting technique that has drawn a significant attention as an unique alternative to CFRP or GFRP due to its pronounced ductile behavior and relatively low material cost (Figure 1), but not compromising the other advantages of FRP like low weight-strength ratio, short installation period and a minimum intervention during the fabrication process. The main objective of using FRPs is to enhance performance of structure at normal loading condition and to offer greater resistance at the time of severe loading. Neither too much stiffness nor the very high strength will be coherent with the overall performance of the masonry structures. Material with high stiffness will produce very little deformation before complete failure and the failure if any will be brittle and explosive in nature without any prior warning, which is not the expected failure mode from a well performed

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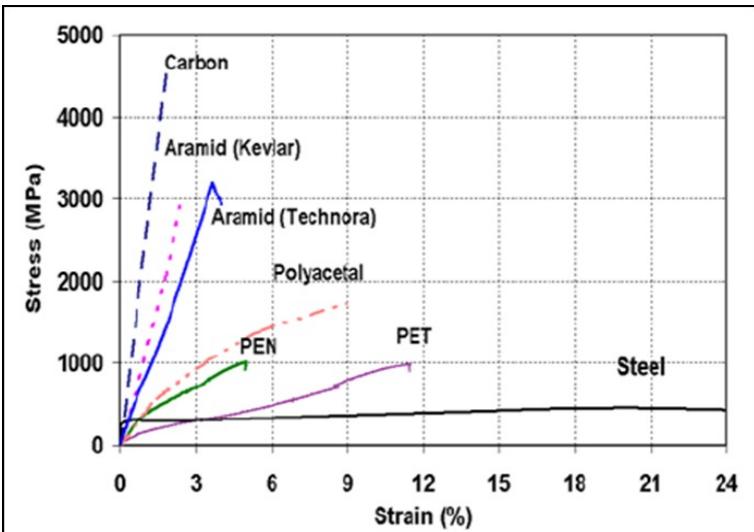
\* Corresponding and presenting author: Email: ataur107@yahoo.com

structure. On the other hand too soft material with nominal strength will not be well fitted with the purpose of strengthening. A variety of approaches has previously been undertaken to investigate masonry strengthened with FRPs. Masonry wall strengthening by GFRP (Stratford et al. 2004) shows quite ductile behavior prior to failure and a significant increase of shear load capacity (65%) where as the failure was primarily for the debonding of the GFRP sheet. Another technique of strengthening is done by mounting the FRP rod inside the horizontal mortar joint and is embedded near the surface as shown in Figure 2a. (Tinazzi et al.2000; Tumialan et al. 2001). Alternative to this system is to attach the FRP strips over the surface of the wall in a diagonal fashion (Schwegler 1994). The FRP strip act as a truss made from unidirectional fibers (Figure 2b).

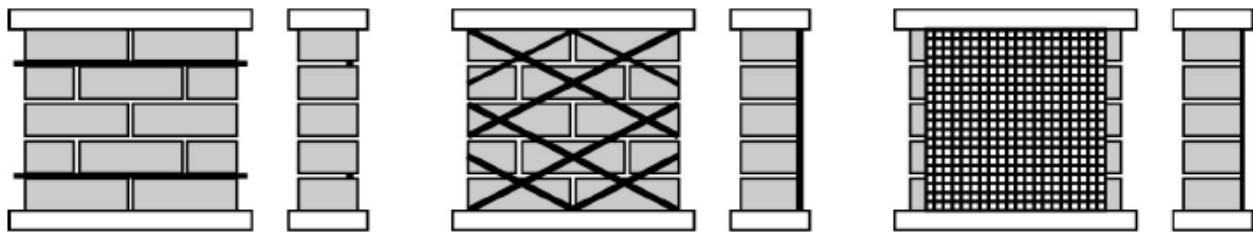
In this study, PET and CFRP have been used as strengthening materials. CFRP has a high stiffness among the other widely used FRPs, whereas PET posses a relatively low stiffness but with a higher fracturing strain than CFRP. The purpose of this study is to show the difference in behavior of masonry shear wall for two distinct FRPs. Ultimate load bearing capacity, deformation at peak load, mode of failures, are observed in this study for different arrangement of the FRPs.

## 2. EXPERIMENTAL PROGRAM

Different loading schemes for testing of masonry shear wall can be found elsewhere in the literatures. TNO 2004 has made an inventory of different test methods with different loading and boundary conditions. In this experimental study, a total of 7 walls having a nominal dimension of  $1200 \times 1000 \times 120$  mm were constructed to test for shear. All of the walls were fabricated with single layer stretcher bond of bricks having a dimension of  $240 \times 120 \times 66$  mm with a compressive strength



**Figure 1: Tensile strength of different FRPs**



(a) Near surface mounted FRP bars   (b) Strip FRP in diagonal fashion   (c) Sheet FRP over the wall

**Figure 2: Different techniques of FRP installation on masonry wall**

of 17 MPa. A 10 mm thick mortar with a compressive strength of 12 MPa were used throughout. Table 1 gives the detail of the walls. In this table RW stands for reference wall, PW for wall strengthening with PET sheet and CW for wall strengthening with CFRP sheet.

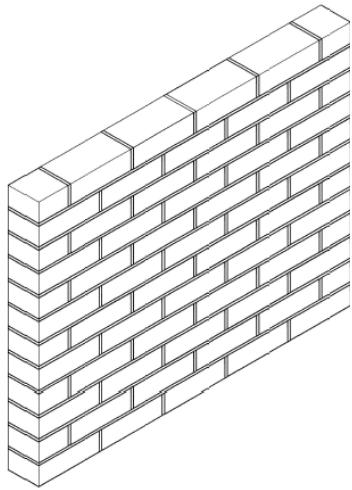
**Table 1: Detail of masonry specimen with different FRP orientations**

| Wall Designation | Properties                                   |  |   |                 |          |      |                 |              |
|------------------|--|--|---|-----------------|----------|------|-----------------|--------------|
|                  | Vertical compression<br>f <sub>v</sub> (MPa) | Brick strength,<br>f <sub>c</sub> <sup>b</sup> (MPa) | Mortar strength,<br>f <sub>c</sub> <sup>m</sup> (MPa) | Area Covered by |          | L/H  | FRP orientation | Peak load kN |
|                  |  |  |   | PET(%)          | CFRP (%) |      |                 |              |
| RW2              | 0.25   | 17   | 12  | —               | —        | 1.25 | --              | 30.0         |
| PW1              | 0.25   | 17   | 12  | 100             | —        | 1.25 | all over        | 168.0        |
| PW2              | 0.25   | 17   | 12  | 40              | —        | 1.25 | checkered       | 90.0         |
| PW3              | 0.25   | 17   | 12  | 20              | —        | 1.25 | diagonal        | 62.0         |
| CW1              | 0.25   | 17   | 12  | —               | 100      | 1.25 | all over        | 107.0        |
| CW2              | 0.25   | 17   | 12  | —               | 40       | 1.25 | checkered       | 99.0         |
| CW3              | 0.25   | 17   | 12  | —               | 20       | 1.25 | diagonal        | 94.0         |

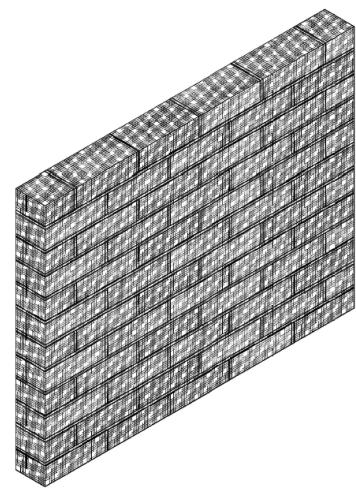
## 2.1 Specimen preparation

PET and CFRP sheet both having unidirectional fiber was applied on wall specimens in three different fashions as shown in Figure 3. The FRPs were applied in wet layup procedure as follows:

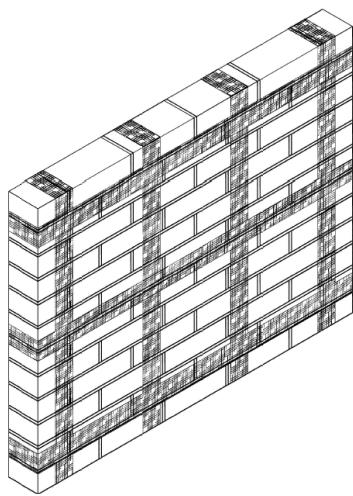
- The wall specimens were cleaned from loose mortar and dirt with the help of a wire brush. Epoxy putty (filler) was used to fill the depression onto the wall that offered a smooth and plane surface ready for FRP laying.
- A thin layer of primer was then applied all over the wall to seal pores in the masonry so that the subsequent application of epoxy resin was not absorbed.
- Epoxy resin having the properties mentioned in Table 2 was then applied over the wall where it was necessary. FRP sheets were cut in accordance with the length needed for the walls to cover the 100%, 40% and 20% of the wall gross area (see Fig. 3). Resin was then applied with the help of a roller brush all over the FRP strip so that it was fully saturated by the resin. As soon as the application of the resin was completed, the FRP strips were laid over the wall and wrapped tightly to keep them in place.
- For diagonal strip, the wall corners were cut in same dimension of the width of the strip to avoid sharp edges and problem in wrapping.



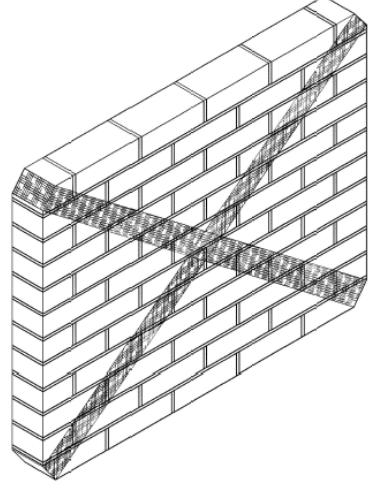
(a) Control wall(RW2)



(b) 100% area covered by FRP (CW1, PW1)



(c) 40% area covered by FRP (CW2, PW2)



(d) 20% area covered by FRP (CW3, PW3)

**Figure3: Wrapping technique of masonry wall by FRP**

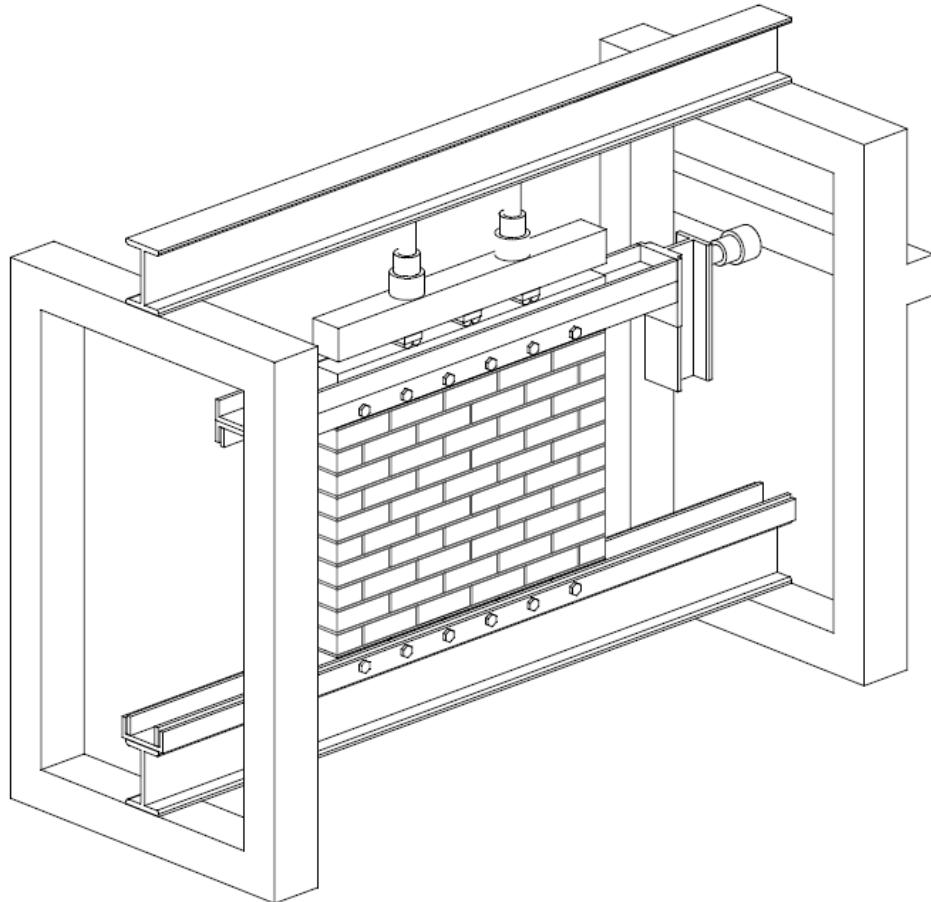
**Table 2: properties of FRPs and resin**

| FRP properties    | PET 600 | CFRP  | Properties                   | RESIN | PUTTY |
|-------------------|---------|-------|------------------------------|-------|-------|
| Fracture Strength | 740     | 3400  | Compressive strength, MPa    | 85    | -     |
| Elastic Modulus   | 10±1    | 245   | Flexural strength, MPa       | 65    | -     |
| Elongation (%)    | 10±1    | 1.5   | Tensile strength, MPa        | 45    | 20.0  |
| Thickness (mm)    | 0.841   | 0.111 | Compressive modulus, MPa     | 2500  | -     |
| *Width (mm)       | 300     | 250   | Tensile modulus, MPa         | 1560  | -     |
|                   |         |       | Elongation after fracture, % | 28%   | -     |

## 2.2 Test setup

After the required curing period, the wall was transferred to the testing frame. The wall top and bottom were anchored with the top and bottom channel beams with the help of six 22 mm bolts as shown in Figure 4. In between wall and the side of the channel beam, a steel plate of 16mm thick was inserted so that the plate creates tremendous pressure on the wall through the tightening of the bolts. Paris plaster was also used to offer a flat surface between wall and steel plate.

A pre-compression of 40 kN which was equivalent to uniform pressure of 0.25MPa was applied on the top of the wall through two hydraulic jacks, ahead of the shear loading to simulate the load of structural component coming on the wall from the above in the real world. Sufficient wire strain gages (KYOWA-5) and LVDTs were used to record all the necessary information during the course of testing. Loads were applied on roller and ball-bearing system to avoid any excessive friction and deviation of loading points. The lateral load was then applied with the help of a hydraulic jack having a capacity of 50 tons. Remote pump was used to increase the lateral load gradually until complete failure of the masonry wall was ensured. All of the data (displacement, strain, load) were accumulated through a digital data logger.



**Figure 4:** Experimental setup for a typical shear wall

### 3. TEST RESULTS & DISCUSSION

The entire shear wall specimens were tested consecutively one after another. Static lateral load was applied gradually and increased at a constant rate of 10kN/min until failure occurred. Application of load was paused intermittently to observe the crack and damage if any, on the wall.

#### 3.1. Load deflection response

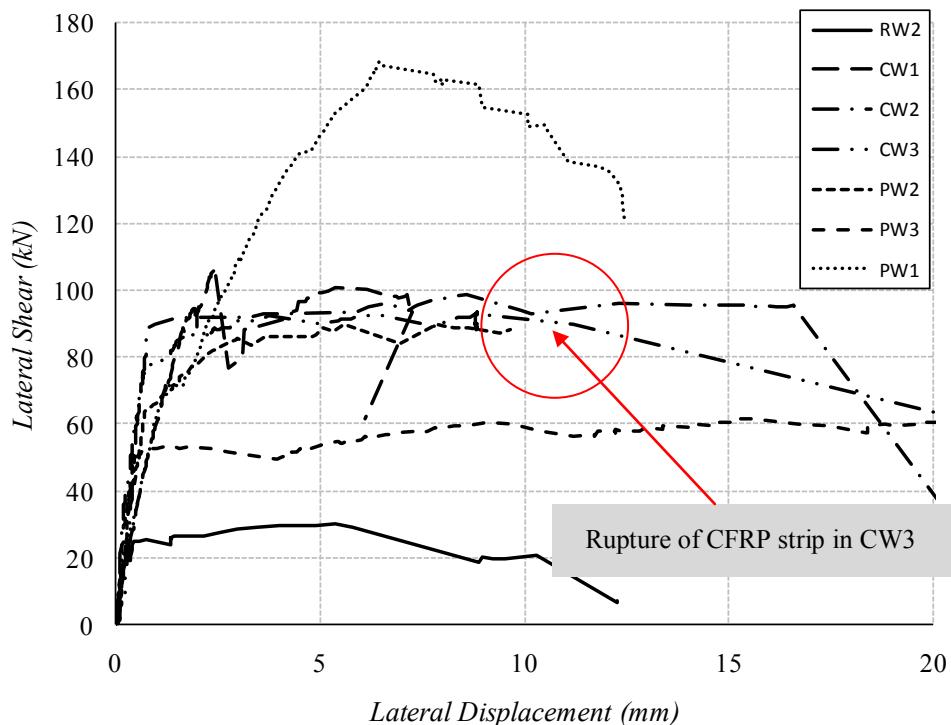
The load deflection relationship for all of the seven shear walls are given in Figure 5. The evolution of damage and critical observation with loading process for each of the walls is given in the following sections.

##### 3.1.1. Reference wall (RW2)

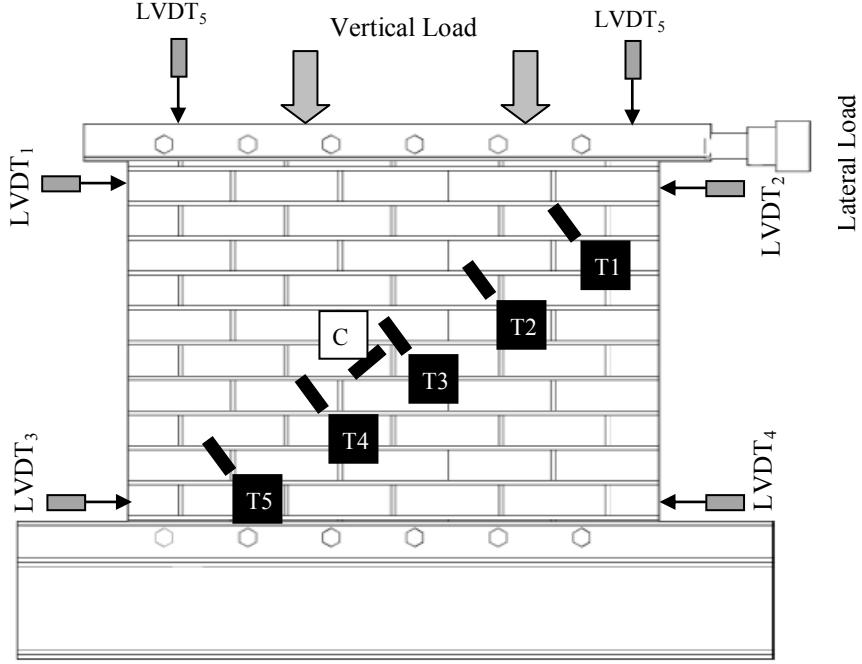
The reference wall was tested as per the test setup shown in figure 6. Six LVDTs are installed at various locations that measure the deflections at that particular location and direction. Variation of diagonal tensile strain along the compression diagonal were measured by five mechanical strain gages orthogonally set along the compression diagonal in equal intervals. One strain is attached in parallel of compression diagonal to measure the compressive strain at the center of the wall.

##### 3.1.2. Observation of Crack

Initially no crack was observed anywhere on the wall. When the load reach about 23kN, a horizontal crack appeared on the wall heel (loading side) at about one third of the height of the wall, the load dropped to 19 kN as a consequence. With the increase of load, the crack further propagated almost halfway of the length of the wall and there after took a turn to downside in a stepped fashion



**Figure 5: Load Vs deflection envelop of shear wall specimens**



**Figure 6: Experimental setup for RW2**

and travelled all the way to the wall heel (Figure 7a). During this evolution of crack no significant degradation of load was observed, rather it increased in a steady state and go to a peak of about 30kN. During this loading process the crack only widened and a wall move slightly to out of plane due to crack opening and separation on wall heel. A faster crushing (Figure 7b) on the wall toe caused a rapid decreased in load.

### 3.3.2 Failure of reinforced masonry

The load-deflection response for the entire shear walls strengthening by PET and CFRP are given in Figure 5. Among them CW3 and PW3 were reinforced by CFRP and PET respectively in diagonal fashion (Figure 2d). These walls were wrapped by CFRP and PET strips having a width of 80 mm from both sides of the wall that covers approximately 20% of the wall area. To facilitate FRP wrapping, the corner of the wall is chamfered as the same width of the FRP strips. Only two strain gages are attached on the wall. One was along the tension diagonal strip and the other one was along the compression diagonal.

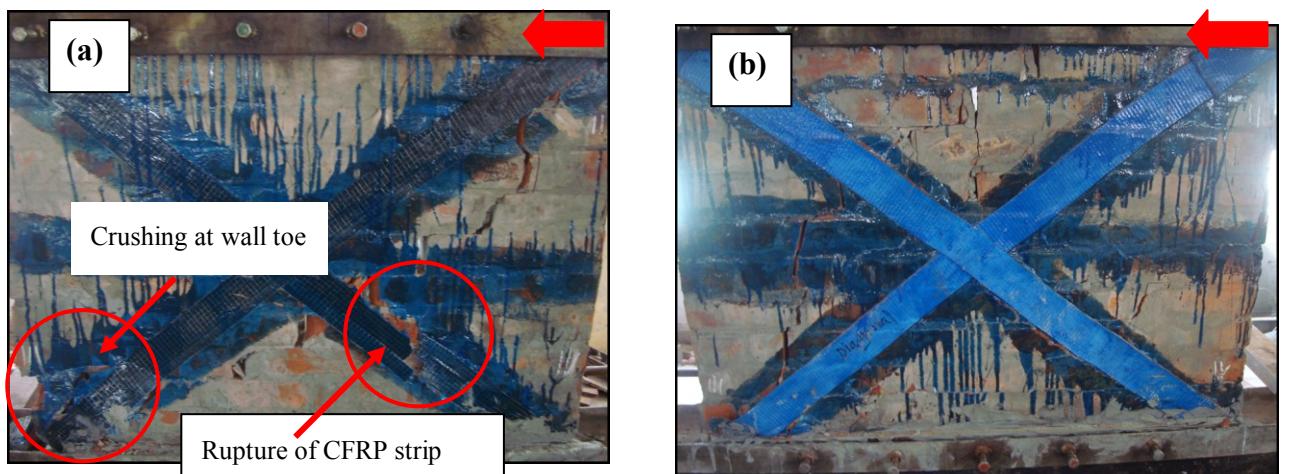
**Failure of CW3:** It is interesting to note that initially the stiffness of the wall was quite high due to the very high stiffness of CFRP strip and that remained unchanged up to 75% of the peak load. At this point some fine line cracks appeared at the top of the wall on loading side and start to propagate downward in a stepped fashion. The crack could not travel further and was arrested at the mid height of the wall by the diagonal tension strip of CFRP. Once the load increased to the maximum, a sudden rupture of the diagonal tension strip of the both sides of the wall happened and the load suddenly dropped to 50% of the peak load. At that time the crack became wider and the crack opening increased remarkably (Fig. 8a). On the other hand, a gradually increased compression stress caused a pilling of the bricks near the wall toe long before the rupture of the CFRP strip.



**Figure 7: a) Crack opening displacement and b) crushing at wall toe for RW2**

Accumulated compressive stress caused a complete failure at wall toe just before the rupture of the CFRP strip which can be seen clearly in Fig. 8a. Debonding of CFRP strip from wall could also be seen at some places specially along the tension diagonal on both sides of the wall.

**Failure of PW3:** The initial stiffness was quite similar to that of CW3 and remains almost same to attain a load of 50kN. During that time some crack appeared at the mid height of the wall on loading side and propagate towards the bottom in a stepped fashion. Another crack appeared almost at the same time along the center line of the wall on the wall top. This crack also travels downward towards the wall toe with a stepped way. Both of these two cracks intercepted at tension diagonal strip of PET and temporarily arrested here to propagate further. At this stage the load climbed to a peak and remained same with the further deformation of the wall. With the applied displacement of the loading jack, the peak load did not change much but some phenomenological changes occurred at the wall. Debonding of the diagonal tension strip was seen at the upper half of the wall and that make it easy for the crack to travel further downward. (Figure 8b). A crushing in the wall toe can also be seen.



**Figure 8: a) Failure wall CW3 with rupture of CFRP strip and b) Failure of wall PW3**

**Failure of CW2:** This wall was strengthened by CFRP strip of 70 mm width in a cheakard fashion as shown in Figure 2c, which cover about 40% of the wall gross area. The initial stiffness was quite similar of that of CW3 and the nature of the curve was almost identical. A crack along the wall heel appeared at a load of 87kN. With the increase of displacement through the jack, the load increased a little but the crack opening widened further. After a little while another crack appeared at the mid height of the wall on the loading side (Figure 9a). The load did not increase further, after that and with increase displacement toe crushing happens and the load gradually felled to a minimum without the rupture of any CFRP strip.

**Failure of PW2:** The initial stiffness traced the same way of that of CW2 but at a load of 63 kN the stiffness reduced to some extent but the load still went up and at a load of 90 kN crack appeared at the mid height of the wall on loading side as can be seen in Figure 9b. After that stage the load did not increased but with the further displacement the wall suddenly slipped from the horizontal jack and the whole experimental process was terminated.

**Failure of CW1:** This shear wall was strengthened with 100% wrapping with CFRP. For this wall the load capacity is so high that the girp at the wall bottom prematurely fail before the wall atatin a peak a shown. The test of this wall might need to be repeated.

**Failure of PW1:** The initial stiffness was quite similar to that of CW1 but the ultimate load capacity is 65% more than that of CW1. Since the wall was fully wrapped by the PET sheet, any damage if any could hardly be detected by visual observation.



**Figure 9: a) Failure at wall CW2 and b) PW2**

#### 4. CONCLUSIONS & RECOMMENDATIONS

This experiment was carried out considering the following boundary conditions:

- a) The two vertical loads equal in magnitude were applied at the wall top prior of lateral load, but were difficult to kept constant during the loading process due to the rotation of the upper beam

on the wall. This rotational movement caused a pressure in the vertical jacks and thus increased the vertical pressure to some extent.

- b) Since the shear capacity of the masonry panel increases with the increase of vertical load following the Mohr-Coulomb failure criteria, the increased vertical pressure in this experiment definitely increased the lateral load to some unknown quantity but could not be verified explicitly. ASTM E 72-61 suggests the standard racking test, where the vertical load  $N$  cannot be controlled if the rotation of the beam is restrained. So, this experiment is aligned with some standard where the vertical load is not controlled. On the other hand if the vertical load is kept constant throughout the loading process, the rotation of the top beam must be allowed to rotate to obtain the equilibrium.
- c) The FRP was installed on the wall panel before the vertical load, whereas in reality the weight of the building above the wall exists as vertical pressure prior of the application of FRP.

Reinforcement of the masonry shear wall by both the PET and CFRP increases the shear capacity to a great extent for different FRP orientation. If the FRP is applied in diagonal fashion that covers only 20% of the panel area, the shear capacity increases twice for PET sheet and thrice for CFRP sheet as given in Table 1 and Figure 5. Whereas for the case of checkered fashion where the FRP covers 40% of panel area, the shear capacity increase about three times for both of the FRPs. When the panel is fully covered by FRPs, the capacity increases to a tremendous amount (five times for PET and 3.5 times for CFRP). Considering all of the cases, it can be concluded that PET offers more effective strengthening than CFRP sheet where strength is not the only considering criteria. The ductility of the panel is of great concern during earthquake and other natural disaster. PET offer greater ductility prior to failure than CFRP. When the cost of the material is also considered, PET is cheaper than the CFRP.

## 5. ACKNOWLEDGMENTS

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