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Effectiveness of CFRP Repair on Shear-Damaged Substandard Captive Columns

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Abstract. The formation of captive columns is inevitable, especially in the boundary columns of the RC frames due to partial infill walls with the presence of openings. Such captive columns attract an excessive amount of shear forces causing brittle shear failure before attaining the flexural capacity of the column. A substandard RC frame with shear-damaged captive columns was repaired with Carbon Fiber Reinforced Polymers (CFRPs). Then the effectiveness of the applied structural repairing scheme with CFRP sheets was investigated through several response quantities of the tested RC frame. Flexural behaviour dominated the overall response of the bare frame (i.e., without infill wall) through the development of plastic hinges at the column ends. In the second specimen, a partial infill wall with a strip window opening was constructed to enforce the captive column defect. The captive columns were severely damaged by the formation of excessive shear cracks causing a brittle type of behaviour. The second test specimen having excessive shear-damaged columns was then repaired by wrapping the damaged columns with the CFRPs. The partial infill wall was removed from the repaired second specimen not to cause any captive column defect. After repeating the test on the repaired specimen, the former lateral load capacity of the damaged columns was exceeded without experiencing any shear failure. More importantly, the displacement capacity of the repaired specimen was increased considerably by wrapping the damaged columns with CFRPs.

Keywords: Captive-Column, Repair, CFRP, Shear Failure, Reinforced Concrete.

1 Introduction

Destructive earthquakes demonstrate that the majority of the existing RC buildings have poor seismic performance because of inadequate material quality, improper design applications, and detailing in RC members in contrast with the earthquake-resistant design principles [1]. To prevent the brittle type of behavior for RC buildings, seismic design codes have imposed several limitations on the formation of structural irregularities in the plan and elevation as well as non-ductile applications such as captive column, short column, strong beam-weak column, etc. The buildings which have one or more irregularities mentioned in TBEC (2018) [2] can be exposed to moderate to severe damage after the earthquake. Depending on the level of structural damage, the damaged buildings can either be demolished or repaired to satisfy the serviceability and life-safety limit state. Through conducting an appropriate repairing technique, the seismic capacity of the damaged members can be recovered or even improved compared to its original capacity.

A brittle type of shear failure was commonly observed in captive columns after damaging earthquakes. Captive column defect is mostly due to the presence of openings for strip windows provided in infill walls between the columns. Infill walls constrain the lateral displacement of the adjacent columns and hence the clear height of the corresponding columns becomes shorter, which causes a substantial increase in the column stiffness. Consequently, such columns, namely captive columns, attract an excessive amount of shear forces causing brittle shear failure before attaining the flexural capacity of the column. There are several studies in the literature on shear failure caused by short and captive column defects [3-5]. To prevent the shear failure of short columns, various techniques have been investigated by scholars [6-10]. Other than the retrofitting studies, there are numerous studies on the structural repairing of damaged RC components, such as beams, columns, and beam-column joints. However, there are limited number of studies that investigate the structural repair of damaged short or captive columns. Jayaguru and Subramanian [11] conducted an experimental study on the repairing of captive column failure by GFRP.

The objective of this study is to investigate the behavior of a substandard frame having captive column defect and the effectiveness of the CFRP sheets used for repairing the heavily damaged captive columns. For this purpose, two 1/3 scale, one-story one-bay substandard RC frames were constructed. After testing the RC frame with a partial infill wall, the damaged captive columns were repaired by CFRP sheets and retested with the same loading protocol. To examine the effectiveness of the repairing technique, the experimental results of the bare frame, the frame with captive column and the repaired frame were compared in terms of various response quantities.

2 Experimental program

2.1 Test specimen and material properties

Two 1/3 scale, one-story one-bay RC frames represent the existing substandard RC buildings in the Turkish RC building stock, which have certain deficiencies such as low-strength concrete, plain reinforcement bars, excessive spacing of ties and strong beam-weak column. The first test specimen (CFRPE_01) is the bare frame, which is considered as the reference specimen. The reference specimen was constructed without infill wall (i.e., bare frame). The second test specimen (CFRPE_02) was constructed with a partial infill wall between the columns leaving an opening to cause captive column defect. The ratio of the opening height to the wall height is approximately 25%. The geometric dimensions of the brick units and the overall infill wall dimensions were scaled in accordance with the scale of the RC frame. After severe damage was observed with the same loading history as the reference specimen, the damaged CFRPE_02 specimen was repaired with CFRP sheets, evolving to CFRPE_03. Before repair action, the damaged infill wall was removed from the frame and the damaged columns were wrapped with CFRP sheets. After the repair, no infill wall was constructed between the columns of CFRPE_03 to prevent the recurrence of the captive column defect. In case of any requirement for the construction of infill wall with the opening resulting in a captive column defect, the partial infill wall should be isolated from the frame with a sufficient amount of gap between the frame and the infill wall provided that the out-of-plane failure of the wall is prevented by taking relevant precautions. This will enable the frame to behave like a bare frame without the formation of captive column defects. All three tested specimens were subjected to similar lateral displacement loading protocol and vertical loading. Fig. 1 illustrates the geometric and reinforcement details of the tested specimens with the frame aspect ratio of 0.58. The aspect ratio is the ratio of frame-height (h) to frame-width (L). All specimens have the same column dimensions of 100 mm x 150 mm and, and beam dimensions of 150 mm x 150 mm respectively. The geometry and cross-section details of the one-story one-bay RC frames were obtained from the study of Akin et al. [12].

Longitudinal reinforcements have a diameter of 8 mm, which corresponds to a reinforcement ratio of 1.3% both for columns and beams. Additionally, plain bars, which have a diameter of 4 mm and are spaced at 100 mm, were used as transverse reinforcement for all members. The average values of yield strength, tensile strength, and modulus of elasticity were determined as 311 MPa, 417 MPa, and 200 GPa, respectively. The target compressive strength of concrete was selected to be 10 MPa to represent the low concrete strength. The unidirectional CFRP sheets were used in the repair of CFRPE_03. Some of the geometric and material properties of the CFRP sheets were provided by the manufacturer. The thickness is 0.111 mm, the modulus of elasticity is 230 GPa, the ultimate tensile strength is 4900 MPa and the ultimate strain is 2.10%. Before wrapping the columns with CFRP sheets, the shear cracks at the top of the columns were filled by injecting the chemical anchorage based on an epoxy acrylate resin.

2.2 Structural repair design

Depending on several constraints such as cost, viability, workmanship, etc., certain techniques can be applied to repair the damaged structural members. Based on the previous studies, it was decided to wrap the damaged captive columns with CFRP sheets, which was proved to be one of the effective techniques for retrofitting and repairing. After the occurrence of severe damage due to the shear cracks in the captive columns under the reversed cyclic lateral displacement (Fig. 2), repairing procedure was applied to the CFRPE_02 specimen.

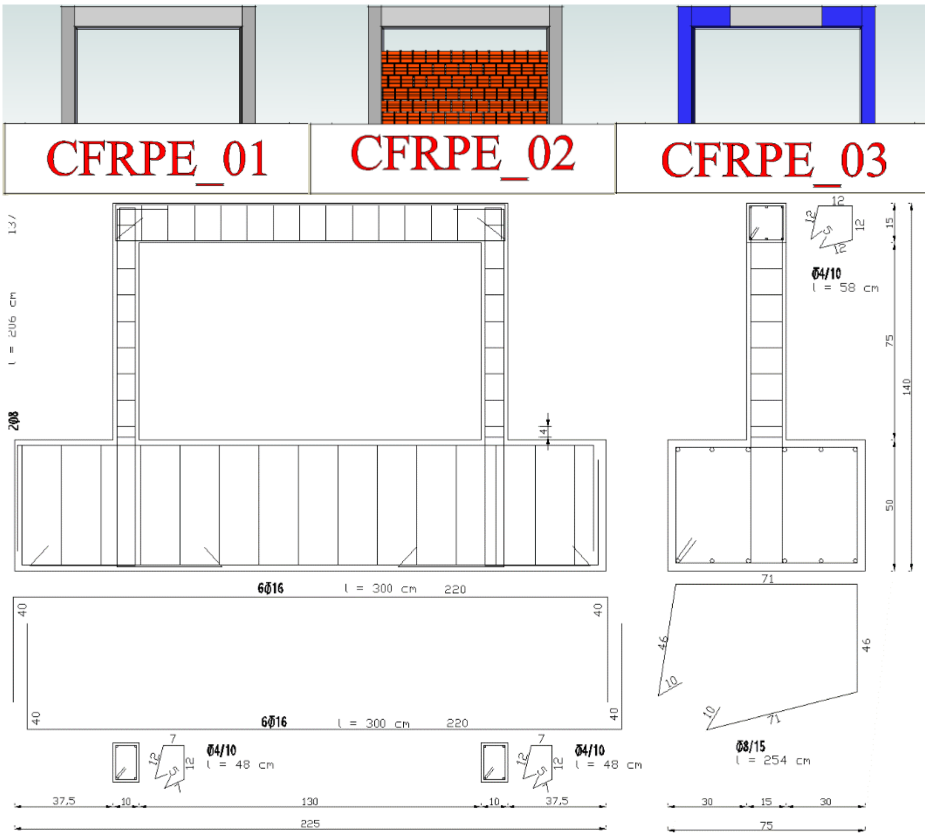


Fig. 1. Dimensions and reinforcement details of the test frames

Fig. 2. Excessive shear cracks on the captive columns before repairing (CFRPE_02)

Before the application of CFRP, the corners of the columns and beam members were rounded with a radius of 10 mm to get smooth corners for the RC sections (Fig. 3(a)). To fill the large shear cracks, observed at the top of the columns, an epoxy acrylate resin called chemical anchorage was injected into the cracks (Fig. 3(b)). The next step of the repairing procedure is the application of repair mortar in the place of spalled concrete (Fig. 3(c)). A primer epoxy coat was used to provide an efficient adhesion between the concrete and epoxy-based repair-anchorage mortar (Fig. 3(d)). The last step before the CFRP wrapping is to cover the repaired parts with an epoxy-based mortar for repairing the wide cracks and to provide a certain level of bonding between the repaired specimen and the CFRP sheets (Fig. 3(e)). Finally, the beam and the columns were wrapped by CFRP sheets with an epoxy resin before hardening the repair-anchorage mortar. The resin is used for establishing a connection between the CFRP sheets and the repair-anchorage mortar. Proper application of CFRP increases the flexural and shear capacity of the applied members (Fig. 3(f)).

(a) Rounding corners (b) Injecting chemical anchorage (c) Applying repair mortar

(d) Applying primer epoxy coater (e) Application of epoxy-based repair and anchorage mortar (f) Wrapping CFRP sheets with saturant material

Fig.3. Repairing procedure for the damaged captive columns

Although the main damage mechanism for the test specimen CFRPE_02 was the brittle type of shear failure at the captive columns, hairline shear and flexural cracks were observed in the beam and beam-column joints. Three layers of CFRP sheets with a width of 150 mm were placed over the joint regions to repair the hairline cracks on the joints. To improve the flexural capacity of the columns, two layers of CFRP sheets were placed longitudinally over the front and backside of the two columns along the direction of the loading. The longitudinal CFRP sheets with a width of 150 mm were extended over the foundation and the beam by 300 mm. The CFRP sheets, which were used for improving the shear capacity of the columns and confining purposes, were placed with three layers continuously through the columns in the transverse direction. The beam was strengthened against the increased shear demands with three layers of 300 mm CFRP sheets applied in the transverse direction from the joint at both ends. For the CFRP sheet configuration employed in this study, the shear capacity of the column was calculated according to Eq. (1) and determined as 22 kN without considering the contribution of the concrete and the stirrups of the damaged captive columns.

$$V_F = \frac{2n_f t_f \omega_f E_f \varepsilon_f d}{s_f} \quad (1)$$

The test system was instrumented to record strain values at critical reinforcement rebars, displacements, and lateral load. These data were used to calculate the response quantities. All the specimens were tested under the combined action of constant column axial load and reversed cyclic lateral displacement. The constant vertical load, which is 10% of the axial load capacity of the columns, was determined by the minimum axial load for the columns according to TBEC (2018) [2].

3 Test results

3.1 Observed damage

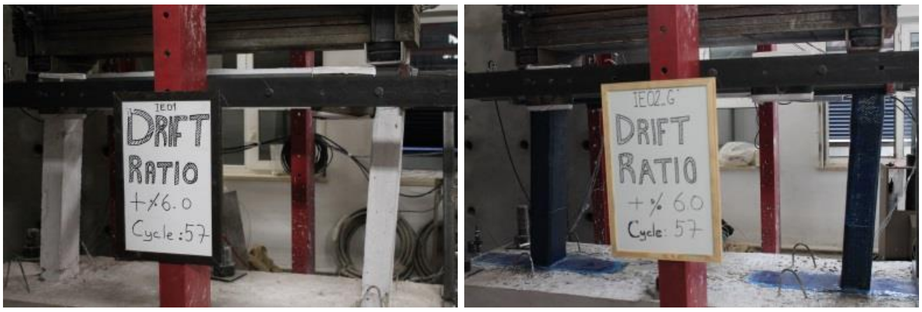
The first frame (CFRPE_01) was the reference frame without an infill wall (i.e., bare frame). Flexural behavior dominated the overall response of CFRPE_01 with the concentration of the flexural cracks mostly in the columns. Under constant axial load and reversed cyclic lateral displacement, a ductile behavior was observed with limited lateral load capacity compared to the lateral load capacities of the other specimens. CFRPE_02 was the second test specimen with captive column defects. Due to the increased strength and stiffness with the presence of the partial infill wall, the maximum lateral load was obtained as 28.2 kN, which is more than 2.5 times the lateral load capacity of the reference frame. Flexural cracks started to occur from the beginning of the experiment at both columns and joints. When the drift ratio reached 0.5%, shear cracks occurred in the captive columns. A sudden drop in the lateral capacity of the frame was observed at 1.0% drift ratio. Because of the severe damage in the captive columns in the succeeding drift ratios, the test for CFRPE_02 was ended at the displacement of 16 mm (2% drift ratio) due to safety concerns. After the damage occurred in CFRPE_02, it was repaired with CFRPs and retested as CFRPE_03, which is the repaired frame. The maximum lateral load of CFRPE_03 was recorded as 21.8 kN, which is almost twice the lateral load capacity of the reference specimen. A strength deterioration was observed specifically in the second cycle for the 4.4% drift ratio in the positive direction and in the first cycle of the 4.3% drift ratio in the negative direction. Although a ductile behavior was observed up to 4% drift ratio, a sharp decrement occurred in the strength. The damage pattern of all the test specimens at 2% drift ratio is shown in Fig. 4a-c. Nevertheless, only CFRPE_01 and CFRPE_03 specimens can displace up to 6% drift ratio. The views from both specimens are presented in Fig. 5a-c to demonstrate the damage pattern at the ultimate displacement.

3.2 Base shear – Lateral displacement relations

To determine the lateral load as well as the displacement capacity of the tested specimens, base shear force vs. top displacement graphs were plotted as given in Fig. 6a-c. The total shear capacity of the CFRPE_01 specimen columns is computed as 24 kN as per TBEC (2018) [2]. As shown in Fig. 6(a), the columns did not reach their shear capacity and shear crack did not occur in CFRPE_01 specimen. The ultimate lateral load of CFRPE_02 was obtained as 28.2 kN and 25.0 kN in the positive and negative directions, respectively (Fig. 6b). A sudden drop in the lateral load was observed after attaining the peak lateral load values due to the shear damage at the captive columns. The calculated shear capacity is in good agreement with the lateral load capacity obtained from the test. Due to the reduction in the effective length of the captive column by the partial infill wall, the stiffness of the captive column increased considerably. As a result, the captive column attracted a shear demand exceeding its shear capacity. This phenomenon caused the shear failure of the columns, which violates the capacity design principles defined in TBEC (2018) [2]. Since the member cracks have remained under the CFRP layers, they could not be apparently seen in the CFRPE_03 specimen. After the 5% drift ratio, flexural cracks were observed at the middle part of the beam, which was not wrapped with CFRP. In Fig. 6(c), two sudden decrements of load values were monitored when the target drift ratio was 4% in the negative direction. However, the fracture of the CFRP sheets could not be apparently observed from the outer CFRP layers of the repaired specimen.

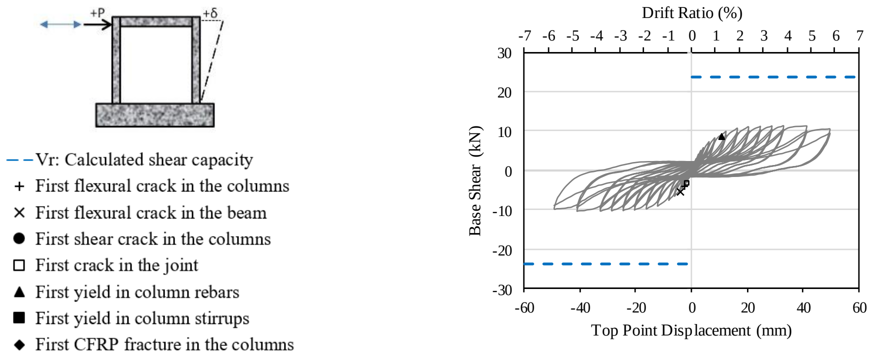
(a) CFRPE_01 (b) CFRPE_02 (c) CFRPE_03

Fig. 4. Damage pattern of the test specimens at 2% drift ratio

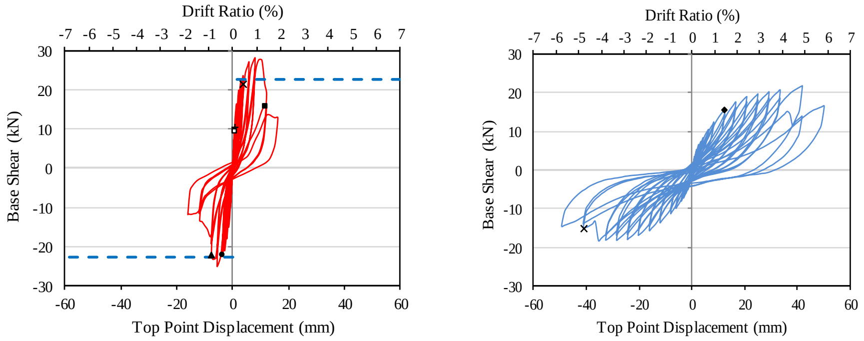


(a) CFRPE_01 (b) CFRPE_03

Fig. 5. Damage pattern of the test specimens at 6% drift ratio



(a) CFRPE_01



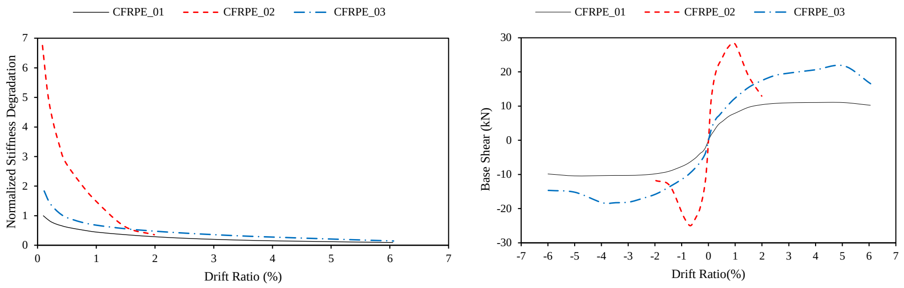
(b) CFRPE_02 (c) CFRPE_03

Fig. 6. Hysteretic loops of the specimens

Envelope curves were constructed by combining the ultimate lateral load values at the target displacement points at the first peak of each cycle, as seen in Fig. 7b. It can be inferred that the strength of the repaired specimen (CFRPE_03) is greater than the one for reference specimen (CFRPE_01). However, if the results were compared with the second specimen (CFRPE_02), the repaired specimen had a 23% lower strength value because of the contribution of the partial infill wall in CFRPE_02. For CFRPE_01, CFRPE_02, and CFRPE_03 specimens, the ultimate strengths were observed at 4%, 1%, and 5% drift ratios, respectively. Except for the CFRPE_02 specimen, the other two specimens can be displaced up to the test displacement limits.

3.3 Stiffness degradation

As the lateral displacement increased, the peak-to-peak lateral stiffness of the test specimens decreased very rapidly due to the formation of cracks and imposed plastic deformations (Fig. 7a). The peak-to-peak stiffness for each cycle was normalized with respect to the one for the reference specimen for the first cycle. CFRPE_03 specimen has a greater stiffness value than the reference specimen. However, after 2% drift ratio, both have very close stiffness values. Although the initial stiffness of the repaired specimen without infill wall is lower than the frame with partial infill wall, its stiffness is almost twice the initial stiffness of the reference specimen. This implies that CFRP wrapping can improve the stiffness of the damaged RC frames even more than its original stiffness values for the bare frame.



(a) Stiffness degradation

(b) Envelope curves

Fig. 7. Comparison of response quantities

4 Conclusions

This study focused on the effectiveness of CFRP sheets for repairing the damaged captive columns, which were exposed to shear damage. The following conclusions can be drawn:

- Depending on the damage level in the captive columns, the structural system can be further in service if effective repairing is applied to prevent the recurrence of the captive column defect in the repaired specimen.
- The lateral load capacity of the repaired specimen without infill wall is almost twice the one for the original bare frame. This result reveals that repairing the damaged captive columns with CFRPs can enhance the performance of its original undamaged bare frame considerably in terms of lateral load capacity.
- Although the test of CFRPE_02 was terminated at 2% drift ratio due to the severe damage in the captive columns, the repaired specimen can attain 6% drift ratio without any excessive strength deterioration. Although the columns were damaged severely in the previous test, wrapping them with CFRP sheets improved their ultimate displacement capacity considerably.
- The experimental results show that seismic repair of captive-column damage with CFRP sheets in substandard RC frames can rehabilitate and even improve the response of the undamaged bare frame.

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