Cyclic Behavior of CFRP as Diagonal Ties and Anchors to Rehabilitate Severe Damaged Masonry Wall

G Huaco$^1$ and J Jirsa$^2$

$^1$ Professor, Peruvian University of Applied Sciences UPC, Lima Peru
$^2$ Emeritus Professor, The University of Texas at Austin, USA
Email: pccighua@upc.edu.pe; jirsa@uts.cc.utexas.edu

Abstract. Seismic rehabilitation using Carbon Fiber Reinforcement Polymer CFRP is more often used worldwide. CFRP jacketing is the most common layout for columns and walls, however installing the CFRP sheet as diagonal ties increase shear capacity to walls instead of jacketing procedures, besides less CFRP materials is used reducing the cost to the retrofit work. It is know that CFRP sheets can be debonded from the concrete or masonry surface causing that the sheets will not develop its tensile capacity. Then CFRP anchors are introduced. It is presented the behavior of CFRP sheets as diagonal ties working even though sliding and CFRP anchors which attach the diagonal ties to concrete base and top of the masonry wall. The diagonal ties work at full tensile capacity even though the debonding and buckling presented under compression forces. CFRP anchors also provided a resistance capacity against sliding.

1. Introduction
Masonry walls are frequently damaged by natural disasters such as earthquakes. The pattern of damage commonly seen in walls is shear cracking and sliding between the wall foundation interfaces or between the courses of the wall. Sliding between courses occurs often when the masonry wall interface has no internal reinforcement. Retrofit using steel plates is effective increasing ductility however installation is difficult because bolt connections and welding [6], see Figure 1a. Therefore it is necessary to explore new procedures to rapid repair instead of replace a new wall. Carbon Fiber Reinforced Polymer CFRP sheet is used to provide tension capacity to structural members. However debonding avoids these sheets to develop their full tension capacity as Alcaino and Santa Maria reports at [2] as it can be seen in Figure 1b. Pampanin and Akgusel [3] improved the attachment installing CFRP U-patches as Figure 1c shows, however important drop of shear capacity of wall is presented because debonding of the CFRP materials.

Figure 1. Masonry wall with steel plates [1] (a) with CFRP diagonal ties with no anchor system [2] (b) and including CFRP patches with no anchorage at corners [3] (c)
Hence it is necessary to apply CFRP anchors to resist shear and pulling forces to assure that CFRP sheets develop their full tensile deformation if debonding is presented [4, 5]. The objective this article aims to study the effectiveness of the CFRP materials to improve both shear capacity and provide ductility to the masonry wall, in addition to reduce sliding at the top and bottom interfaces of the wall.

2. Rehabilitated Masonry Wall

A hollowed masonry wall was repaired after to receive severe damage such as sliding at the base, diagonal cracks and crushing of the toes at corners. The hollow concrete masonry units used to build the wall had normal dimensions 16x8x8in and 1.25in wall thickness. The compression resistance was 3.1ksi. The wall was reinforced internally with #4 bars Grade 60 spaced vertically at 8in through the hollow cores in the concrete blocks and grouted. Dowels were installed. One #4 horizontal bar was placed between each course of the wall.

CFRP sheets of 0.04in thickness were attached to the wall along the diagonals to produce a tension brace or tie, and, CFRP anchors were installed to at the ends of the sheets. Figure 2a shows the location of the concrete ring and the CFRP materials. Then this was subjected to constant axial load of 160kips also 16 hysteretic lateral cycles loads. Rotations at the top and bottom of the wall were restrained. Figure 2b shows the behavior of the repaired masonry wall. It is appreciated when occurs sliding and rupture of CFRP anchors. Details of test results are reported by Huaco & Jirsa [6].

![Figure 2](image)

(a) (b)

**Figure 2.** Repaired masonry wall with CFRP ties and anchors, unit in inches (a) Hysteretic cycle response of the masonry wall [6]

3. Behavior of CFRP Materials

3.1. Response of the Two 9in. wide layers of CFRP Diagonal Tie Sheets

CFRP sheets worked as axial tension brace when the masonry wall was loaded to the south. Debonding of the CFRP diagonal strips appeared at the 5th cycle. This was noticed by a noise heard, being this more clear on the 9th cycle and further. In the 11th hysteretic cycle the maximum strain was reached in tension, 0.23% and 0.36% for the front and back face of the wall respectively. The pattern of the strain deformation is shown in Figure 3a and Figure 3b. Compression strains reached 0.20% (20% of the maximum tensile strain capacity). This was measured on the lower strain gage applied on the CFRP diagonal strip. The strain deformation in compression was larger for the bottom part of the CFRP diagonal strip, indicating that there was a major concentration of stress at the bottom tie. It is observed that the strain gages near the bottom exhibited larger strain than the gages near the top. The CFRP tie buckled as is shown in Figure 4.
3.2. Response of the 12 in. wide CFRP Diagonal Tie Sheets

CFRP sheets worked as axial tension punctual brace when the masonry wall was loaded to the north. In the 7th hysteretic cycle, some noise was heard indicating the beginning of the debonding. The CFRP anchors transferred tension from the CFRP sheets to the top and bottom support of the wall. The maximum strain measured at CFRP sheet at front face was 0.52% which is slightly above 50% of the strain capacity of the CFRP according to the producer’s specification 1%. The maximum strain deformation measured on the CFRP sheet on the back face was 0.39%. Figure 1a and Figure 1b shows cycle behavior of the CFRP diagonal ties measured by strain gages.

Figure 3. (a) Strain deformation of the two 9in. layers CFRP sheet on west face of the masonry wall (b) Strain deformation of the two 9in. layers CFRP sheet on east face of the masonry wall.

Figure 4. Debonding and buckling of the CFRP tie of two 9in. layers

Figure 5. (a) Strain deformation of the one 12 in. layer CFRP sheet on front face of the masonry wall (b) Strain deformation of the one 12 in. layer CFRP sheet on back face of the masonry wall
Compressive strains in the CFRP strips were measured under loading to the south. The maximum strain in compression prior to buckling was 0.16%. However, when the buckling occurred CFRP on front face of the wall, the compressive strain was 0.27% as Figure 5a shows, and 0.14% on the back face of the wall as it can be seen in Figure 5b. It was observed also that the strain measured was longer on the bottom part of the diagonal ties, having concentration of compression stress on this region. The CFRP strip buckled as is shown in Figure 6.

Figure 6. Debonding of the CFRP tie of one 12in layer

3.3. Behavior of CFRP Anchors on Rehabilitated Masonry Wall

It was observed during the test that the CFRP anchor provided resistance against the sliding at top of wall. CFRP anchors provided to the rehabilitated wall a capacity against sliding. Figure 7a and Figure 7b shows the tensioned and broken CFRP anchors and the final sliding. The anchor worked until their full tension capacity previous the rupture. No evidence of pulling out was found.

Figure 7. Initial and final condition of the CFRP Anchors on top south corner presenting slip and rupture on front face (a) and back face of the retrofitted masonry wall (b)

Figure 8 shows a body diagram of the forces implied to the behavior of the CFRP anchors when the specimen was loading to north direction. There are two types of forces applied to the anchor: pulling loads due the tension load from the diagonal ties, and the sliding forces due the lateral load from the top concrete beam. Each of these forces is divided by the correspondent number of anchors. Using the parallel and perpendicular forces component respectively to the direction of the anchor, the CFRP anchor resists two types of load: pulling load (parallel to the anchor’s direction) and shear force (perpendicular to the anchor’s direction). It is not considered the dowel effect on the sliding. Then,
Equation 1 and Equation 2 show the developed formulas for the two types of forces applied in the CFRP anchor in base of the body diagram of forces for the north corner:

\[ F_{\text{tension tie/4}} + \left( \frac{F_{\text{sliding}}}{8} \right) \cos \alpha = \text{CFRP anchor Pulling Force} \]  
\[ \left( \frac{F_{\text{sliding}}}{8} \right) \sin \alpha = \text{CFRP anchor Shear Force} \]  

\[ F_{\text{sliding/8}} \cos \alpha = \text{CFRP anchor Pulling Force} \]  
\[ F_{\text{sliding/8}} \sin \alpha = \text{CFRP anchor Shear Force} \]

4. Conclusions

It is concluded that the CFRP anchors had a very important role for the resistance of the masonry wall against its sliding at top. Diagonal Ties also provided tension capacity to the retrofitted masonry wall. CFRP ties regions at the opposite site of the sliding presents larger tension deformation than near regions and they also buckled, therefore it is very important the use of the CFRP anchor to assure that CFRP ties take complete tension forces, besides when compression occurs allow buckled ties to recover tension capacity.

For optimal use of CFRP materials, it is very important that strict quality control be carried out in the application of the CFRP. Without high quality installation, the capacity of the CFRP is compromised and may not reach the capacity desired.

It is recommended to develop a laboratory test program to study the response of CFRP anchor under cycle loads for pulling, beside shear forces at diagonal direction of the anchor simulating the action shown on this research.

References

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