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EFFECTIVE STRENGTHENING OF RC FRAMES WITH AND WITHOUT LAP SPLICE PROBLEMS

G. Erol[1], C. Demir[2], A. Ilki[3], E. Yuksel[4] and H.F. Karadogan[5]

ABSTRACT

A series of tests were performed at ITU Earthquake and Structural Engineering Laboratory, for examining strengthening of poorly designed brittle brick infilled RC frame specimens by carbon fiber reinforced polymer (CFRP) composite fabrics. The aim of this experimental work was to reach an effective and economical strengthening technique without causing excessive disturbance to occupants. Seven ½ scale two story-one bay RC frames were tested under constant vertical load and reversed cyclic lateral loads. First three specimens were constructed with inadequate lap splices of longitudinal reinforcement of the columns at first and second story levels. The other four specimens were constructed with continuous longitudinal column reinforcement without any lap splicing problem. Each group of specimens included one reference bare frame, one infilled frame and one or two infilled frame specimens strengthened by CFRP fabrics. Two different methods were used for strengthening. For the first one, one ply of CFRP fabrics were pasted by epoxy over two diagonal directions of infill walls on both sides, while for the second method two plies of CFRP fabrics were applied only on one side of the specimens. Test results were evaluated in terms of lateral load capacities, stiffnesses and failure mechanisms. It is concluded that strengthening of the infill walls by applying CFRP composites in diagonal directions, provides significant enhancement in lateral strength and stiffness.

Introduction

It is well known that many existing structures in the seismic areas of the world are poorly designed and constructed. The strengthening of existing poorly constructed reinforced concrete frame structures are a major concern for Turkey. Considering the large stock of this kind of structures and economical situation of the country, extensive research on economical and easily applicable strengthening techniques are important.

[1]Research Assistant, Architectural Faculty, Istanbul Technical University, Taksim, 34437, Istanbul, Turkey.
[2]Research Assistant, Civil Engineering Faculty, Istanbul Technical University, Maslak, 34469, Istanbul, Turkey.
[3]Associate Professor, Civil Engineering Faculty, Istanbul Technical University, Maslak, 34469, Istanbul, Turkey.
[4]Assistant Professor, Civil Engineering Faculty, Istanbul Technical University, Maslak, 34469, Istanbul, Turkey.
[5]Professor, Civil Engineering Faculty, Istanbul Technical University, Maslak, 34469, Istanbul, Turkey.

Considering the infill walls as nonstructural members during design is a common assumption, which may sometimes lead to misprediction of the actual behavior of structures. The observations made after the recent major earthquakes in Turkey and research performed throughout the world have shown that the infill walls are actually important resources of strength, stiffness and damping under lateral loads. These contributions of the infill walls may be lost by premature damage during earthquakes. It may be an effective strengthening technique to keep the infill walls in their locations by strengthening the infill and RC frame elements together and force them to work as a whole until the end of the earthquake. Using fiber reinforced polymer composites for this kind of strengthening is recently an appealing area for the researchers.

In this study, seven ½ scale two story-one bay RC frames, which included two bare, two frames with infill walls and three frames with CFRP strengthened infill walls, were tested under constant vertical load and reversed cyclic lateral loads. The aim of the study was to understand the behavior of CFRP strengthened infilled RC frames experimentally and collect data to be used in theoretical work. At the end of the tests, it was observed that strengthening infill walls with CFRP composites in diagonal directions, provided significant enhancement in lateral strength and stiffness.

Experimental Work

The geometry, reinforcing details of the specimens and the loading protocol were selected considering the applications in practice, the room and loading capacities of laboratory and the structural features of earlier tests carried out at different institutions (Akguzel 2003), (Ersoy 2003). Some of the structural features of the specimens are tabulated in Table 1. In this table, f'_c refers to the concrete standard cylinder characteristic strength obtained at the end of 28 days.

Table 1. Structural features of the specimens

Specimen		f'_c (MPa)	Bare/Infill Wall	Longitudinal Reinforcement	Strengthening
First Group	BL-0-1-8.6	8.6	Bare	Lap spliced	No
	IL-0-1-17	17.0	Plastered infill wall	Lap spliced	No
	IL-C1-1-10	10.0	Plastered infill wall	Lap spliced	1 ply of CFRP diagonals on two sides
Second Group	BC-0-1-14	14.0	Bare	Continuous	No
	IC-0-1-11	11.0	Plastered infill wall	Continuous	No
	IC-C1-1-10	10.0	Plastered infill wall	Continuous	1 ply of CFRP diagonals on two sides
	IC-C2-1-22	22.0	Plastered infill wall	Continuous	2 plies of CFRP diagonals on one side

The cross-section dimensions of the columns of the specimens were 160 mm x 240 mm, while the dimensions of beam cross-sections were 240 mm x 240 mm. ϕ12 plain longitudinal bars of the columns had 20ϕ=240 mm lap splice length at the critical sections of three specimens

(first group) having lap splice deficiency, in order to represent the lap splice deficiencies encountered frequently in practice, see Figure 1. It should also be noted that no hooks were formed for the longitudinal bars at the end of the splices. For the other five specimens (second group) the longitudinal bars of the columns were continuous at the foundation and interstory levels, see Figure 1.

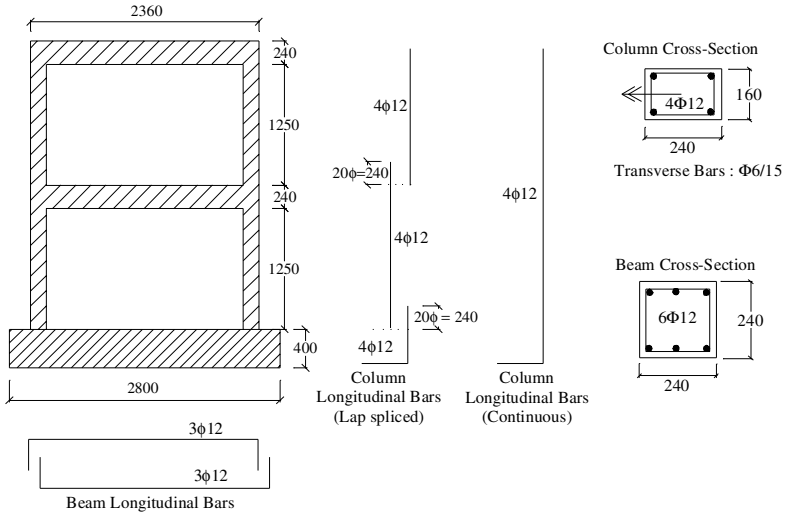


Figure 1. Dimensions and reinforcing details of specimens (all dimensions are in mm)

Five of the specimens were eccentrically infilled with 135 mm x 200 mm x 200 mm brittle bricks, which were cut in half in the transverse direction to the holes. Low strength brittle bricks that are widely used in the nonstructural partitioning walls in Turkey, were selected as infill material. The compressive strength of this type of bricks in the direction of the holes was between 2.5 and 10 MPa, and the void ratio of bricks was around 60%. The water:cement:lime:sand volumetric mix-proportions of the mortar was 1:1:0.5:4.5 and the thickness of the mortar layer was around 10 mm. All infilled frames were plastered and the thickness of the plaster was around 10 mm. Different types of specimens are presented in Fig. 2.

The general appearance of three strengthened specimens, with continuous and lap spliced longitudinal reinforcements, are presented in Fig. 3. One ply of CFRP fabrics were applied on both sides of the first specimen with lap splice deficiency and the second one with continuous longitudinal reinforcement. The third specimen with continuous longitudinal reinforcement was strengthened by two plies of CFRP fabrics that were applied only on one side of the specimen.

The first stage of the two sided CFRP application was same for two specimens, (IC-C1-1-10 and IL-C1-1-8.6). One ply of CFRP fabrics were bonded in diagonal directions on both sides of the infill walls of upper and lower stories, using epoxy resin. Diagonal CFRP on two sides of the infill were connected to each other by means of anchors made of CFRP. Load to be carried by diagonal CFRP fabrics was spread over a relatively larger area with the additional CFRP fabrics at the corners of the wall. The fibers of these layers of CFRP were oriented in two perpendicular directions, namely horizontal and vertical directions and they were connected to the beam/column by two CFRP anchors. Connection of diagonal CFRP fabrics to the foundation

were maintained by CFRP anchors as well. In order to make these connections, holes were drilled in frame elements and foundation, cleaned thoroughly and filled with epoxy. CFRP fabrics were then folded and placed into these holes. The fibers that were left outside were spread and bonded on the wall using epoxy resin.



Figure 2. Different types of specimens

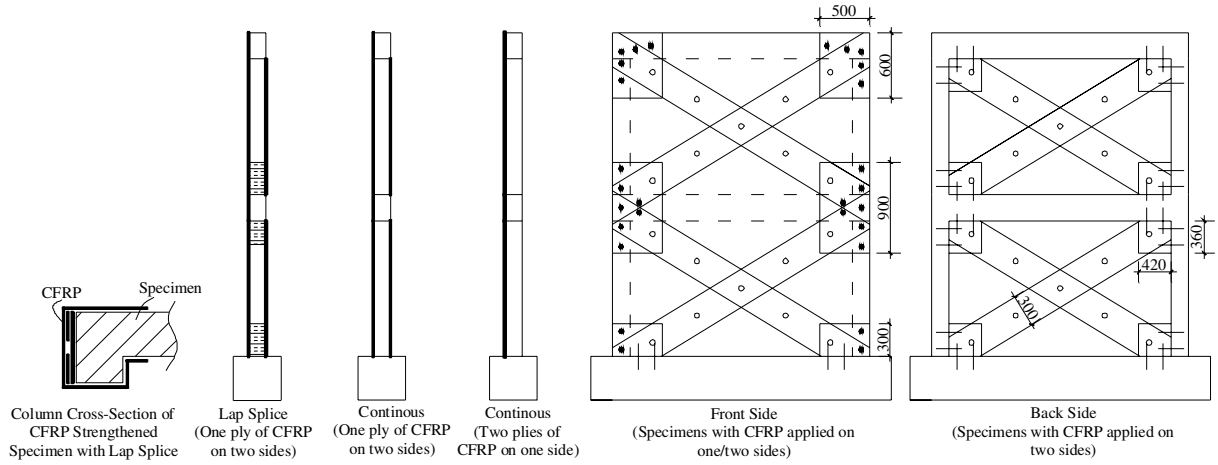


Figure 3. General view of the strengthened specimens (all dimensions are in mm)

In addition to the strengthening procedure explained above, for the specimen with lap splice deficiency (IL-C1-1-8.6), some extra measures were taken. For suppressing the lap splice deficiency, CFRP fabrics with fibers in vertical direction, were bonded on the sides of the column, parallel to the column longitudinal reinforcement, see Fig. 3. Then two CFRP anchors were placed at the foundation level. Finally one ply of transverse CFRP fabric was bonded on these areas for confining the column and extended over the infill wall. The strengthening procedure of the specimen, where CFRP applied only on one side (IC-C2-1-22), was similar to the previous ones. Two plies of CFRP were pasted on the diagonals and at the corners, in order to keep the effective width of CFRP fabrics same. Load to be carried by diagonal CFRP fabrics were spread by the additional CFRP as it was explained above.

It should also be noted here that at the first test of IL-C1-1-8.6, the depths of CFRP anchors in the foundation were about 100 mm, which were not sufficient enough to transfer the tensile forces from the diagonal CFRP fabrics to the foundation. Thus, these anchors were pulled

out and an early failure was observed. Before it was retested, damage at the lower corners of the first story infill wall had been repaired, CFRP anchors had been rebuilt and epoxy had been injected into the bending cracks of the first story columns. This time the depth of CFRP anchors was 160 mm, which proved to be sufficient after the test.

12 mm diameter plain steel reinforcement was used for the longitudinal beam and the column bars. Experimentally obtained stress-strain relationships of the mild reinforcing steel are shown in Figure 4.

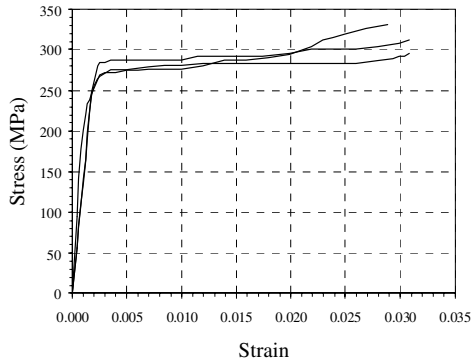


Figure 4. Stress-strain relationships of longitudinal reinforcement

Unidirectional high strength CFRP fabrics were used during the strengthening process. The mechanical properties of CFRP fabrics as supplied by the manufacturer are given in Table 2. Further features of the experimental work are presented by Yuksel 2005.

Table 2. Mechanical properties of CFRP

Fiber Type	**Fiber Orientation**	**Weight** (g/m^2)	**Fabric Design Thickness** (mm)	**Tensile Strength of Fibers** (N/mm^2) (Nominal)	**Tensile E-Modulus of Fibers** (N/mm^2) (Nominal)	**Strain at Break of Fibers** (Nominal)
High strength carbon fibers	0°	220± 10%	0.12	4100	231000	1.7%

Testing Setup

The general view of a specimen at the testing stage is shown in Fig. 5, together with the necessary adapter pieces and the devices used for applying lateral and vertical loads on to the specimen.

All the loading was applied through displacement control using the external displacement transducer positioned at the level of the second story. Two MTS actuators, each having ±250 kN and ±300 mm displacement capacities, were used for this purpose. The load

was distributed to the stories as the support reactions of the rigid steel loading beam connected to the actuators, keeping the constant lateral load distribution in the ratio of 2/3 and 1/3 for the second and first stories, respectively. It should be noted that two actuators were controlled separately. The axial force, which was approximately 23% of the axial load capacity of RC columns, was applied to each column by a hydraulic jack through a steel beam and measured by a load cell, Fig. 5.

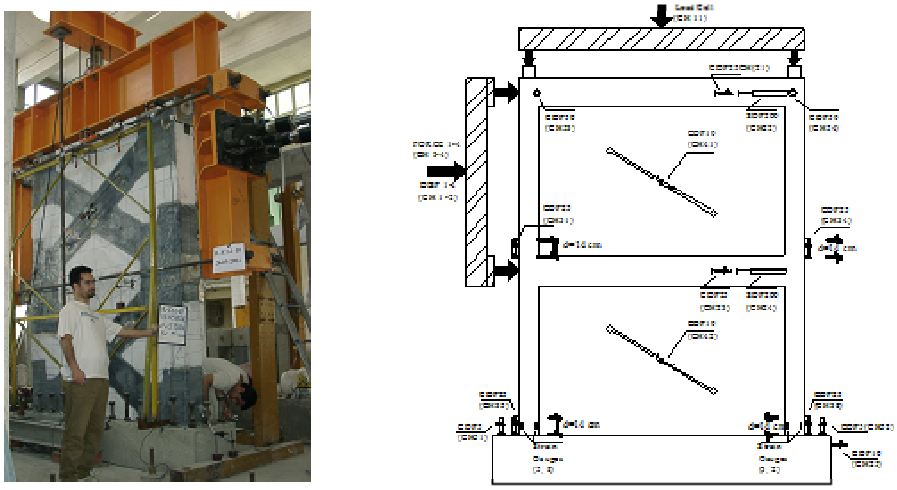


Figure 5. The general view of a specimen at testing stage and locations of measuring devices

The lateral displacements at story levels, in-plane and out-of-plane movements of the foundation and specimen, the critical column section rotations and the infill walls' diagonal deformations were measured and recorded by the linear variable displacement transducers (LVDTs). Strains of the column longitudinal bars at the critical column sections were also measured with strain gages.

Test Results

Experimentally found base shear versus top displacement curves of the bare and the infilled frame specimens with continuous longitudinal reinforcement, namely BC-0-1-14 and IC-0-1-11 are drawn together in Fig. 6. It can be seen from these curves that the lateral stiffness of the infilled frame, IC-0-1-11, is significantly high and the ultimate load of IC-0-1-11 is approximately 4 times higher than the bare frame, BC-0-1-14. However, it should be pointed out that this increase could not be sustained until high displacement levels.

Experimentally found base shear versus top displacement curves of the bare and the infilled frame specimens with lap splice deficiency, namely BL-0-1-8.6 and IL-0-1-17 are drawn together in Fig. 7. The stiffness and lateral load capacity of the infilled frame IL-0-1-17 is significantly higher than the bare frame BL-0-1-8.6 .

Experimentally found base shear versus top displacement curves of the two sided CFRP applied infilled frame specimens with and without lap splice deficiency, namely IC-C1-1-10 and IL-C1-1-10 are shown in Figs 8 and 9, respectively. Base shear versus top displacement curves

of the one sided CFRP applied infilled frame specimen without lap splice deficiency, namely IC-C2-1-22, is given in Fig. 10. The envelopes of the base shear-top displacement curves of all specimens are also shown together for a better comparison Fig. 11.

The damage accumulated at the beam-column joints and the lower parts of the first story columns at the bare frame specimens, while bending cracks were spread along the columns of the infilled specimens. Although one or two diagonal cracks were formed on the infill walls prior to retrofitting of the specimens, the crucial damage of the infills was corner crushing. The contribution of the infill walls to the lateral load capacity of the specimen seemed to end after corner crushing.

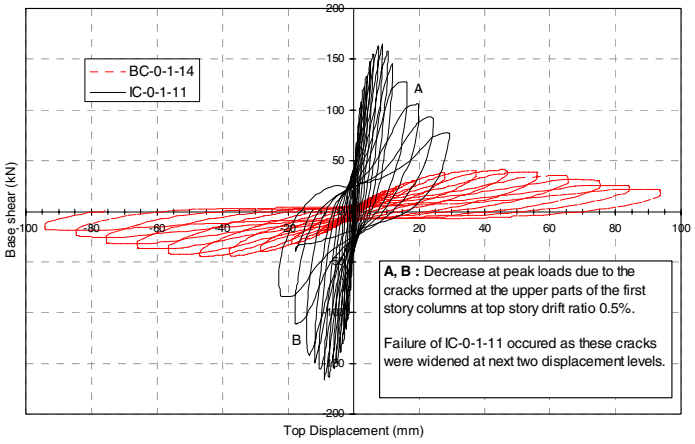


Figure 6. Base shear versus top displacement curves of BC-0-1-14 and IC-0-1-11

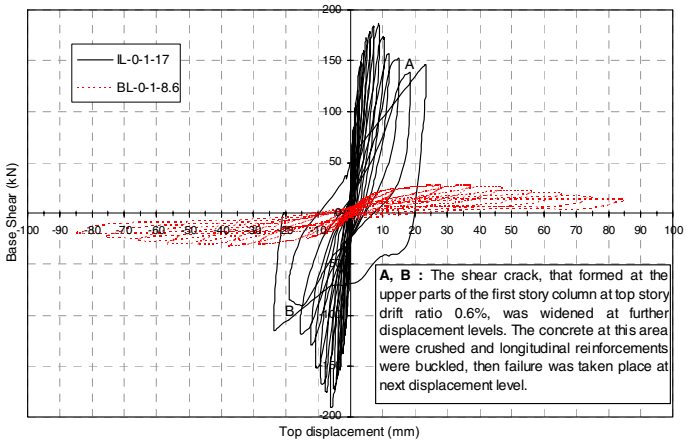


Figure 7. Base shear versus top displacement curves of BL-0-1-8.6 and IL-0-1-17

Bending cracks were formed on the frame elements at the early stage of the tests of CFRP strengthened specimens, diagonal cracks were observed on the infill walls and diagonal CFRP fabrics debonded partly over the infill. After the diagonal CFRP fabrics were broken one after the other at the following displacement levels, the failure of the specimens took place due to the wide shear cracks formed at the upper parts of the first story columns.

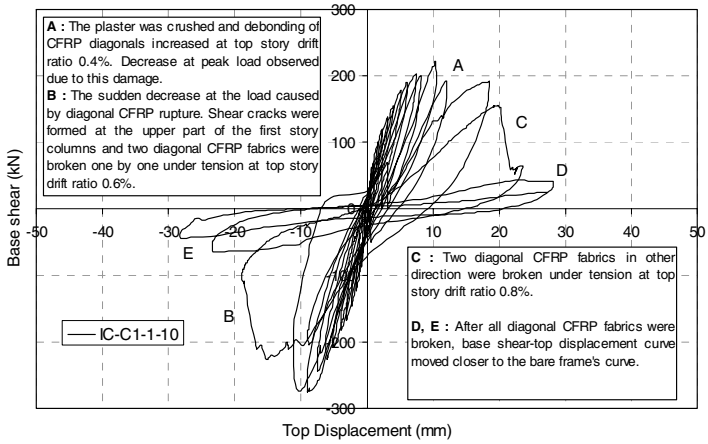


Figure 8. Base shear versus top displacement curve of IC-C1-1-10

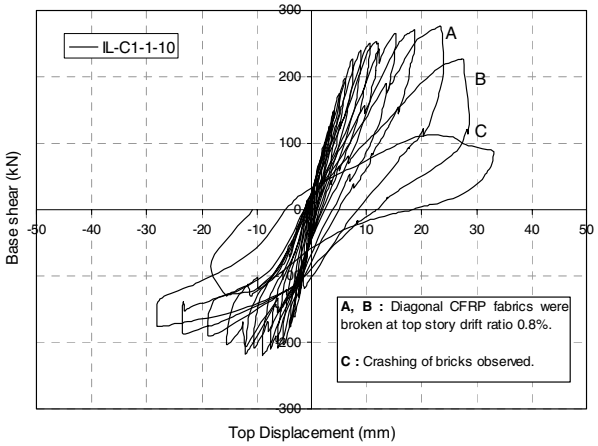


Figure 9. Base shear versus top displacement curve of IL-C1-1-10

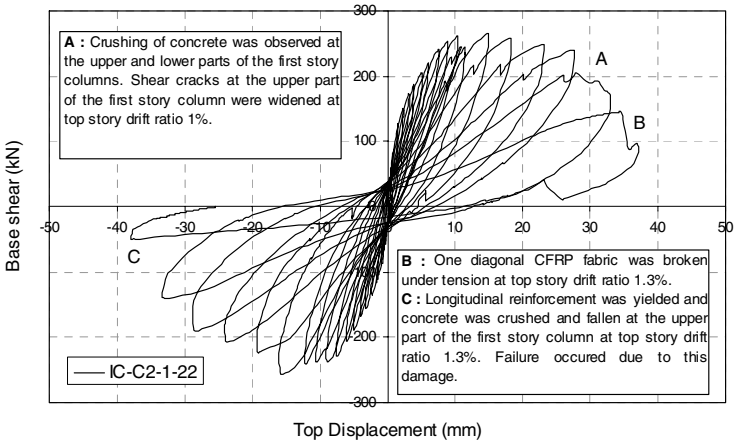


Figure 10. Base shear versus top displacement curve of IC-C2-1-22

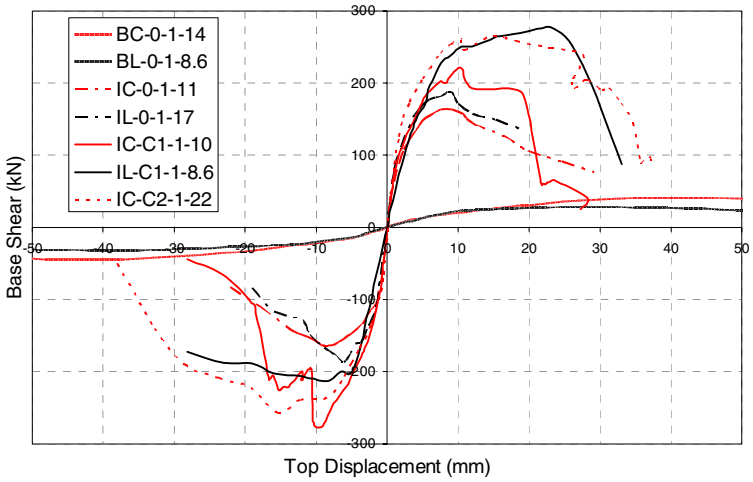


Figure 11. Envelopes of base shear versus top displacement curves of all specimens

The initial stiffnesses of the unstrengthened infilled specimens IL-0-1-17 and IC-0-1-11 were very close to each other but the ultimate lateral load of IL-0-1-17 was approximately 15% higher than IC-0-1-11. Although this proportion was expected to be vice versa, as IL-0-1-17 had lap splice deficiency, it should be noted that the compression strength of the concrete used at IL-0-1-17 was higher than IC-0-1-11.

The results of IL-C1-1-8.6 indicate that the behavior of the specimen at pulling and pushing was not symmetrical. Simply because of that, the results of IL-C1-1-8.6 can not be generalized for the lap splice improvement by CFRP application.

One more specimen will be tested which has lap splice deficiency and strengthened by CFRP applied on one side of the specimen. The tests results of this specimen may give a chance to make a better comparison about lap splice deficiency.

Conclusions

The results that were reached by the evaluation of the base shear versus top displacement curves, failure modes and the observations made during tests, are presented below.

- Application of two point lateral loads at the story levels by a rigid beam, controlled the failure mechanisms of specimens and as a result, damage of the frame elements and the infill wall of the second story were limited. The critical sections were the upper parts of the columns and infill walls of the first story.
- The lateral strength and stiffnesses of the infilled specimens were significantly higher than the bare frame specimens. The damage formations indicate that the bare frame specimens' frame type behavior changed into shear wall type behavior by the introduction of the infill walls.
- Strengthening the specimens by CFRP prevented corner crushing of the infill wall and the diagonal cracks spread over the whole infill. Although the infill walls were severely damaged at the end of the tests, total collapse of the infill walls was not observed.

- CFRP anchors placed into the foundation and the frame elements worked properly until the end of the tests. CFRP anchors that connected diagonal CFRP fabrics on both sides of the infill walls, prevented CFRP from debonding. This kind of behavior was observed clearly at IC-C2-1-22, where diagonal CFRP was applied on one side of the specimen and connected to the plastered infill wall on the other side by CFRP anchors.
- Strengthening the infilled frame specimens by CFRP, increased the lateral load capacities and the lateral stiffnesses. The sudden load drops, observed at base shear versus top displacement curves due to diagonal CFRP rupture, showed that the contribution of diagonal CFRP on overall behavior is substantial. It should also be noted that even all the diagonal CFRP fabrics were broken, the specimens continued carrying lateral load and the base shear versus top displacement curves moved closer to the curves of the bare frame specimens.
- It can be said that the number of the displacement reversals before failure was increased by the contribution of CFRP. Consequently, the energy dissipation capacities of the specimens were increased by CFRP application.
- General observations and the test results of IC-C2-1-22 showed that CFRP application only on one side of the specimen were quite effective. This is an important advantage, as CFRP application on two sides may be not always be possible in practice. It should also be noted that the connection of CFRP diagonals that were on one side to the plastered wall on the other side by CFRP anchors improved behavior.

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