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Research Article

Experimental Assessment of RC Beam-Column Connections with Internal and External Strengthening Techniques

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This paper presents the performance of reinforced concrete beam-column connections strengthened with carbon fiber-reinforced plastic (CFRP) sheets externally and steel bars internally. The work emphasized joint behavior under reverse cyclic loading to assess deformation capacity and strength. The study aims the existing buildings designed inadequately in joint sections. For experimental analysis, an exterior joint application was used. In strengthening, four different strengthening configurations were used. Each configuration was designed to illustrate the effect of strengthening at joint sections of the samples. Cyclic performance of the retrofitted samples compared to the control sample satisfies the current building code requirements. Test results indicated that bearing capacity and ductility of the connections were closely related to the original condition of the element and strengthening application.

1. Introduction

There are many reinforced concrete buildings needed to be upgraded according to the current building codes in Turkey, especially in big cities. This necessity comes up due to insufficient original design limits, construction errors, poor maintenance, or change in the use of the buildings. By now, various strengthening methods, mostly reinforced concrete jacketing method, were used; therewith, strengthening with fiber-reinforced plastics (FRPs), an alternative method, becomes a widely used one. On the contrary, a sufficient code for use of FRP strengthening techniques does not exist, and feedback of their application is not available. Therefore, there is a need to verify specifications about applications of strengthening techniques with FRP.

Carbon fiber-reinforced plastic (CFRP) is one of the widely used alternative materials in structural rehabilitation, strengthening, or retrofitting. Many academic studies indicate that using CFRP in structural rehabilitation, strengthening, or retrofitting is an effective way to increase the performance of the certain structural members that also would increase the performance of the buildings. Studies are mainly focused on the effect of strengthening techniques on the behavior of the beam under flexure and/or shearing, application techniques of the CFRP sheets on the behavior of the beam, and failure mechanism of the strengthened beam [1–11]; although there are plenty of studies about the subjects mentioned, only a few of them are referenced here. In the studies performed, besides the performance evaluation of reinforced concrete strengthened with CFRP under loads by means of increase in strength, the behavior of the strengthened beam is also categorized by the failure modes. Studies completed indicate that the failure modes in reinforced concrete members strengthened with CFRP are usually governed by concrete-CFRP debonding [12–14].

On the contrary, there are limited studies about strengthening RC beam-column connections with CFRP under cyclic loading [15–24]. It is well known that beam-column connections have a common structural weakness in detailing for seismic retrofitting. The reinforced concrete beam-column connections were typically nonengineered. The studies [25–33] about retrofitting of RC joints with FRP express the occurrence of strength increase in joint sections with brittle failure. In addition to all the studies about retrofitting reinforced concrete members, there are few studies about fatigue behavior of the strengthened members, expressing long-term behavior [34].

This study is mainly focused on behavior of the column-beam connection in the case of strengthening joints itself and in the case of strengthening whole column and/or beam. In the study, four different combinations of strengthening applications on a reinforced concrete beam-column connection were used: one was retrofitting the joint section only externally using CFRP; thus, in the case of strengthening the weaker joint section only, the response of the column-beam joint and whether the plastic hinges move to the beam can be seen. Second was retrofitting the joint section only internally using steel bars; the same reason for the previous scheme was also used here, but only the strengthening material was different. Third was strengthening the column and beam parts of the sample externally using CFRP and strengthening the joint internally. This scheme was designed to see how effective was the joint strengthening if the members were retrofitted. The last one was strengthening the whole sample including the joint section externally using CFRP. In this scenario, we could find whether the expected joint capacity was reached if the column-beam and the joint were wrapped by using CFRP. Therefore, contribution of the strengthening of the elements or joints to the performance of the column-beam joints may be understood.

2. Objective

The main objective of this research is to establish an effective approach for commercial applications of strengthening of reinforced concrete buildings. Commercial applications with FRP sheets in Turkey usually consist of wrapping the column and attaching the FRP component to the visible faces of the beam. Joints are usually neglected due to difficulty in application of any strengthening components. With the lack of codes about strengthening, many commercial applications were performed believing that any technique could provide strengthening. This study is focused especially on strengthening applications already used in the construction industry. Therefore, this study will provide understanding about the effectiveness of existing applications and how a strengthened sample comes close to a specimen designed in accordance with the local building code. Thus, we could find whether the strengthened member achieved the capacity comparable to the target.

3. Experimental Study

3.1. Specimens. A total of 6 full-scale specimens representing an exterior-reinforced concrete beam-column connection of a reinforced concrete (RC) frame were prepared and tested with reverse cyclic loading representing the effect of earthquake. All the specimens had identical dimensions. Beams were of 300 mm wide and 360 mm deep; columns were of 300 mm wide and 300 mm deep. One of the specimens (target) had an exterior T connection and was designed according to the current building code and had reinforcement in the joint section; one of the specimens was considered the control specimen that it did not contain any reinforcement in the joint section (control); and four of the specimens have been poorly detailed of both the joint section and the beam and column parts regarding shear (Samples 1 through 4). Columns had symmetrical 2Ø20 longitudinal reinforcement, and beams had longitudinal reinforcement 2Ø20 at top and 3Ø20 at bottom. Shear reinforcement of the target and control specimens was designed according to the local building code which was adopted from ACI 318. Shear reinforcement for specimens to be retrofitted was designed deliberately weak to resemble the existing buildings. Samples were placed when the load applied at the beam end created a counterclockwise moment, and bottom reinforcement would be under tension. Dimensions and reinforcement details are given in Table 1, and configurations of the samples are given Figures 1–3 for target, control, and specimens, respectively.

Based on the geometrical and reinforcement characteristics of the specimens, the beam moment resistance was $M_{rb} = 92.7$ kN·m where the longitudinal reinforcement of 3Ø20 was under tension and $M_{rb} = 64.9$ kN·m where the longitudinal reinforcement of 2Ø20 was under tension, the axial compression resistance of the column was $Nr = 1125$ kN, and the pure moment resistance was $M_{rc} = 55$ kN·m. The beam-column flexural moment capacity ratio ($\Sigma M_{rc}/\Sigma M_{rb}$) was equal to 1.69 while the moment was clockwise and 1.18 while the moment was counterclockwise. The plastic moment (ultimate moments) of the sections was obtained by multiplying the flexural moment capacity with 1.4. The used concrete compressive strength was measured from supplementary compression tests of six standard 150×300 mm cylinders. The mean value was equal to 30.3 MPa (age of 28 days). Steel yield strength was 423 MPa for the longitudinal bars and stirrups. The mix composition of the concrete is given in Table 2. The concrete mix design was made according to local building codes.

The samples retrofitted were expressed as follows and schematic representations of the strengthening techniques are given in Figures 4 and 5:

(i) Joint section of the sample was retrofitted by using CFRP externally only (Sample 1, Figure 4(a))

(ii) Joint section of the sample was retrofitted by using steel bars internally only (Sample 2, Figure 4(b))

(iii) Column and beam except joint are strengthened by using CFRP externally, only joint was strengthened by diagonal steel bar internally (Sample 3, Figure 5(a))

(iv) Whole sample was strengthened by using CFRP externally (Sample 4, Figure 5(b))

3.2. Materials. Materials used and their properties are listed in Table 3. Concrete was commercially available ready-to-use concrete manufactured according to the local building code TS EN 206-1. The other materials were obtained from the market. Materials properties of concrete were gathered by testing cylinder samples according to ASTM C873 standards.

Table 1: Characteristics of column-beam joint specimens.

Specimen ID	Column characteristics					Beam characteristics					Joint reinforcement	Retrofitting	
	Dimension	Longitudinal bars	Stirrups	ρ_l (%)	ρ_s (%)	Dimension	Longitudinal bars	Stirrups	ρ_l (%)	ρ_s (%)	Stirrups	In joint	In member
Target	300 × 300	4Ø20	Ø8/100	1.13	0.33	300 × 360	2Ø20 (top) 3Ø20 (bottom)	Ø8/100	1.13 1.69	0.33	2Ø10 (both directions)	—	—
Control	300 × 300	4Ø20	Ø8/100	1.13	0.33	300 × 360	2Ø20 (top) 3Ø20 (bottom)	Ø8/100	1.13 1.69	0.33	—	—	—
Sample 1	300 × 300	4Ø20	Ø8/300	1.13	0.11	300 × 360	2Ø20 (top) 3Ø20 (bottom)	Ø8/300	1.13 1.69	0.11	—	Externally retrofitted by CFRP	—
Sample 2	300 × 300	4Ø20	Ø8/300	1.13	0.11	300 × 360	2Ø20 (top) 3Ø20 (bottom)	Ø8/300	1.13 1.69	0.11	—	Internally retrofitted by 4Ø12 diagonal bars	—
Sample 3	300 × 300	4Ø20	Ø8/300	1.13	0.11	300 × 360	2Ø20 (top) 3Ø20 (bottom)	Ø8/300	1.13 1.69	0.11	—	Internally retrofitted by 4Ø12 diagonal bars	Externally retrofitted by CFRP
Sample 4	300 × 300	4Ø20	Ø8/300	1.13	0.11	300 × 360	2Ø20 (top) 3Ø20 (bottom)	Ø8/300	1.13 1.69	0.11	—	Externally retrofitted by CFRP	Externally retrofitted by CFRP

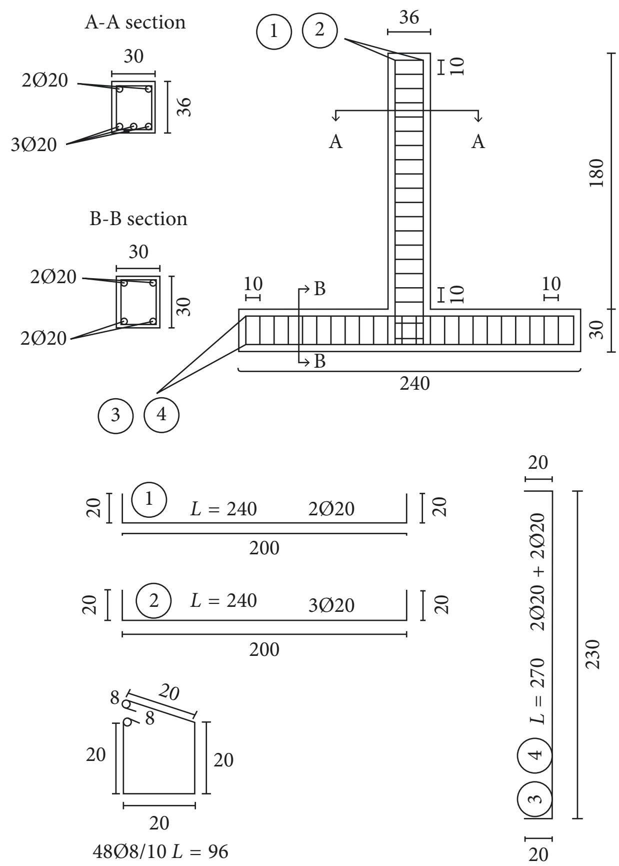


Figure 1: Design of reinforced concrete beam-column for the target sample.

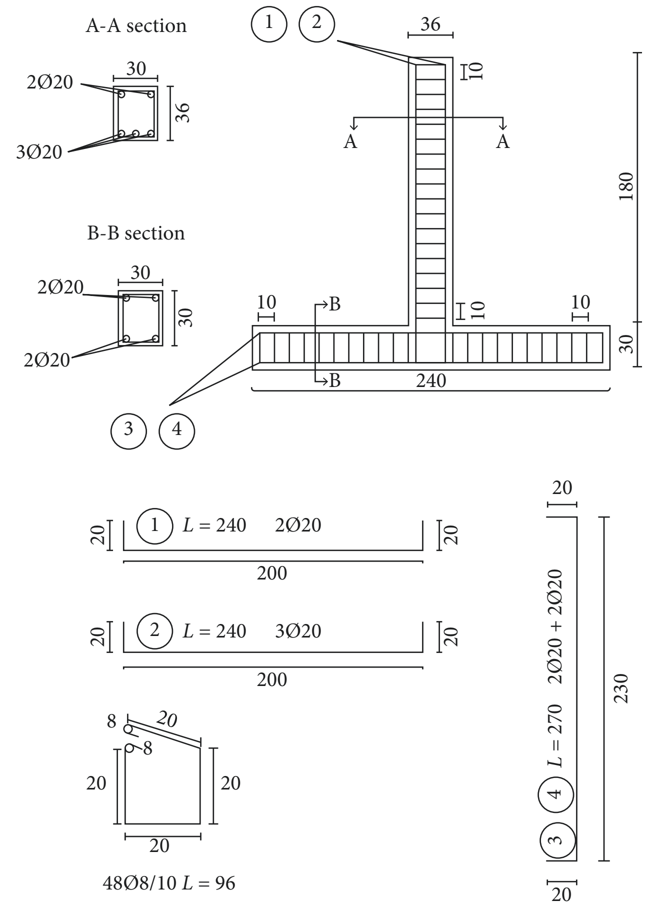


Figure 2: Design of reinforced concrete beam-column for the control sample.

3.3. Application of the Strengthening Components

3.3.1. Application of CFRP. Three specimens were strengthened using CFRP (SikaWrap 300C and 0.166 mm thick; properties of the CFRP are given in Table 2), CFRP was applied as two layers, and epoxy was applied as per the instruction given by the manufacturer. All the issues regarding application of epoxy and CFRP were taken cared of. In order to provide well wrapping, corner of the samples beveled; thus, debonding issue was minimized.

The reason for strengthening the whole sample with CFRP (Figure 5(b)) was to express the result of such commercial applications (many commercial applications are performed without engineering calculation in Turkey due to lack of any building codes for strengthening applications) and the effect of such strengthening on the connection points.

3.3.2. Application of Reinforcing Bars. Two of the specimens were strengthened with reinforcing bars (12 mm diameter ribbed rebar), and one of the specimens was strengthened with both steel bars and CFRP. The reinforcing bars were placed through the holes drilled diagonally in the connection, and end of the bars was anchoraged using epoxy. In Figures 4(b) and 5(a), placement of reinforcing bars for strengthening is displayed schematically. The application shown in Figure 4(b) aimed at strengthening of only the connection section in order to understand efficiency of the application.

3.4. Test Configuration. The test samples were placed in the loading system as shown in Figure 6. The lateral member represents the column, and it was loaded axially to have a constant compressive load in the column; the vertical member represents the beam and it was loaded horizontally at the top to have moment and shear effect about the joint. The loading system consists of two 500 kN load and 30 cm stroke capacity hydraulic pistons. The cyclic load was applied at the top of the sample. The horizontal member was loaded with 250 kN axial load using another hydraulic system. When the sample was loaded at the top, the axial load in the column may be changed slightly, and in order to keep the axial load constant, the pressure applied was adjusted each time.

The beam component of the sample was loaded with cyclic load as given in Figure 7 to represent the earthquake effect imposed to the free end of the beam (vertical member) by a pinned-end actuator, as shown in Figure 6. All specimens were loaded by the same cyclic loading. Each load cycle was repeated two times: ±10 kN 1st and 2nd, and ±20 kN 3rd and 4th loading stages, and loading was

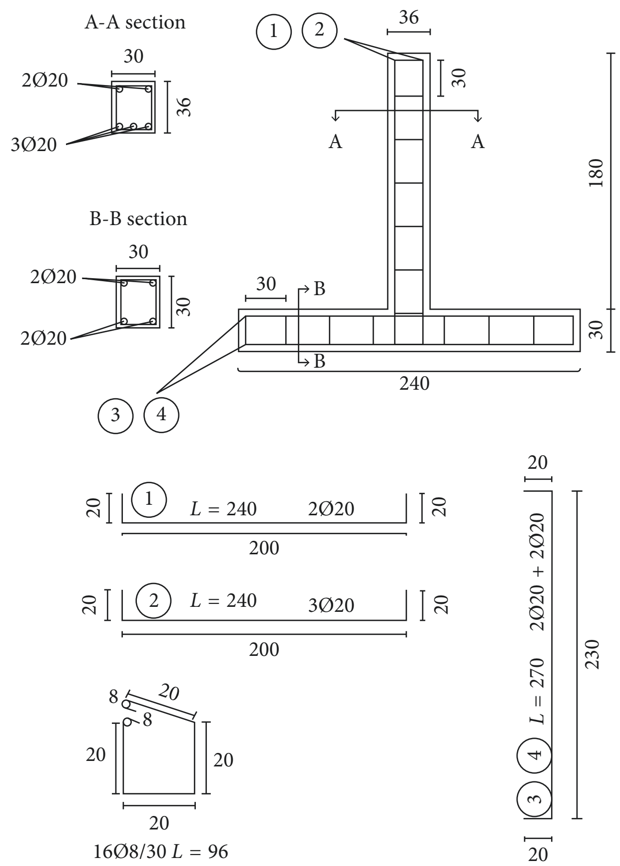


Figure 3: Design of reinforced concrete beam-column for Samples 1 to 4.

Table 2: Mix composition of 1 m^3 concrete.

Material	Weight (%)
Cement	17.4
No 2 aggregate (16–32 mm)	19.8
No 1 aggregate (4–6 mm)	17.7
No 0 aggregate (0–4 mm)	33.8
Water	11.2
Water/cement ratio	64.4

continued until the specimen failed. During loading, deformation of the specimens was measured by potentiometers (location of the potentiometers is shown in Figure 6).

3.5. Testing. The sample was placed the loading system as it is shown in Figure 8. At point marked A, the column was loaded with axial compression load, the sample was held at the other end marked B, a load cell was placed at the same location, and therefore the change in the axial load might be measured. At point marked C, the beam part of the sample was loaded horizontally to generate moment and shear at the joint section of the sample. The horizontal displacement at location C was measured by potentiometer located at the same location. At the joint section (marked D), the vertical and diagonal displacements were also measured.

In application of cyclic load, each cycle was repeated two times to the same load. All data from potentiometers were collected. The loading was continued until failure of the sample.

4. Experimental Results and Evaluation

To evaluate the effect of three different strengthening methods on behavior of a reinforced concrete beam-column connection, five test samples including a control sample were loaded with the same cyclic load history (Figure 7), and displacements from six different locations were collected. During testing, crack formations and failure were video recorded and failure modes were explained.

The testing of the samples is shown in Figure 8, and the vertical member is considered as "beam" and the horizontal member is considered as "column." The load-displacement graphics for each testing are given in Figure 9. The control sample started to crack at the beam's top surface (it is the "left side" in the figure, and that was under tension), while the load reached 20 kN, cracks were in small scale.

Next, the loading direction was changed, and when the load started to reach 30 kN causing counterclockwise moment, the cracks occurred at the bottom side of the beam (it is the "right side" in the figure, and this time it was under tension) that they were assumed to be flexural cracks. Later, the crack formation continued by increasing load. The joint failed at the load of 71.1 kN and displacement of 22.38 mm. The failure was brittle, which is an undesirable failure mode in reinforced concrete structures (Figure 10). Since it was an exterior beam-column joint, the concrete at the exterior side of the column at the beam level was collapsed.

In the sample retrofitted only at the joint by CFRP from outside (Sample 1), the first crack formed at the beam's top surface while the load reached 30 kN. When the crack formed at the top side of the beam, the loading was reversed, and the bottom side of the beam cracked at the load of 40 kN. Cracks occurred were classified as flexure cracks. Later, the crack formation continued by increasing load. At the same time while the load was increased to 50 kN, the diagonal deformation at the joint was measured to be 1.6 mm. The reinforcement at the top of the beam was yielded at the 67 kN load, and displacement was 14.47 mm. Following yielding, the load was reversed and the beam was loaded until bottom side of the reinforcement to yield. At this time, the yielding load was 82.46 kN (Figure 11). Although the capacity of the connection not increased, the sample exhibited better behavior compared to the control sample.

The sample retrofitted only at the joint by steel bars from inside (Sample 2) was loaded similar to the control sample. The first crack formed at the beam's top surface while load reached 20 kN. When the crack formed at the top side of the beam, the loading was reversed as it was done for the previous samples, and the bottom side of the beam cracked at the load of 30 kN. Later, the crack formation continued by increasing load. The reinforcement at top of the beam was yielded at the 70.6 kN load. At the same time while the load was increased to 70.6 kN, the diagonal deformation at the

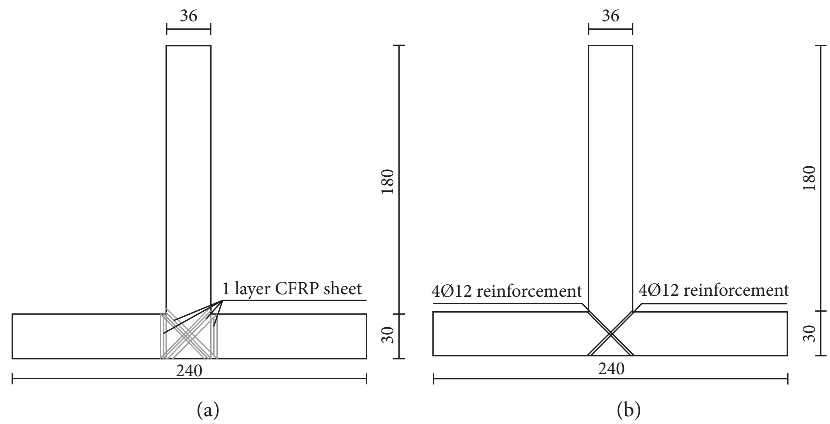


Figure 4: Schematic presentation of strengthening techniques: (a) Sample 1 and (b) Sample 2.

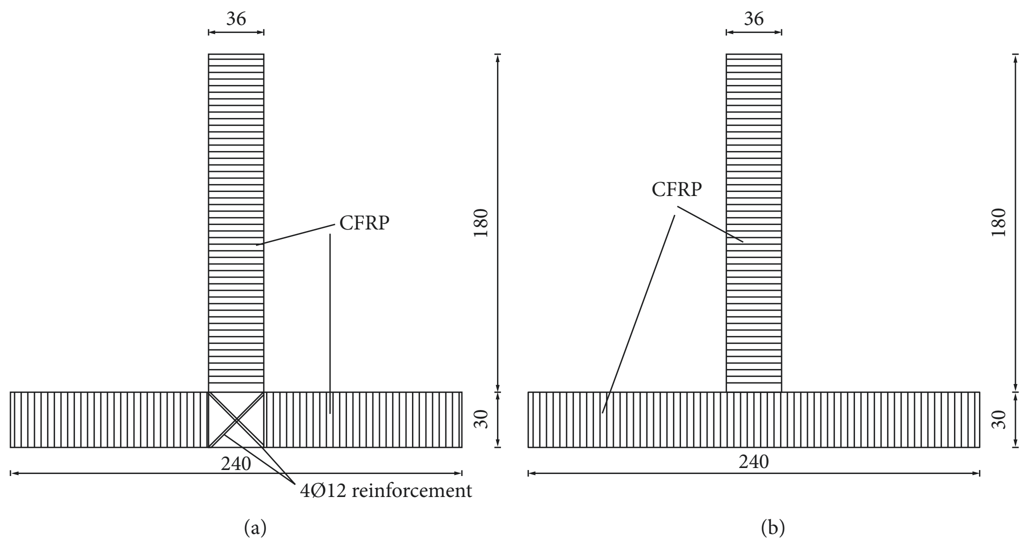


Figure 5: Schematic presentation of strengthening techniques: (a) Sample 3 and (b) Sample 2.

Table 3: Material properties of concrete, steel rebars, and CFRP sheets.

Material	Compression strength, f_c (MPa)	Yielding strength, f_y (MPa)	Ultimate strength, f_u (MPa)	Modulus of elasticity, E (GPa)
Concrete	30	—	—	
Reinforcing steel	—	420	500	200
CFRP sheets	—	3900	4100	230

joint was measured to be 1.6 mm. The load was reversed and the beam was loaded until bottom side of the reinforcement to yield. At this time, the yielding load was 88.2 kN (Figure 12).

In Sample 3, since the column-beam parts of the sample were wrapped with CFRP, any crack formation was invisible, cracks were observed after they propagated to the joint while the load was 50 kN. The reinforcement was yielded at the 59.6 kN load. Following yielding, the load was reversed and the beam was loaded until bottom side of the reinforcement to yield. At this time, the yielding load was 81.26 kN (Figure 13).

For Sample 4, again the whole sample is wrapped with CFRP, and any crack formation was invisible. The reinforcement was yielded at the 66.8 kN load. Following yielding, the load was reversed and the beam was loaded until bottom side of the reinforcement to yield. At this time, the yielding load was 94.1 kN (Figure 14).

The target sample was designed to represent the RC beam-column connection in accordance with the recent local building code that the connection contains stirrups at the joint section. The sample exhibited very ductile behavior. The sample had cracking first at the load of 40 kN, and it was on the beam 25 cm away from the column surface. It was

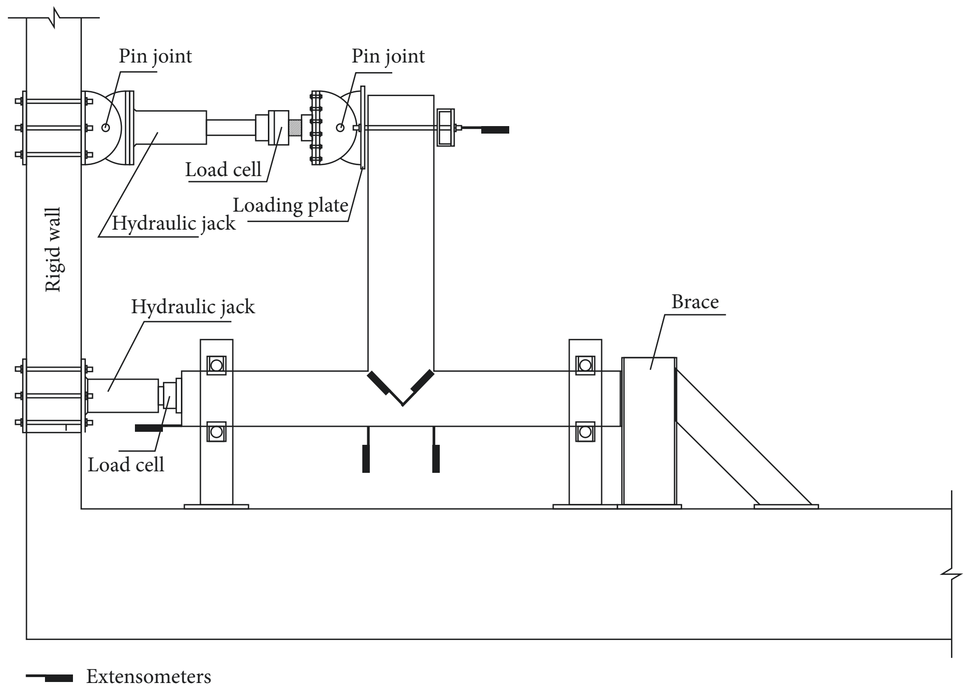


Figure 6: Schematic testing configuration.

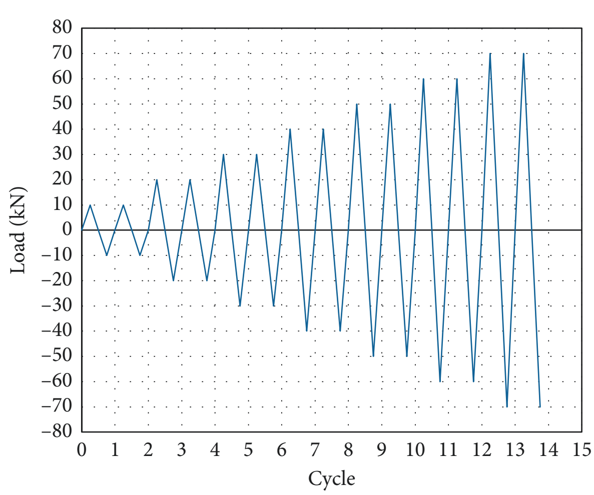


Figure 7: Load cycle graphics.

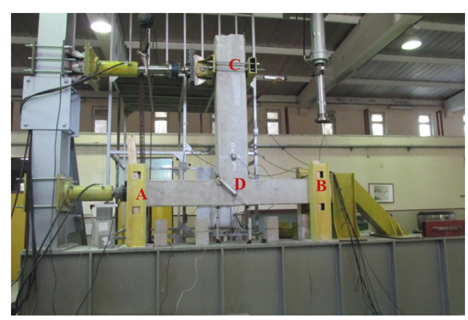


Figure 8: Loading system and a sample.

considered flexural crack. Later, the crack formation continued by increasing load. The sample failed at the load of 75.5 kN (Figure 15). The sample exhibited ductile failure as expected, and the capacity of the connection also increased.

The envelope curves of the response of the samples to cyclic loading are given in Figure 16. As it is seen from Figure 16, behaviors of the samples are controlled by weak longitudinal reinforcement in the beam. The effect of strengthening appears to be increasing the ductility in moderate amount relative to the control sample, but designing the joint as it is in the target sample provides considerable ductility that is desirable in reinforced concrete buildings.

Comparison of moment and shear capacity of the samples and failure locations are presented in Table 4.

5. Conclusions

Many strengthening applications are performed in order to increase the capacity of RC buildings. Studies performed indicated that strengthening applied to a beam or column increases the capacity. On the other hand, a combination of several types of strengthening may not give the desirable results. In this study, four different strengthening applications were studied. The results indicate that strengthening of a structure locally may not increase the capacity but may increase the ductility. This result is important because joint strengthening in reinforced concrete buildings does not necessarily provide capacity increase in all structures. Based on the test results, the following concluding remarks are derived:

(i) Joint-only strengthening technique applied in this study appears not to be effective it was expected. Results obtained from the testing of Sample 1 show that the amount of retrofitting in the joint section is not enough, and either the amount of CFRP or

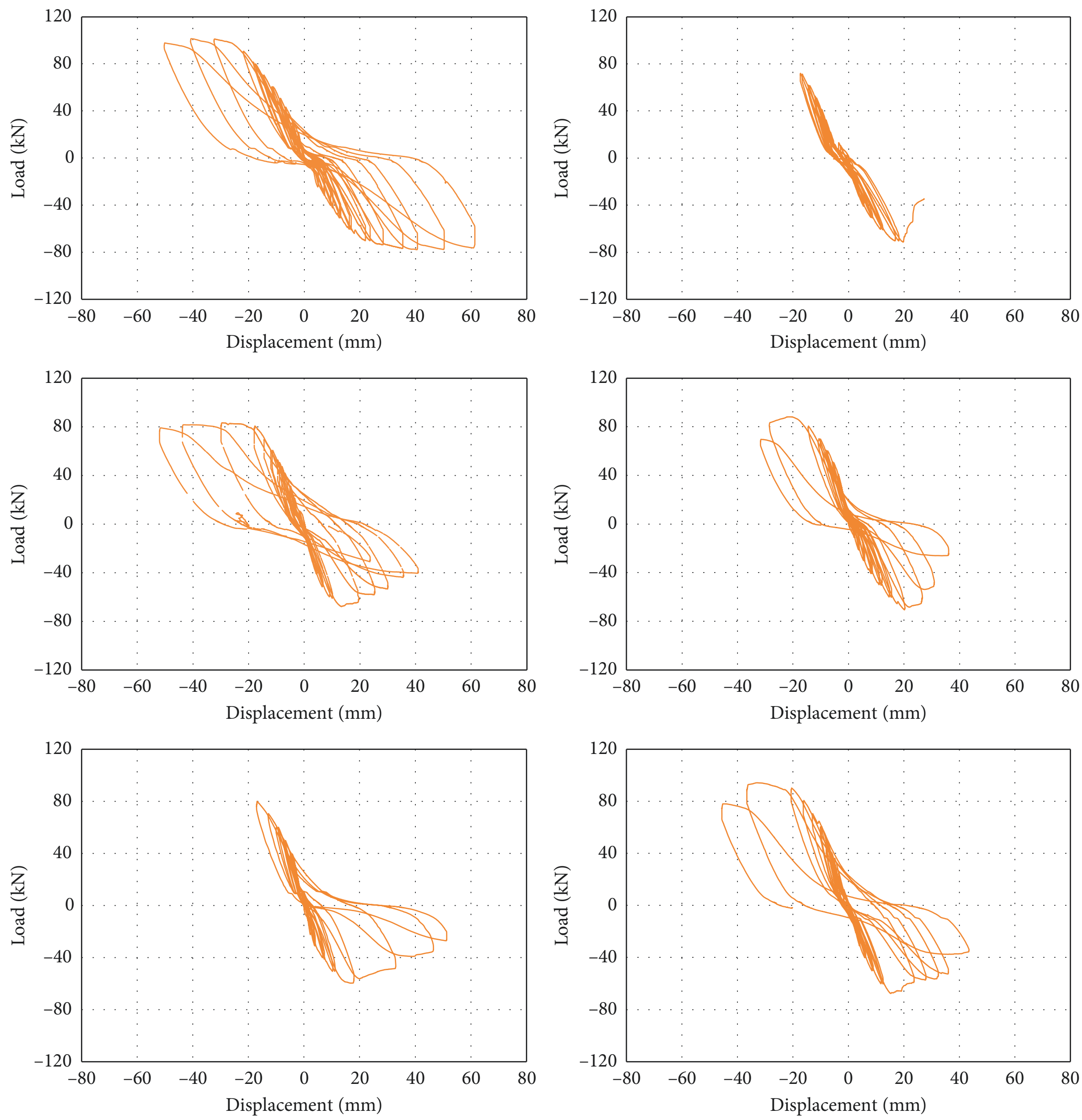


Figure 9: Load-displacement cyclic load of the samples. (a) Target; (b) control; (c) Sample 1; (d) Sample 2; (e) Sample 3; (f) Sample 4.

Figure 10: Failure of the control sample.

Figure 11: Failure of Sample 1.

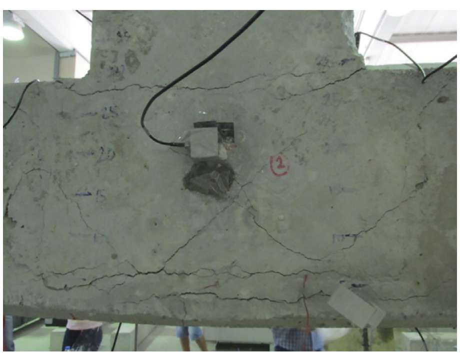
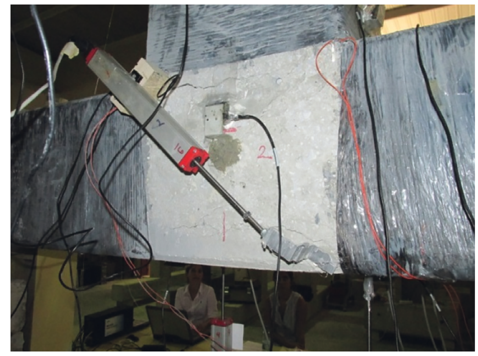


Figure 12: Failure of Sample 2.

application shape leads to less efficiency. The increase of the number of CFRP layers applied diagonally might give better results. On the other hand, this strengthening certainly has effect on increase in the ductility of the specimen. Similarly, results obtained from the testing of Sample 2 show that rebars added to the joint diagonally provide ductility, but not enough strength. It is suspected that the underlying reason is not having enough friction between rebars and concrete in the joint. The rebars used to retrofit should be tied with steel plates to increase bonding. In future studies, this point should be considered in detail.

(ii) The strengthening method followed in Sample 3 also gives unsatisfactory results regarding strength. Wrapping beams and columns with the CFRP increased rigidity of the beam and column members and whole stress concentrated at joint; thus, the specimen failed unexpectedly with strain softening at the joint and it appears that the rebars placed to the joint did not work properly.



(a)

(b)

Figure 13: Failure of Sample 3.

Figure 14: Failure of Sample 4 (flexural failure cannot be seen because of CFRP wrapping).

(iii) The strengthening method followed in Sample 4 exhibits better strength and ductility; however, the application of such strengthening techniques must be examined whether it is feasible and realistic.

Figure 15: Failure of the target sample.

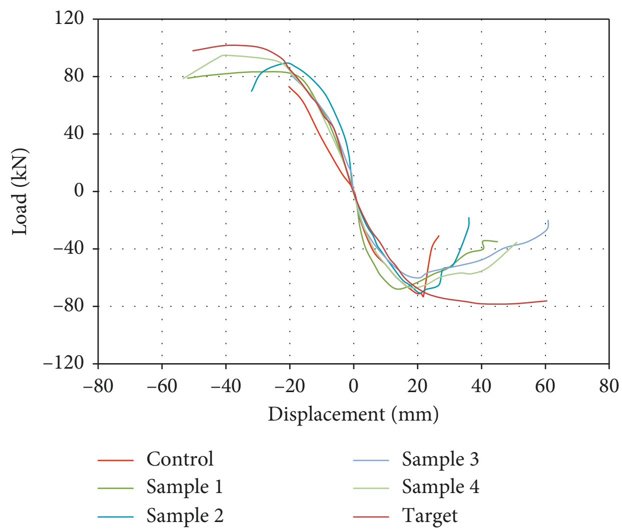


Figure 16: Envelope curves of the load-displacement test results.

Table 4: Experimental results.

Specimen ID	Flexural yield load (kN)		Joint failure load (kN)	Beam failure moment (kN·m)		Displacement (mm)		Rigidity until first crack (kN/mm)	Energy absorption capacity (kN·mm)	Failure type
	Left	Right		Left	Right	Yield	Failure			
Target	97.83	73.77	—	137	102.78	27.17	—	7.76	37668.83	Flexural yielding of beam
Control	—	—	71.1	—	—	—	17.66	3.76	11322.43	Brittle failure of joint
Sample 1	83.1	67.04	—	116.34	93.86	14.47	40.1	5.98	23696.6	Strain softening of joint
Sample 2	88.14	73.85	—	123.5	103.4	20.84	32.04	5.49	15092.03	Strain softening of joint
Sample 3	—	59.6	—	—	83.44	19.81	47.85	4.21	11882.27	Strain softening of joint
Sample 4	94.09	67.64	—	131.76	94.7	15.23	43.44	7.46	28111.8	Strain softening of joint

Further studies should be performed in larger-scale components, such as a frame, in order to understand actual behavior of strengthened members whether increases capacity or not. Strengthening of reinforced concrete building should strictly follow the application codes in order to prevent arbitrary practice.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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