SEISMIC STRENGTHENING OF INFILLED RC FRAMES BY CFRP

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ABSTRACT :

A series of tests were performed for investigating the strengthening of masonry infill walls of poorly designed RC frame specimens by CFRP fabrics. The main objective of this experimental work was to evaluate the contribution of CFRP applied on infill walls over selected parameters. The first part included diagonal tension tests of 28 masonry wall panel specimens. These tests were conducted in order to observe the effects of different CFRP types and applications over inital stiffness, shear strength and failure modes. At the second part of experimental work, five ½ scaled one story-one bay reinforced concrete frame specimens were tested under cyclic in-plane lateral loads. One bare frame specimen and one infilled frame specimen were the reference frames. The other three specimens were strengthened with different CFRP application types and connection details. Lateral load-top displacement hysteresis curves of specimens were evaluated in terms of lateral load capacity, initial stiffness and energy dissipation. It was concluded that strengthening of infill walls by CFRP as done in this study were effective on increasing lateral load carrying capacity and initial stiffness of infilled RC frame specimens.

KEYWORDS: Masonry, strengthening, FRP, infill wall.

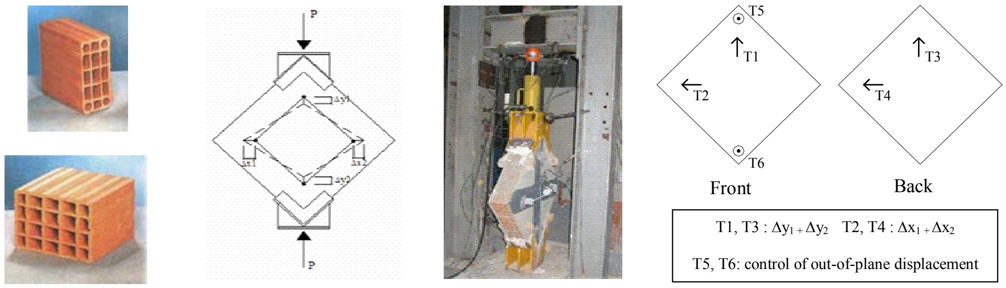
1. INTRODUCTION

The contributions of the infill walls to lateral strength, stiffness and energy dissipation of RC structures subjected to lateral loads, may be lost by premature damage during earthquakes. It would be an effective strengthening technique to keep the infill walls in place by strengthening the infill and RC frame elements together and forcing them to work as a whole until the end of the earthquake. Using Fiber Reinforced Polymer Composites (FRP) for this kind of strengthening is recently an appealing area for the researchers and have been presented in the latest released Turkish Code for Building in Seismic Zones, (2007). It is important that extensive experimental data with various parameters should be obtained from different researches in order to improve the relatively new analytical background of this strengthening technique.

In this study, a series of tests were performed for investigating the strengthening of masonry infill walls of poorly designed RC frame specimens by CFRP fabrics. The main objective of this experimental work was to evaluate the contribution of CFRP applied on infill walls over selected parameters such as lateral stiffness and lateral load carrying capacity. The first part of tests consisted of diagonal tension tests of 28 masonry wall panel specimens. At the second part of experimental work, five ½ scaled one story-one bay reinforced concrete frame specimens were tested under cyclic in-plane lateral loads. Lateral load-top displacement hysteresis curves of specimens were evaluated in terms of lateral load capacity, initial stiffness and energy dissipation.

2. DIAGONAL TENSION TESTS

The diagonal tension tests of 28 masonry wall panels were performed. An experimental technique that was similiar to the one described at ASTM C 1391-81, (1981) was used, but some modifications were made according to the previous studies carried at I.T.U. Structural and Earthquake Engineering Laboratory. The brittle clay brick wall panel specimens, having dimensions of 755 mm x 755 mm, were loaded until failure and their shear strength, initial stiffness and various strengthening methods by CFRP were investigated, Figure 1. The test results were also used to investigate the effects of strengthening parameters for one story-one bay infilled RC frame specimens. While establishing a mathematical model of infilled RC frames, infill walls may be replaced with one or more equivalent struts. Some of the infill wall characteristics, that would be needed for these equivalent struts, were intended to derive from the experimental results and observations of diagonal tension tests of wall panels.



(a) (b) (c)

Figure 1 Brittle clay bricks (a), testing setup of diagonal tension tests (b) and measuring devices (c)

Masonry wall panel and infill wall specimens were fabricated using brittle clay bricks that were widely used in Turkey. Two different brick thicknesses, 135 mm and 85 mm, were chosen for production, Figure 1a.The other two dimensions of the bricks were 190 mm. The compressive strength of clay bricks perpendicular to the holes and paralel to the holes were given as 2.5 MPa and 10 MPa, respectively. All the wall specimens were fabricated by running bond style by a professional worker. Bricks were laid as their holes were paralel to the continuous mortar layer. The water:cement:lime:sand volumetric mixture proportions of mortar was 1:1:0.5:4.5 and mortar thickness was 10 mm. Some of the masonry wall panel specimens were plastered. The water:cement:lime:sand volumetric mixture proportions of plaster was 1.25:1:0.5:4.5. The plaster thickness was approximately 10 mm. Three different types of CFRP were used for strengthening masonry wall panel specimens. The mechanical features of these CFRP types given by the manufacturer are listed in Table 1. Two different types of epoxy resin were selected for CFRP application. The tensile strength of Epoxy-1 was 30 MPa, tensile modulus was 4500 MPa and elongation at break was 0.9%. The tensile strength of Epoxy-2 was 4 MPa, tensile modulus was 1000 MPa and elongation at break was 0.4%.

The masonry wall panel specimens were fabricated in 3 groups. First group consisted of 17 wall panels. The three parameters were chosen prior to the fabrication of specimens. The first parameter was the thickness of the wall specimens and two different brick types, with 135 mm and 85 mm thicknesses, were used. The second parameter was the existence of plaster on the wall surface. CFRP fabrics were bonded over both plastered and non-plastered wall specimens. Third parameter was the surface area of CFRP applied over the wall specimens. Two different applications of CFRP fabrics were done. One of them was covering all the surface area of wall panel with CFRP fabrics in two diagonal directions and the other was strengthening the wall panel with 300 mm width CFRP fabrics. CFRP fabrics were applied on both sides of the wall panels and their fiber directions were aligned with the wall diagonals. Furthermore, CFRP fabrics were embedded in the continuous mortar layers of some specimens at the fabrication stage. All types of specimens can be seen in Figure 2 and are tabulated in Table 2.

Depending on the early results of the first group of specimens, a second group of 7 specimens were fabricated. Since the plastered specimens had relatively higher ultimate loads and initial stiffness, in the second group all new specimens were plastered. At the pilot test of infilled RC frame, it was observed that main factor which controlled the failure mode was the brittle behavior of the brick and failure took place by the separation of CFRP from the wall surface, after the shear strength of brick had been reached. For being able to benefit from CFRP until the failure, CFRP anchors bonding CFRP layers on the both sides of the specimens were used at the new wall panel specimens. Finally, the widths of CFRP fabrics were chosen as the last parameter for investigating a cost effective solution. CFRP fabric widths of second group were 300 mm, 150 mm and 100 mm. Two wall specimens were fabricated for each width and one of them had CFRP anchors while the other did not. In order to place CFRP anchors, five holes were drilled on the wall panels. CFRP fabrics were folded and put into these holes in a way that approximately 100 mm long ends of CFRP anchors were left outside the wall surface.Afterwards, fibers of these ends were separated and bonded on the wall with adhesive. Each CFRP anchor had the same width with CFRP fabrics that it bonded, Figure 2.

Table 1 The mechanical features of CFRP fabrics

CFRP Type	Fiber Type	Fiber Orientation	Weight (± %10) (g/m²)	Fabric Design Thickness (mm)	Tensile Strength of Fibers (MPa)	Tensile E-Modulus of Fibers (MPa)	Strain at Break of Fibers (%)
CFRP No.1	Mid- strength carbon fibers	0° (unidirectional)	230	0.131	4300	238000	1.8
CFRP No.2			200	0.111	3900	230000	1.5
CFRP No.3			100	0.056	3900	230000	1.5

Third group consisted of four specimens. Two new parameters were chosen which were new CFRP and epoxy types. Two wall panel specimens of this group were strenghened by new type of CFRP applied with epoxy resin, Epoxy-1, while the other two specimens were strengthened by old type of CFRP applied with new type epoxy resin, Epoxy-2. The width of CFRP fabrics at third group specimens were 300 mm and were applied on both sides of the wall.

Table 2 Features of masonry wall panel specimens

Spec. No	Group	t_d (mm)	f_m (MPa)	f_p (MPa)	Strengthening: CFRP type	Strengthening: CFRP width (mm)	Strengthening: CFRP anchors	Strengthening: Epoxy Type	P_{ult} (kN)	ε (Δ_{vult}/l) (%)	G (MPa)	K_{int} (P/Δ) (kN/mm)
S25	1	135	3.93	-	-	-	-	-	71	0.171	604	203
S9			4.8	-	-	-	-	-	68	0.092	-	238
S16		85	11.5	-	-	-	-	-	66	0.208	321	131
S18			6.21	-	-	-	-	-	77	0.167	417	152
S11		135	5.82	-	No. 1	In mortar layer	-	Epoxy-1	85	0.116	585	184
S12			5.82	-			-		82	0.152	589	193
S13			4.44	-			-		122	0.140	1019	307
S14		85	4.44	-			-		73	0.135	366	128
S2		135	5.75	8.22	-	-	-	-	134	0.118	1406	353
S6			6.55	7.27	-	-	-	-	224	0.201	1615	509
S8			7.16	8.22	-	-	-	-	207	0.149	1603	560
S22	2		5.18	3.23	-	-	-	-	190	0.097	-	624
S15	1	85	11.5	14.59	-	-	-	-	212	0.218	1385	422
S17			11.5	14.59	-	-	-	-	207	0.210	1577	553
S7		135	7.16	-	No. 1	Whole surface	-		221	0.404	1307	425
S19			9.28	14.59			-	Epoxy-1	384	0.187	2429	768
S1			8.56	14.59		300	-	Epoxy-1	281	0.217	3203	676
S5			6.55	6.58			-		386	0.134	2218	759
S10	2		4.8	2.98	No. 2		-		199	0.113	-	647
S21			5.18	3.23			yes		212	0.144	1448	478
S28			3.05	2.98		150	-		190	0.113	1559	561
S24			3.93	3.23			yes		197	0.172	1259	444
S27			2.71	2.98	No. 2	100	-		103	0.064	2029	642
S26			2.71	2.98			yes		142	0.072	1401	477
S33	3	135	3.87	2.49	No.3	300	-	Epoxy-1	257	0.182	1552	522
S34			3.87	2.49			-		203	0.117	1756	526
S29			4.6	3.2	No. 2		-	Epoxy-2	193	0.130	1758	663
S30			4.6	3.2			-		167	0.184	1724	445

P_{ult} : Ultimate vertical load ; Δ_{vult} : Vertical displacement at P_{ult} , ε : vertical strain, G : Shear modulus, K_{int} : Initial stiffness of P-Δ envelope

1.1. Testing Setup

45° diagonal loading were increased gradually until failure. A force controlled testing technique was used with the intention of keeping the loading speed constant. A hydraulic jack with a capacity of 500 kN was used for loading and the load values were measured by a load cell having a capacity of 500 kN, Figure 1b.. Each load increments were repeated three times. Vertical and horizontal displacements were measured by four displacement transducers (LVDT) from each side of wall panel. The out-of-plane displacements were controlled by two other LVDTs. The testing setup and the measuring devices are shown in Figure 1c.

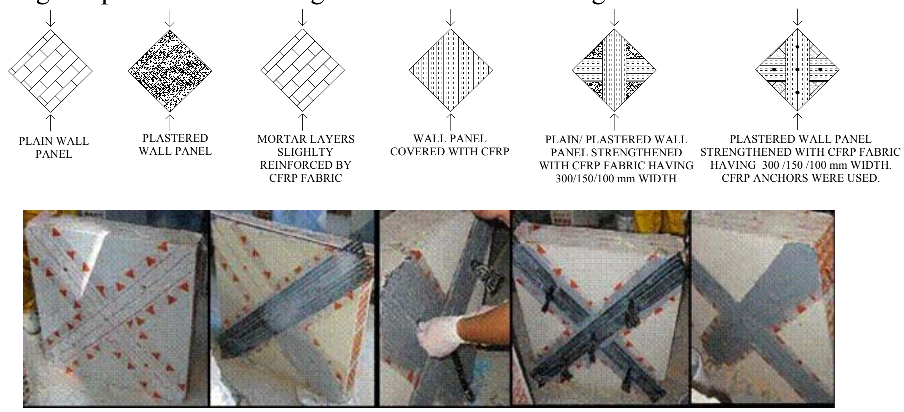


Figure 2 Masonry wall panel specimens

1.2. Test Results

Load-vertical displacement (P-Δ) and nominal shear stress-shear deformation (τ-γ) curves were obtained using experimental data, (ASTM C 1391-81, 1981 and Karadogan *et al.,* 2005). Shear modulus (G) of each specimen was calculated as the slope of τ-γ curve between the values of 5% and 30% of τ_{ult}. Initial stiffness (K_{int}) was also obtained as the slope of P-Δ between the values of 5% and 30% of P_{ult}, Table 2. Some of the important results that were reached by evaluating the P-Δ and τ-γ curves of wall panel specimens, failure modes and observations made during tests are summarized as follows;

- Despite the ultimate loads of non-plastered wall panel specimens were not affected with the decreasing thickness of the wall panels, namely shear area, the initial stiffness decreased. For the plastered walls the major factor affecting the initial stiffness appeared to be the compressive strength and thickness of the plaster rather than the wall thickness.
- The initial stiffness of plastered specimens was considerably higher than the non-plastered ones. The ultimate loads of the plastered wall panels could reach approximately 2.5 times of the ultimate loads of non-plastered wall panels.
- Embedding CFRP into the mortar layers did not have a significant effect on both the initial stiffness and ultimate loads, but it prevented the specimen from crushing at the failure and the failure took place by sliding along a mortar layer.
- It was observed that the initial stiffness values of plastered wall panels strengthened by CFRP were much higher than the non-plastered strengthened one. In the case of application of CFRP over the plastered wall panels, CFRP and plaster work together without any considerable separation until high load values.
- The ultimate load and initial stiffness values of plastered and non-plastered wall panel specimens strengthened by CFRP fabrics increased significantly compared to the unstrengthened ones for the first group of specimens. Tough initial stiffness values and ultimate loads of strengthened specimens of the second group were recognizably lower than the similar specimens of the first group. It should be noted that plaster and mortar compressive strengths and fiber tensile strength of CFRP No.2 used at specimens of second group were lower than the first group specimens.
- Even though the initial stiffness values and ultimate loads of the second group specimens were closer to the unstrengthened plastered specimens, their failure modes were just like the strengthened specimens of first group. So it may be said that strengthening is the major factor over the failure modes.
- CFRP anchors did not show a significant effect over stiffness, ultimate load and failure load. There was not any important damage observed at the CFRP anchors. While 300 mm wide CFRP fabrics on tension diagonal and plaster separated together over the bricks, no such separation were observed for the specimen with 300 mm CFRP where CFRP anchors used.

- Epoxy type did not have an important effect on ultimate load or initial stiffness. Adhesion problems encountered during the application using Epoxy-2 and these test results emphasized the importance of proper application procedures.

3. ONE STORY-ONE BAY RC FRAME SPECIMENS

A group of five identical, ½ scale, one story-one bay brittle clay brick infilled reinforced concrete frame specimens were tested under constant axial load and cyclic in-plane loads. Same type of brittle clay bricks that were used in diagonal tension tests of wall panels, were selected as the infill material, Figure 1a. Infill wall of all the specimens were plastered and were constructed in the same sense with the wall panel specimens. Epoxy-1 was used for CFRP strengthening. All the structural features, including the reinforcing details of specimens, are given in Figure 3 and summarized in Table 3.

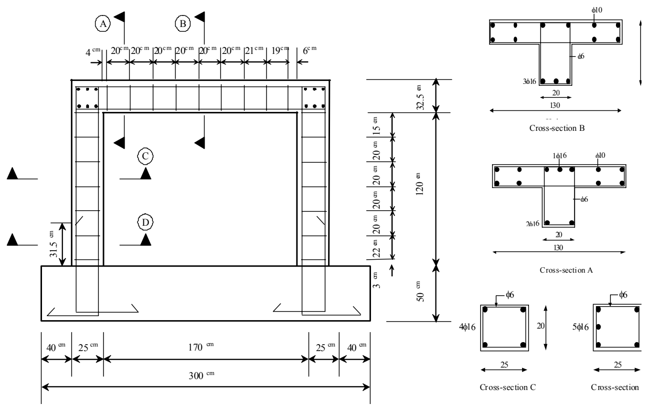


Figure 3 Dimensions and the reinforcing details of one story-one bay RC frame specimen

The reinforced concrete bare frame specimen and plastered infilled frame Specimen N1, were essentially the reference frames. Specimen N2 was an infilled frame strengthened by CFRP, Figure 4a. One layer of CFRP was applied over the plastered infill wall on both sides in diagonal directions. CFRP overlays, that were 300 mm wide, were connected to the surrounding columns and beam by using additional two layers of CFRP fabric applied in lateral and vertical directions. CFRP fabrics, which were placed on two sides of wall, were attached to each other by means of anchors made of same CFRP. The CFRP anchors, with 300 mm width, were folded and placed into the holes that were drilled through the wall. The fibers that were left outside of the wall were then spread and bonded on the wall with epoxy resin. Connections of CFRP fabric to the foundation were also done by CFRP anchors.

Table 3 Some features of one story-one bay RC frame specimens.

Specimen No.	Specifications	f_c [a] (MPa)	f_m [b] (MPa)	f_p [c] (MPa)	Strengthening CFRP Type (Dia)	Strengthening CFRP Type (Frame)	P_{ult}^+ (kN)	P_{ult}^- (kN)	K_{int}^+ (kN/mm)	K_{int}^- (kN/mm)
Bare Frame	Bare RC frame	16	-	-	-	-	133.4	122.6	23.6	22.8
N1	Infilled RC frame	15.8	4.3	3.4	-	-	130.9	233.2	87.4	74.2
N2	CFRP strengthened	10.8	4.1	3.9	No 2.	No.1	330.1	311.9	236.4	239.4
N3	CFRP strengthened	12.9	10.1	2.3	No.2	No.2	239.7	278.1	181.5	209.5
N4	CFRP strengthened	16.7	3.4	1.3	No.2	No.2	225.3	217.3	154.3	122.6

[a] f_c : Compressive strength of concrete; [b] f_m : Compressive strength of mortar; [c] f_p : Compressive strength of plaster; *Dia* : Type of diagonal CFRP; *Frame* : Type of CFRP used for frame connections; P_{ult}^+, P_{ult}^- : Ultimate lateral loads of specimens at pushing and pulling, respectively; K_{int}^+, K_{int}^- : Initial stiffness of specimens at pushing and pulling, respectively.

A different kind of connection detail for diagonal CFRP layers to peripheral frame elements was applied at Specimen N3 in order to overcome application difficulties in practice, Figure 4b. Load to be carried by diagonal CFRP fabric were spread over a larger area with additional CFRP fabrics at the corners of the wall. The fibers of these two layers of CFRP were oriented in two directions, namely horizontal and vertical directions and they were connected to the beam/column by two CFRP anchors. The other infill wall strengthening stages of Specimen N3 were identical to Specimen N2.

A different application type was made at Specimen N4, Figure 4c. Diagonal CFRP layers were not pasted on the infill wall by epoxy and CFRP fabric was just bonded to the wall at the corners by epoxy adhesive. Four CFRP anchors were 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 was the same procedure used for Specimen N2.

(a) (b) (c)

Figure 4 Specimen N2 (a), Specimen N3 (b) and Specimen N4 (c)

2.1. Testing Setup

Displacement controlled testing facilities were utilized for both pulling and pushing of the specimen by two MTS actuators used simultaneously. Axial force, that was approximately 20% of the axial load capacity of reinforced concrete column, was applied to each column by a hydraulic jack through a steel beam and measured by a load cell, Figure 5. Essentially the target story drift ratio reached after each increment was imposed to the specimen only once at each cycle for small story drift ratio values, from 0.0025% to 0.03%. On the other hand three cycles were preferred for further story drift ratio values, from 0.05% to 2%. Lateral displacement values at the top of the specimen, displacements of columns, infill wall and along the wall diagonals were measured by means of displacement transducers (LVDT). Out-of-plane displacements, the possible relative displacements with respect to foundation and the rotation of foundation were also controlled during testing.

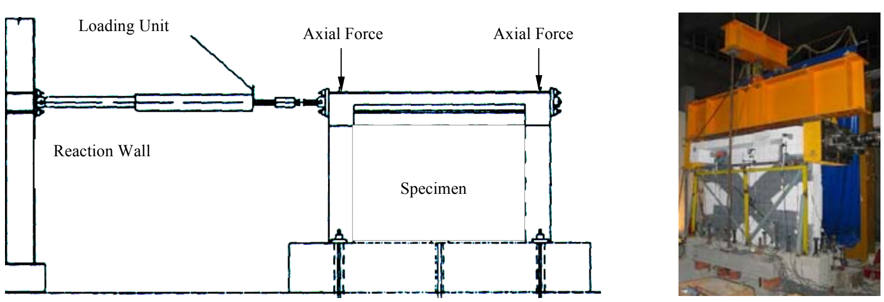


Figure 5 The testing setup of one story-one bay RC frame specimen tests

2.2. Test Results

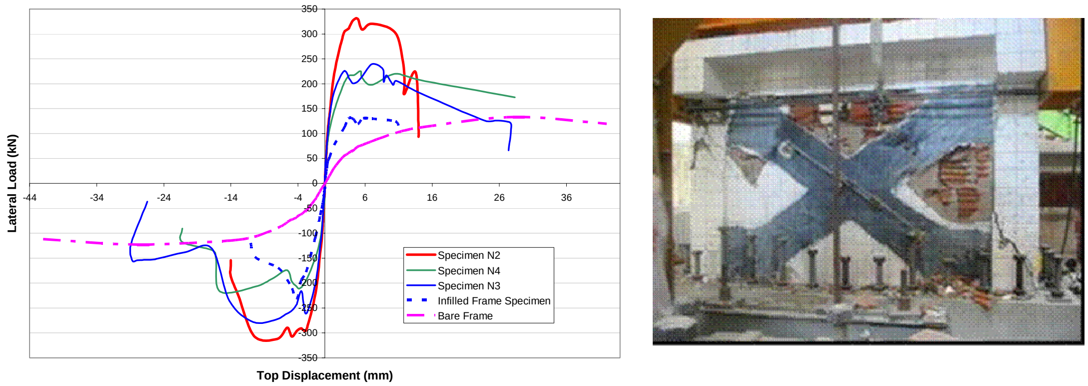
Lateral load versus top displacement hysteresis loops of all the specimens were obtained using experimental data, Figure 6a. Ultimate lateral loads of all specimens for pushing and pulling (P_{ult}^{+}, P_{ult}^{-}) are listed at Table 3. Initial stiffness values of specimens for pushing and pulling (K_{int}^{+}, K_{int}^{-}) were calculated as the slope of envelope of hysteresis loops between the values of 5% and 35% of P_{ult}, Table 3. Peak-to-peak stiffness values were calculated as well, Figure 7a. Finally energy dissipation values were calculated and shown all together in Figure 7b. Failure picture of Specimen N3 is presented in Figure 6b. Some of the important results that were reached by lateral load-top displacement hysteresis loops, failure modes and observations made during tests are summarized as follows;

- The initial stiffness of bare frames were significantly lower than the infilled reference frame N1 and CFRP strengthened frames, which pointed out that the modeling of structures as bare frames could not be a realistic approach, Table 3. In this study strengthening of infilled frames by CFRP, increased the initial stiffness of specimens compared to the infilled reference frame N1. The effect of this stiffness increase at to the structural behavior should be considered carefully during strengthening project is prepared. It is due to the fact that increasing stiffness of the structure either increases or decreases the lateral load applied to the structure according to the local ground characteristics. Comparing the initial stiffness of strengthened specimens, it should be pointed out that all strengthened specimens had very close initial stiffness values.
- While a comparison was made in terms of lateral load capacity, it could be said that lateral load capacity increased with strengthening infill walls by CFRP. The lateral load capacities of Specimen N2, N3 and N4 were approximately 1.76, 1.42 and 1.2 times of that of infilled reference frame N1, respectively, Table 3. The evaluation of tests of strengthened specimens show that Specimen N2 had a lateral load capacity which was 24% and 47% more than of Specimen N3 and N4, respectively.
- For the infilled reference specimen N1, the load transfer between the frame elements and infill wall reduced after there had been damage at the upper parts of the wall. It was observed that load transfer between frame and infill wall continued until higher displacement levels at strengthened specimens.
- The CFRP anchors, which were used to connect diagonal CFRP on two sides of the wall, worked successfully and this connection between diagonal CFRP on both sides were achieved until failure.
- Both types of connection details of diagonal CFRP to frame elements for transferring load from CFRP to the frame were achieved successfully. At Specimens N2 and N4, although some of CFRP connection layers slightly debonded from the wall and the columns at high displacement levels, load transfer had been kept effective until failure. At Specimen N3, connections by CFRP anchors resulted in transferring localized loads inside the frame elements, as a result more damage were observed at this area compared to Specimens N2 and N4. It should also be noted that even tough some fibers of these CFRP anchors were torn, they continued to transfer load until failure.
- As the tensile strength of masonry wall was low, the diagonal tension stress of infill wall carried by CFRP on the wall. Diagonal CFRP on the infill wall also achieved load transfer until failure, providing the behavior of the specimen as a whole. Furthermore, CFRP pasted on the infill wall by epoxy took part in carrying compressive stresses by keeping the masonry in place under compression and spreading the compressive stress over a larger area.
- For strengthened specimens Specimen N2 and N3, failure took place after CFRP fabrics on diagonals of both sides were broken off in tension, one after the other, for the story drift ratios (δ/H) 1% and 0.75%, respectively. Sudden load drops caused by CFRP rupture could be seen at the hysteresis loops. Cracks that had formed at previous displacement level at the column and at the interface of beam-column, widened and concrete at this area was crushed, Figure 6b. At Specimen N4, shear crack formed at one of the columns at the previous displacements widened at the story drift ratio (δ/H) 2%, and caused the buckling of the column which lead the specimen to the failure.

3. CONCLUSIONS

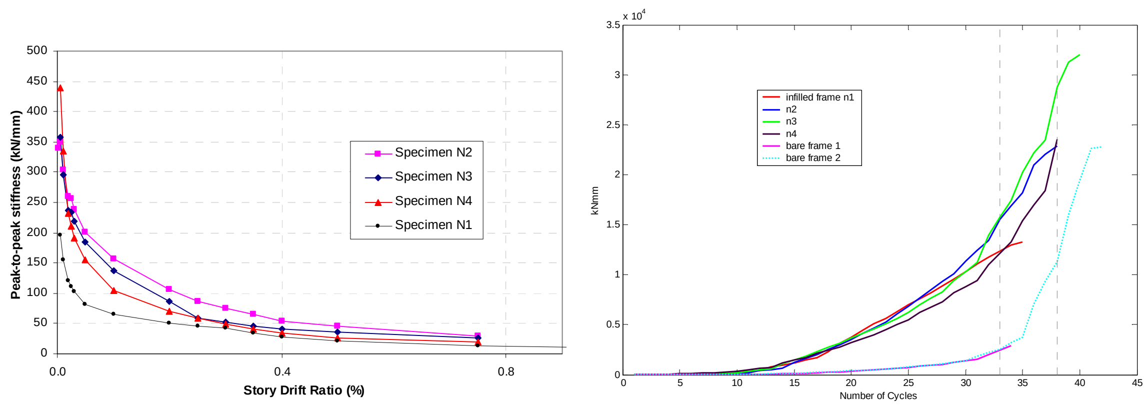
An experimental study was performed for investigating the strengthening of masonry infill walls of RC frame specimens by CFRP fabrics. The first part included diagonal tension tests of 28 masonry wall panel specimens. These tests were conducted in order to observe the effects of different CFRP types and applications over initial stiffness, shear strength and failure modes. Load-vertical displacement (P-Δ) and nominal shear stress-shear deformation (τ-γ) curves were obtained using experimental data. Shear modulus and initial stiffness of each specimen were given. The summary of the important results that were evaluated by test results were presented.

At the second part of experimental work, five ½ scaled one story-one bay reinforced concrete frame specimens were tested under cyclic in-plane lateral loads. Three strengthened specimens had different CFRP application types and connection details. Lateral load-top displacement hysteresis curves of specimens were evaluated in terms of lateral load capacity and initial stiffness. Peak-to-peak stiffness and energy dissipation values of specimens were presented. Some of the important results that were reached by test results are summarized. It was concluded that strengthening of infill walls by CFRP as done in this study were effective on increasing lateral load carrying capacity and initial stiffness of infilled RC frame specimens. It was also observed that different CFRP connections successfully transferred the load carried by CFRP applied on the wall to the frame elements until failure. Macro modeling of presented specimens is ongoing study.



(a) (b)

Figure 6 The envelopes of hysteresis loops of all specimens (a) and failure picture of Specimen N3 (b)



(a) (b)

Figure 7 Peak-to-peak stiffness degradation (a) and energy dissipation (b) diagrams of all specimens

ACKNOWLEDGMENTS

This experimental study is financially supported partially by The Scientific and Technological Research Council of Turkey (TUBITAK, Project no: 104M562) and Sika Construction Chemicals, Turkey. It should be noted that none of the assessments, establishments and opinions presented in this paper is official conception of TUBITAK.

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