Strengthening of infilled RC frames by CFRP

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Abstract

A series of tests has been performed at I.T.U. Structural and Earthquake Engineering Laboratory, to examine the differences between the structural behaviour of infilled RC frames strengthened by CFRP fabric with different connection details.

Five identical ½ scale, one storey-one bay brittle brick infilled reinforced concrete frame specimens have been tested under cyclic lateral loads. The reinforced concrete bare frame and plastered brittle brick infilled RC frame are essentially reference specimens. Three other specimens have been strengthened using CFRP fabric with different connection details.

The comparative results including lateral load capacities, failure modes and energy dissipation are presented in this paper.

Keywords: infill wall, strengthening, CFRP, masonry.

1 Introduction

Neglecting the effects of non-structural brittle infill walls on dynamic characteristics of structures, such as stiffness and lateral strength, is a common assumption during the design and sometimes during the assessment stages of reinforced concrete structures subjected to lateral load. The field observations made after the recent major earthquakes in Turkey and many researchs performed throughout the world showed that this kind of approach leads to mispredicting the real behaviour of reinforced concrete infilled structures under lateral load. Research should be done to obtain a more relastic mathematical model that takes the infilled frame behavior into account and a strengthening method that includes infill wall properties for having cheaper rehabilitation alternatives.

The experiential work that is presented in this paper is a part of four complementary experimental works of research project launched in Structural...
and Earthquake Engineering Laboratory of Istanbul Technical University. The aim of this work is to evaluate lateral strength, stiffness and mechanical characteristics of infilled reinforced concrete structures strengthened by CFRP and to investigate technically appropriate and relatively cost effective strengthening methods using CFRP, [1]. According to this, five identical, ½ scale, one story-one bay brittle brick infilled reinforced concrete frame specimens have been tested under cyclic lateral loads. The reinforced concrete bare frame specimen and plastered brittle brick infilled frame specimen are essentially the reference frames. The other specimens are used to examine the differences between the structural behaviour of infilled frames strengthened using CFRP fabrics with different connection details.

The comparative results including lateral load capacities, failure modes, energy dissipation are also presented.

2 Test specimens

A group of five identical, ½ scale, one story-one bay brittle brick infilled reinforced concrete frame specimens have been prepared in the laboratory for cyclic testing.

Low strength brittle bricks, which are widely used in non-structural partitioning walls in Turkey, are selected as the infill material. The compressive strength in the direction of the holes of this type of brittle bricks is between 2.5-10 MPa. The void ratio of bricks is around 60%. The water:cement:lime:sand volumetric mixture proportions of mortar are 1:1:0.5:4.5 and mortar layer thickness is around 10 mm. Infill wall of all the specimens are plastered.

The reinforced concrete bare frame specimen and plastered brittle brick infilled frame Specimen N1, shown in Figure 1a, are essentially the reference frames. The compressive strengths of concrete and mortar of Specimen N1 are 16 and 4 MPa, respectively.

Specimen N2 is a CFRP strengthened infilled frame, Figure 1b. One layer of CFRP has been applied over the plastered infill wall on both sides in diagonal directions. CFRP overlays, that have 300 mm width, has been connected to the surrounding columns and beam by using additional two layers of CFRP fabric applied in lateral and vertical directions. CFRP fabrics, which are placed on two sides of wall, are attached to each other by means of shear connectors made of same CFRP. The CFRP shear connectors, with 300 mm width, are folded and placed into the holes that drilled through the wall. The fibers that are left outside of the wall are then spread fiber by fiber and bonded on the wall with epoxy resin. The compressive strengths of concrete and mortar of Specimen N2 are 11 and 4 MPa, respectively. CFRP application stages of Specimen N2 are shown in Figure 2.

The connection between peripheral frame elements and diagonal CFRP layers are provided by two layers of additional CFRP fabric at Specimen N2. It is obvious that this kind of connection has certain difficulties and may not always be applicable in practice. In order to overcome this problem, a different kind of connection detail is applied at Specimen N3, Figure 1c.
Figure 1: Bare Frame’ and Specimens N1, N2, N3 and N4.

N1 : Reference frame specimen with plastered infill wall

N2 : Frame with plastered infill wall. Two sided diagonal CFRP fabrics connected to peripheral RC elements. CFRP shear connectors are used to connect CFRP on both sides.

N3 : Frame with plastered infill wall. Two sided diagonal CFRP fabrics connected to peripheral RC elements by CFRP shear connectors. CFRP shear connectors are used to connect CFRP on both sides.

N4 : Frame with plastered infill wall. Two sided diagonal CFRP fabrics are not bonded to the wall. Only the connection area to peripheral RC elements are bonded with epoxy.
The first stage of the strengthening procedure of Specimen N3 has been made in the same way with Specimen N2. One layer of CFRP has been applied over the plastered infill wall on both sides in diagonal directions. Diagonal CFRP fabrics, which are pasted on two sides of wall, are attached to each other by means of shear connectors made of CFRP. At the second stage of the strengthening procedure, load to be carried by diagonal CFRP fabric are spread over a larger area with additional CFRP fabrics at the corners of the wall. The fibers of these two layers of CFRP have been oriented in two directions, namely horizontal and vertical directions and they are connected to the beam/column by two CFRP shear connectors. The compressive strengths of concrete and mortar of Specimen N3 are 13 and 10 MPa, respectively.

Figure 2: CFRP application stages of Specimen N2.

Figure 3: Specimens N2, N3 and N4.

CFRP fabric applied on the diagonals of the infill wall is subjected to both tension and compressive stresses under the cyclic loads that simulates lateral earthquake loads. Previous tests have shown that as CFRP fabric becomes very brittle after the application of epoxy adhesive, it may buckle under compressive stresses at big displacement levels. These weakened cross sections may cause sudden rupture of CFRP at the following cycle, which cause tension on CFRP. As for avoiding this brittle nature of CFRP, a different kind of application has been made at Specimen N4, Figure 1d. Diagonal CFRP layers have not been pasted on the infill wall by epoxy and CFRP fabric has just been bonded to the wall at the corners by epoxy adhesive. Four shear connectors are used at these
corners to bond the CFRP layers on two sides of the wall. The procedure used for the connection of CFRP fabric to the beam and columns is the same procedure used for Specimen N2. The compressive strengths of concrete and mortar of Specimen N4 are 17 and 3 MPa, respectively.

Specimens N2, N3 and N4 are shown all together in Figure 3.

3 Testing setup

Displacement controlled testing facilities have been utilized for both pulling and pushing of the specimen. Two MTS actuators, each having ± 250 kN loading and ± 300 mm displacement capacity, have been used simultaneously for this purpose. Axial force, that is approximately 20% of the axial load capacity of reinforced concrete column, has been applied to each column by a hydraulic jack through a steel beam and measured by a load cell, Figure 4.

![Figure 4: The testing setup.](image)

<table>
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<th>Target Top Displacement (mm)</th>
<th>Story Drift Ratio (δ/H)</th>
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<th>Story Drift Ratio (δ/H)</th>
<th>Target Top Displacement (mm)</th>
<th>Story Drift Ratio (δ/H)</th>
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Table 1: Drift ratios for target displacements.

Essentially the total target displacement reached after each increment is imposed to the specimen only once at each cycle for small displacement levels, on the other hand three cycles have been preferred for further displacement levels. The whole displacement protocol referred for that purpose and corresponding story drift ratios (δ/H) are given in Table 1.
Lateral displacements at the top of the specimen have been recorded during testing by means of displacement transducers. Displacements of columns and infill wall have also been measured. The displacements along the wall diagonals are recorded by transducers placed on both sides of specimen. Finally, out-of-plane displacements, the possible relative displacements with respect to foundation and the rotation of foundation are measured by transducers and controlled during testing. Crack patterns and failure mode have also been recorded manually during the whole course of testing. Although there are a lot of measurements taken from the specimens, the top displacement versus base shear relationships are presented here.

4 Test results

Experimentally achieved hysteresis loops of Specimen N2, N3 and N4 are presented in Figure 5, 6 and 7 respectively.

Figure 5: Hysteresis loops of Specimen N2.

Failure of Specimen N2 have taken place after CFRP fabrics on diagonals of both sides have been broken in tension, one after the other, at the displacement level ± 14 mm. Sudden load drops caused by CFRP rupture can be seen at the hysteresis loops.

Diagonal CFRP fabric of Specimen N3 on both sides has been broken simultaneously at 10.5 mm displacement. Cracks that have formed at previous displacement level at the column and at the interface of beam-column have widened and concrete at this area has been crushed. These damages have lead the specimen to the failure at the last pushing cycle of +28 mm.
At Specimen N4, shear crack formed on one of the column at the previous displacements have widened at the first pulling cycle of 28 mm and caused the buckling of the column which have lead the specimen to the failure.

The envelopes of hysteresis loops of reference bare frames and Specimen N1, are drawn together with the envelope of strengthened specimens for comparison, see Figure 8. The compressive strength of concrete of ‘Bare frame 1’ and ‘Bare frame 2’ are 12 and 16 MPa, respectively.

![Hysteresis loops of Specimen N3.](image)

**Figure 6:** Hysteresis loops of Specimen N3.

![Hysteresis loops of Specimen N4.](image)

**Figure 7:** Hysteresis loops of Specimen N4.
5 Conclusions

The main contribution of CFRP strengthening to the structural behavior of one story-one bay RC frame specimens can be evaluated by comparing the envelopes of base shear-lateral load hysteresis loops of all specimens in terms of initial stiffness, lateral strength and energy dissipation. The results that have been reached by evaluation of base shear-top displacement curves, failure modes and observations made during tests, are all explained below.

- It can be clearly seen that the initial stiffness of bare frames are significantly lower than the infilled reference frame and CFRP strengthened frames, which points out that the modelling of structures as bare frames can not be a realistic approach, see Figure 8.

- It can be said that strengthening by CFRP have increased the initial stiffness of specimens compared to the infilled reference frame, Figure 9. The influence of this increase at stiffness to the structural behaviour should be considered carefully while strengthening project is prepared, because increasing stiffness of the structure by strengthening either increase or decrease the lateral load applied to the structure due to the local ground characteristics. Therefore it may be appropriate to let the rocking of the foundation up to some degree and in this way to reduce the natural period of structure which is increased by increasing of stiffness.

- If a comparison is to be made for initial stiffnesses of strengthened specimens, it should be pointed out that all strengthened specimens have very close initial stiffness values but these stiffnesses ends at different displacement levels.

- If the lateral load capacity of all specimens is compared, it can be said that lateral load capacity have increased with strengthening by CFRP. The lateral load capacity of Specimen N2, Specimen N3 and Specimen N4 are...
approximately 1.76, 1.42 and 1.2 times bigger than infilled reference frame, respectively, Figure 8.

- Comparing the lateral load capacity of strengthened specimens, lateral load capacity of Specimen N2 is 1.24 and 1.47 times bigger than Specimen N3 and Specimen N4, respectively, Figure 8.

- It is obvious that strengthening by CFRP have increased energy dissipitation. As the energy dissipitation of strengthened specimens are very close to each other, comparison should be made between mathematically calculated energy dissipitation values. Besides, a certain displacement limit should be selected for this comparison because each specimen have reached to different displacement levels at failure.

- Although infill wall of infilled reference frame have contributed to carry lateral load at small displacement levels, the load transfer between the frame elements and infill wall reduced after there have been damage at the upper parts of the wall. It is observed that at strengthened specimens load transfer between frame and infill wall have been kept until higher displacement levels. The most important evidence of this structural behaviour is the inclined cracks that have formed at the beam and columns, continuing on the infill wall and reaching out to the other column.

- The CFRP shear connectors, which are used attach diagonal CFRP on two sides of the wall, have worked successfully and these shear connectors have also decreased the buckling length of the diagonal CFRP.

- Load carried by diagonal CFRP have been transferred to the frame elements by the means of two different connection details and load transfer is achieved successfully until failure by both of the connection details.

- Load is transferred from diagonal CFRP to the frame elements and spread over an area by additional CFRP fabrics at Specimens N2 and N4. Although some of these CFRP fabrics have slightly debonded from the wall and the columns at high displacement levels, load transfer has been kept effective properly until failure.

- At Specimen N3, load to be carried by diagonal CFRP is transferred to the frame elements by the means of CFRP shear connectors. As this kind of connection results in transferring localized loads inside the frame elements, more damage has been observed at this area compared to Specimens N2 and N4. It should also be noted that even same fibers of these CFRP shear connectors have been torn, they continue to transfer load until failure.

- As the tensile strength of brittle brick is low, CFRP applied on the diagonals of infill wall have carried the tension stress and also achieved load transfer until failure, providing the behaviour of the specimen as a whole. Furthermore, even it is presumed that diagonal CFRP does not carry compressive stress, CFRP pasted on the infill wall by epoxy have taken part in carrying compressive stresses by keeping the masonry in place under compression and spreading the compressive stress over a larger area.

- Carrying tension stress of diagonal CFRP have been observed clearly at Specimen N4, where diagonal CFRP have not been pasted on the infill wall by epoxy. Diagonal CFRP have only carried the tension stress and less
damage have been observed at the infill wall compared to the other strengthened specimens. Although the buckling of CFRP fabric have been prevented by not pasting the fabric on the infill by epoxy, the change in the damage and failure mode should be taken into account.

- The story drift ratio limit given in Turkish Seismic Code is 0.035 or 0.02/R, where R is a coefficient depending on the ductility of structure. Failure has been reached far beyond from this limit at all of the strengthened specimens and no severe damage has been observed at limit displacement level.

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Reference