Seismic Strengthening of Infilled Reinforced Concrete Frames by CFRP

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SUMMARY:
The objective of this research was to evaluate strengthening of infilled RC frames by CFRP in terms of lateral strength and stiffness. Effects of CFRP strengthening to overall behavior of system were investigated experimentally and theoretically. Experimental work consisted of two parts. The first part is the diagonal tension tests of 28 masonry wall panel specimens. In the second part, six one story-one bay RC frames were tested under cyclic in-plane lateral loads. Lateral load-top displacement hysteresis curves and failure modes were obtained. Initial stiffness, peak-to-peak stiffness, effective stiffness, equivalent displacement ductility, strength reduction factors, energy dissipation capacities and hysteretic damping ratios were evaluated comparatively. In the theoretical part, structural models of the CFRP strengthened infilled one story-one bay RC frames were established. Analytical pushover curves and experimental results were compared. Analytical results compared well with the experimental results in terms of lateral load capacity and initial stiffness.

Keywords: CFRP, RC, Infill, Strengthening

1. INTRODUCTION

The contributions of the infill walls to lateral strength, stiffness and energy dissipation of reinforced concrete (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 and these data to be evaluated in order to improve the relatively new analytical background of this strengthening technique.

The objective of the presented study was to explore seismic strengthening of masonry infill walls of poorly designed RC frame specimens by Carbon Reinforced Polymer Composites (CFRP) fabrics. For this purpose, effects of CFRP strengthening to the overall behavior of the system and effects of different application techniques were investigated experimentally and theoretically. Experimental work consisted of two parts. The first part is the diagonal tension tests of 28 masonry wall panel specimens. In the second part of experimental work, six ½ scaled one story-one bay RC frame specimens were tested under cyclic in-plane lateral loads. Lateral load-top displacement hysteresis curves of these specimens were evaluated in terms of lateral load capacity, initial stiffness and energy dissipation. In the theoretical part of this study, structural models of the infilled one story-one bay RC frame specimens strengthened by CFRP were established in order to achieve the generalization of experimental results of limited number of tests.

2. EXPERIMENTAL WORK

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. Experimental work consisted of two major parts. The first part is the diagonal tension tests of 28 masonry wall panel specimens. These tests were conducted in order to observe the effects of CFRP application on plastered and non-plastered wall panel specimens and the contributions of different CFRP types and applications on initial stiffness, shear strength and failure modes. Six one story-one bay reinforced concrete frame specimens were tested under the cyclic in-plane lateral loads in the second part. Experimental work is summarized below and further details of the specimens and tests were given at Erol (2010).

2.1. 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 with some modifications made according to the previous studies carried at I.T.U. Structural and Earthquake Engineering Laboratory. The 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, Fig. 2.1.

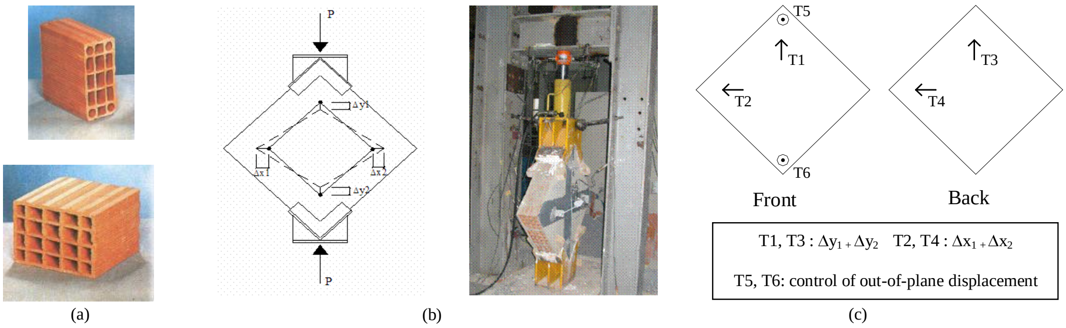


Figure 2.1. Brittle clay bricks (a), testing setup of diagonal tension tests (b) and measuring devices (c)

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, Fig. 2.1a.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. Some of the masonry wall panel specimens were plastered. Three different types of CFRP were used for strengthening masonry wall panel specimens, Table 2.1. Two different types of epoxy resin were selected for CFRP application. The tensile strength of Epoxy-1 was 30 Mpa and tensile modulus was 4500 MPa. The tensile strength of Epoxy-2 was 4 MPa and tensile modulus was 1000 MPa.

Table 2.1. The Mechanical Features of CFRP Fabrics

CFRP Type	**Fiber Type**	**Fiber Orientation**	**Weight (± %10) (g/m^2)**	**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

The masonry wall panel specimens were fabricated in 3 groups. First group consisted of 17 wall panels. The three parameters chosen prior to the fabrication of specimens were thickness of the wall specimens, existence of plaster on the wall surface and the surface area of CFRP applied over the wall specimens. CFRP fabrics were bonded over both plastered and non-plastered 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 are tabulated in Table 2.2.

Depending on the early results of the first group of specimens, a second group of 7 specimens were fabricated. All specimens in the second group were plastered. In order to prevent seperation of CFRP from wall surface and 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. The widths of CFRP fabrics were chosen as the 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. Third group consisted of four specimens. Two parameters chosen 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 2.2. Features of masonry wall panel specimens

Spec. No	Group	t_d mm	f_m MPa	f_p MPa	Strengthening				P_{ult} kN	ε (Δ_{vult}/l) (%)	G MPa	K_{int} (P/Δ) kN/mm
					CFRP type	CFRP width mm	CFRP anchors	Epoxy Type				
S25		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			5.82	-			-		85	0.116	585	184
S12	1	135	5.82	-	No. 1	In mortar layer	-	Epoxy-1	82	0.152	589	193
S13			4.44	-			-		122	0.140	1019	307
S14		85	4.44	-			-		73	0.135	366	128
S2			5.75	8.22	-	-	-	-	134	0.118	1406	353
S6		135	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		85	11.5	14.59	-	-	-	-	212	0.218	1385	422
S17			11.5	14.59	-	-	-	-	207	0.210	1577	553
S7	1		7.16	-		Whole surface	-		221	0.404	1307	425
S19			9.28	14.59	No. 1		-	Epoxy-1	384	0.187	2429	768
S1			8.56	14.59			-		281	0.217	3203	676
S5			6.55	6.58		300	-		386	0.134	2218	759
S10		135	4.8	2.98			-		199	0.113	-	647
S21			5.18	3.23	No. 2		yes		212	0.144	1448	478
S28	2		3.05	2.98		150	-	Epoxy-1	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			3.87	2.49	No.3		-	Epoxy-1	257	0.182	1552	522
S34	3	135	3.87	2.49		300	-		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

A force controlled testing technique was used with the intention of keeping the loading speed constant. 45° diagonal loading were increased gradually until failure. A hydraulic jack was used for loading and the load values were measured by a load cell, Fig. 2.1b. 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 Fig. 2.1c.

2.2. One Story-One Bay RC Frame Specimens

A group of six identical, ½ scale, one story-one bay reinforced concrete frame specimens were tested under constant axial load and cyclic in-plane loads. Four of the specimens had brittle clay brick infill walls. Same type of brittle clay bricks that were used in diagonal tension tests of wall panels, were selected as the infill material, Fig. 2.1a. Infill wall of all the specimens were plastered and 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 Fig. 2.2 and summarized in Table 2.3.

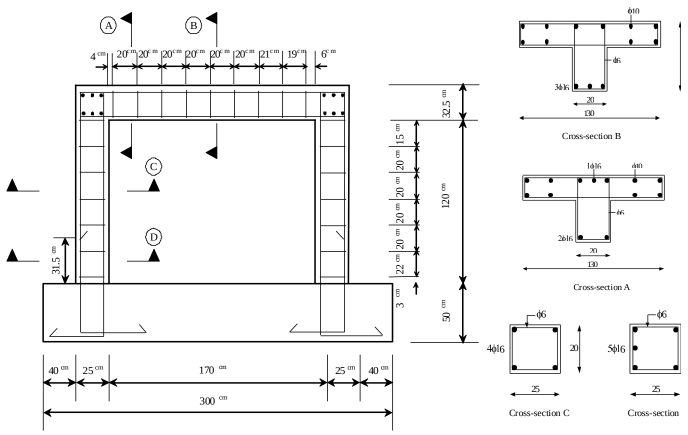


Figure 2.2. Dimensions and the reinforcing details of one story-one bay RC frame specimen

The reinforced concrete bare frame specimens and one plastered infilled frame (Specimen N1) were essentially the reference frames. Specimen N2 was an infilled frame strengthened by CFRP, Fig. 2.3a. 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.

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, Fig. 2.3b. 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 strengthening stages of Specimen N3 were identical to Specimen N2. Another application type was made at Specimen N4, Fig. 2.3c. 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.

Table 2.3. 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_{G1}^{+} (kN)	P_{G1}^{-} (kN)	K_{int}^{+} (kN/mm)	K_{int}^{-} (kN/mm)
Bare Frame-1	Bare RC frame	11.6	-	-	-	-	130.9	228.8	87.4	84.2
Bare Frame-2	Bare RC frame	14.2	-	-	-	-	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	228.3	227.9
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) (b) (c)

Figure 2.3. Specimen N2 (a), Specimen N3 (b) and Specimen N4 (c)

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, Fig. 2.4. 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%. 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.

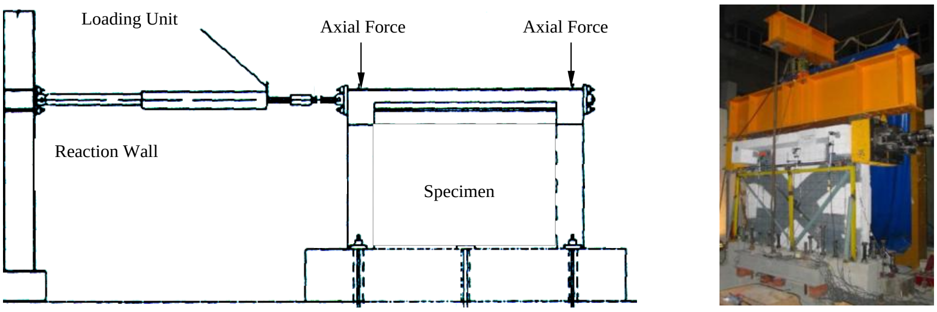


Figure 2.4. The testing setup of one story-one bay RC frame specimen tests

2.3. Test Results

2.3.1. Diagonal tension tests

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 2.2. Equivalent shear strength of the specimens were calculated for each specimen. Failure modes of all specimens were recorded and classified according to their types.

Equivalent modulus of elasticity (E_e) and equivalent compressive strength (f_{me}) of the specimens were calculated as well. These values were evaluated comparatively with the corresponding values recommended at Turkish Code for Building in Seismic Zones (2007). It was concluded that the values given in Seismic Code underestimated both modulus elasticity and compressive strength of infill walls made with the same type brittle bricks used in diagonal tension tests. Equivalent modulus of elasticity of non-plastered and plastered walls were calculated as 2500 MPa and 6000 MPa, respectively, from experimental data, while in Seismic Code it is given as 1000 MPa regardless of plaster existence. It is also observed that equivalent modulus of elasticity of plastered walls with strengthening may be taken as 6000 MPa. Similarly, equivalent compressive strength of non-plastered and plastered walls were obtained experimentally as 2 MPa and 5 MPa, respectively. In the Turkish Code for Building in Seismic Zones (2007) this value is recommended to be taken as 1 MPa for the infill walls made of same type of materials.

While establishing a structural 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 be derived from the experimental results and observations of diagonal tension tests of wall panels. For this purpose, vertical load-displacement (P-Δ) curves of specimens were represented by bi-linear curves. First of all, all the specimens were categorized. The P-Δ curves of specimens with similar parameters (i.e. plaster, CFRP, width of CFRP) were evaluated together and idealized as bilinear curves, (shown schematically in Fig. 2.5). Then, load and displacement values at these idealized curves were non-dimensionalized by using P_{max} and Δ_{max}. The slope of the second line was also given as a ratio of slope of the first line. Finally, these described values are investigated together in three categories, namely specimens without plaster, with plaster and with strengthening and plaster. The results achieved by this bi-linearization gave the approximate ratios of described values (i.e. load, displacement, and slope) for each category and could be used in structural model. Further details of test results of diagonal tension tests are given at Erol (2010).

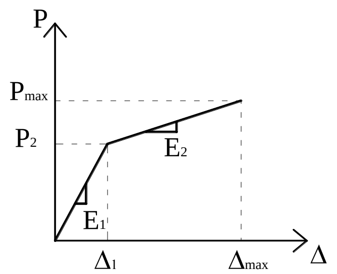
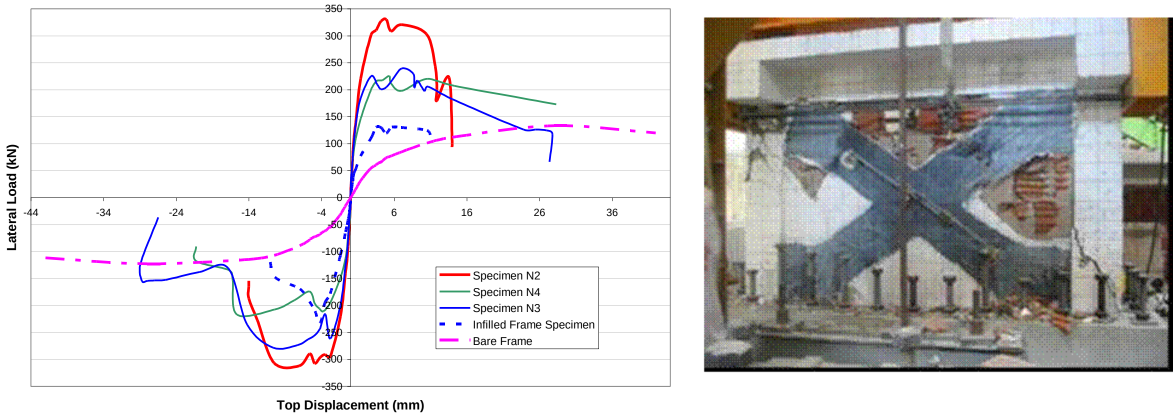


Figure 2.5. Schematic display of bi-linear P-Δ curve of diagonal tension test infill wall specimens.

2.3.1. One Story-One Bay RC Frame Specimens

Lateral load versus top displacement hysteresis loops of all the specimens and their envelope curves were obtained using experimental data, Fig. 2.6a. The important points on lateral load-top displacement envelopes and idealization of these envelopes as bi-linear are shown schematically in Fig. 2.7. Ultimate lateral loads of all specimens for pushing and pulling (P_{G1}^{+}, P_{G1}^{-}) are listed at Table 2.3. P_{G1}^{+} and P_{G1}^{-} values are different for some specimens as expected because of non-symmetrical behavior of plastic deformation for pushing and pulling. If a comparison is made in terms of lateral load capacity, it can be seen that lateral load capacity increased with strengthening infill walls by CFRP. The lateral load capacities of Specimen N2, N3 and N4 were approximately 1.79, 1.44 and 1.23 times of that of infilled reference frame N1, respectively. The difference of frame and infill material characteristics should also be considered while evaluating this comparison. 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 2.3 and Fig. 2.7. Effective stiffness (K_{eff}) and peak-to-peak stiffness values were obtained as well, Fig. 2.7 and 2.8a. It should be noted that the ratio of effective stiffness to initial stiffness of all specimens were approximately 10%. Energy dissipation values of specimens were calculated and shown all together in Fig. 2.8b. Energy dissipation values of bare frame specimens are lower, while there is no significant difference between the energy dissipation values of infilled reference specimen N1 and strengthened specimens. Three different definition of ductility were used for obtaining equivalent displacement ductility. Strength reduction factors were also calculated and evaluated comparatively. Behaviors of specimens were inspected closely during tests and damage stages were recorded in details. Failure mode of Specimen N3 is presented in Fig. 2.6b as an example. A collective damage index is generated for the specimens with CFRP strengthening using these observations. Further details of test results of diagonal tension tests are given at Erol (2010).



(a) (b)

Figure 2.6. The envelopes of hysteresis loops of all specimens (a) and failure mode of Specimen N3 (b)

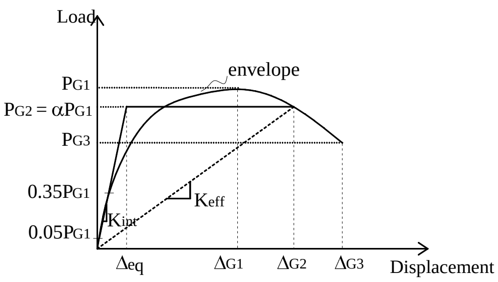
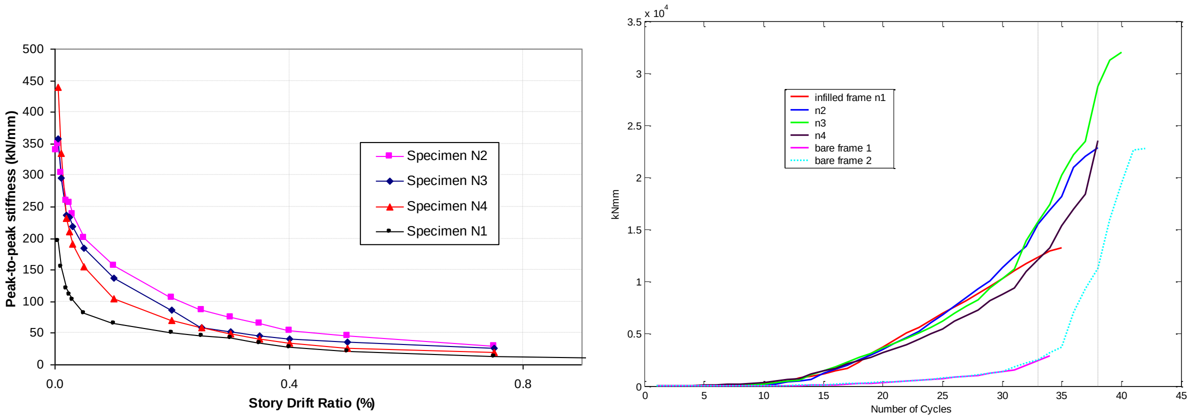


Figure 2.7. Idealization of envelopes of lateral load-top displacement envelopes of one story-one bay specimens.



(a) (b

Figure 2.8. Peak-to-peak stiffness degradation (a) and energy dissipation (b) diagrams of all specimens

3. THEORETICAL WORK

In the theoretical part of the research, structural models of the CFRP strengthened infilled one story-one bay RC frame specimens were established in order to achieve the generalization of experimental results of limited number of tests.

First of all, a structural model based on the principals that were given in Turkish Code for Building in Seismic Zones (2007) is prepared for reference specimens and strengthened specimens. Material nonlinearity and plastic hinge theory were utilized for pushover analysis, Fig. 2.9. Strengthened infill wall was represented by two equivalent struts (tension and compression) as recommended. The idealized load-displacement curves were taken from Seismic Code as well, Fig. 2.10. Analytical pushover curves and experimental results were compared, Fig. 2.11. Due to this comparison, some modifications made for the structural model. Diagonal tension and one story-one bay RC frame test results were used in modification as well as the experimental observations.

The main modifications of the structural model was performed for the compression strut of infill wall. Failure mechanisms and previous researches were also evaluated during this process. Finally, load-displacement curve given in Fig. 2.12 were chosen for compression strut in structural model. Load and displacement points shown in the figure were selected according to experimental findings. Material characteristics of infill wall (i.e. modulus of elasticity, compressive strength) were taken from experimental results as well. Analytical results of modified structural model compared well with the experimental results in terms of lateral load capacity and initial stiffness, Fig. 2.13. Further details on structural modeling are given at Erol (2010).

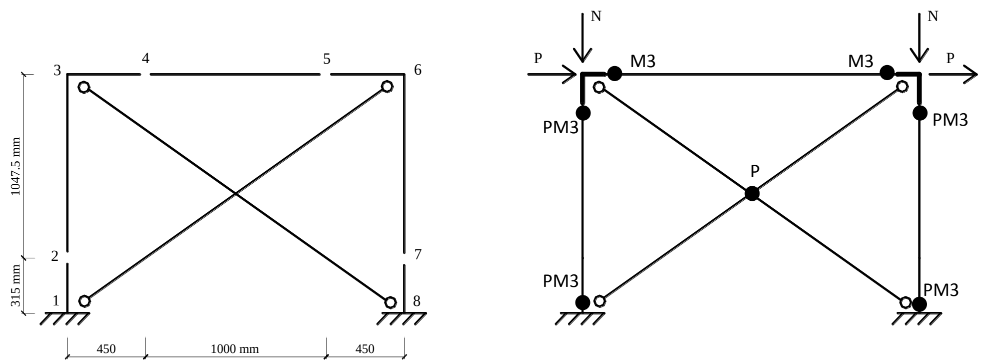


Figure 2.9. Structural model elements of one story-one bay RC frame specimens

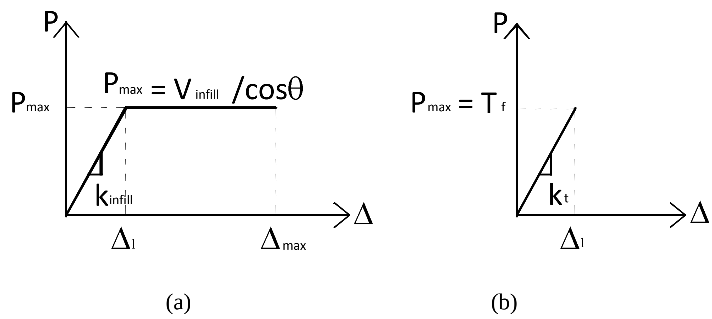


Figure 2.10. Load-displacement curves for equivalent compression (a) and tension (b) struts representing strengthened infill wall as recommended in Turkish Code for Building in Seismic Zones (2007).

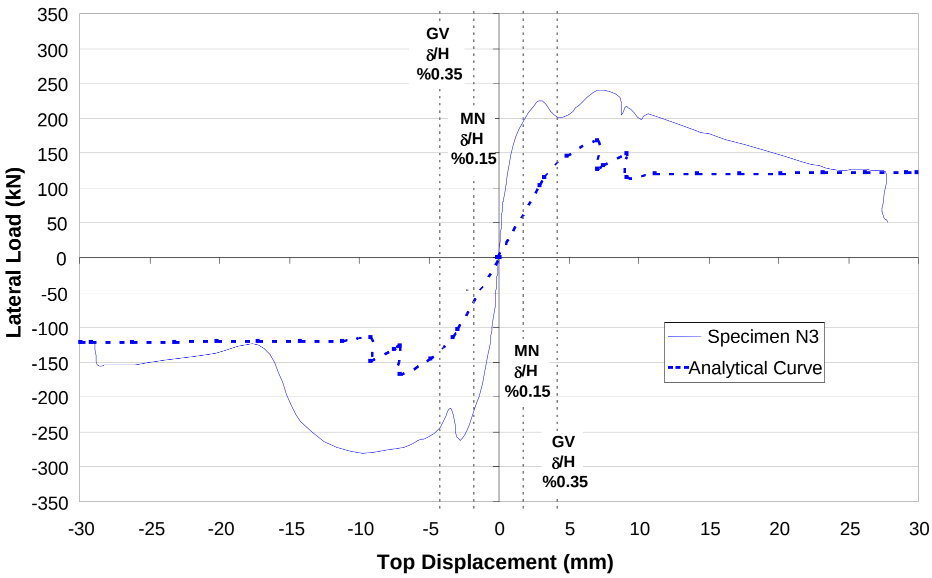


Figure 2.11. Analytically and experimentally conducted curves of strengthened Specimen N3.

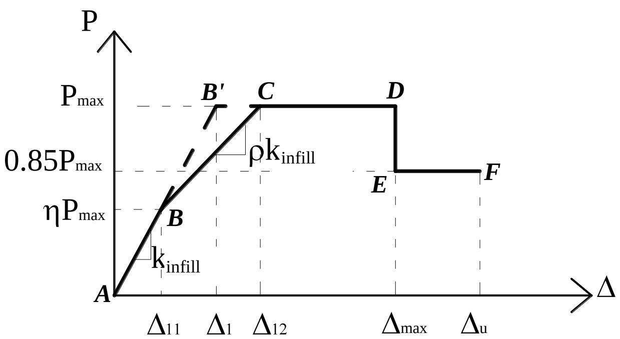


Figure 2.12. Load-displacement curve used for equivalent compression strut at the proposed structural model.

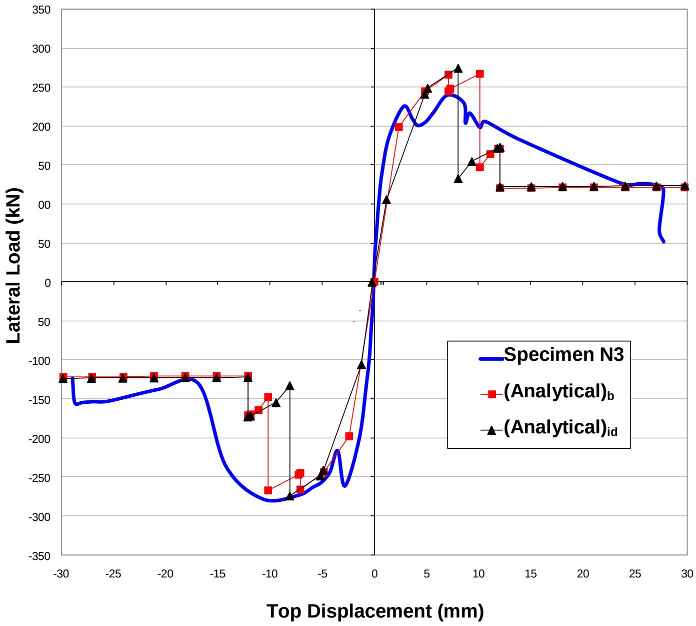


Figure 2.13. Analytical curve of Specimen N3 conducted by proposed structural model and comparison with experimental results.

4. CONCLUSIONS

The objective of the presented research was to evaluate seismic strengthening of infilled RC frames by CFRP in terms of lateral strength, stiffness and mechanical characteristics. For this purpose, the effects of CFRP strengthening to the overall behavior of the system and different application techniques were investigated experimentally and theoretically.

Experimental work consisted of two parts. The first part is the diagonal tension tests of 28 masonry wall panel specimens. The vertical load-displacement (P-Δ) curves and the shear stress-shear strain (τ-γ) curves were obtained from the experimental data. Shear modulus, equivalent modulus of elasticity, equivalent compressive strength and equivalent shear strength of the specimens were calculated. These values were evaluated comparatively with the corresponding values recommended at Turkish Code for Building in Seismic Zones (2007). P-Δ curves of specimens were represented by bi-linear curves, which were intended to be used in the structural modelling of one story-one bay infilled RC frame specimens.

Six one story-one bay reinforced concrete frame specimens were tested under the cyclic in-plane lateral loads in the second part of the experimental work. The lateral load-top displacement hysteresis curves and the failure modes of specimens were obtained from experimental data and observations. Initial stiffness, peak-to-peak stiffness, effective stiffness, equivalent displacement ductility, strength reduction factors, energy dissipation capacities and hysteretic damping ratios were calculated and evaluated comparatively. Envelopes of the lateral load-top displacement curves were idealized and special coordinates of this bilinear curves were estimated. A collective damage index was prepared for the CFRP strengthened specimens.

In the theoretical part of the research, structural models of the CFRP strengthened infilled one story-one bay RC frame specimens were established in order to achieve the generalization of experimental results of limited number of tests. Structural modelling was based on the principals that were given in Turkish Code for Building in Seismic Zones (2007), with some modifications made according to the experimental data and observations. Pushover analysis results compared well with the experimental results in terms of lateral load capacity and initial stiffness.

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REFERENCES

American Society For Testing And Materials. (1981). ASTM C 1391-81 : Standard Test Method for Diagonal Tension (Shear) in Masonry Assemblages, U.S.A., pp : 1-4.

Erol, G. (2010). RC Frames with Infill Walls Strengthened by CFRP, (In Turkish). *PhD. Thesis*, Istanbul Technical University, Istanbul, Turkey.

Karadogan, H.F., Yuksel, E., Erol, G., Saruhan, H. (2005). Low Strength Brick Infill Walls Strengthened by CFRP Fabric, Interim Report-II, Istanbul Technical University, Istanbul, pp 1-110.

The Ministry of Public Works and Settlement, (2007). Turkish Code for Building in Seismic Zones, p.166.