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EFFECT OF REINFORCEMENT AROUND WEB OPENING ON THE CYCLIC BEHAVIOR OF EXTERIOR RC BEAM-COLUMN JOINTS

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A B S T R A C T

In many situations, it is necessity to have a beam web opening in the plastic hinge location. However, very limited studies investigated the behaviour of reinforced concrete (RC) beam-column joints with a nearby beam web openings. A previous study was conducted for investigating the behaviour of beam-column joints with unreinforced nearby web opening. In this study, the effect of adding additional reinforcing around a nearby web opening on the seismic behaviour of RC exterior Beam-Column joints is being investigated. Nine full-scale beam column joints were tested, four joints had unreinforced opening, while five joints had reinforced opening. The behaviour of the beam-column joints is described in terms of maximum resisting load, deflection, energy dissipated and stiffness degradation. The behaviour was significantly affected by the nearby opening. The increase in opening width and the reduction in distance between the opening and the column resulted in decreasing the strength and ductility of the RC beam-column joint. However, adding additional reinforcement improved the behaviour. Thus, it is recommended to provide additional reinforcement all around the opening.

Introduction

Openings are needed in reinforced concrete (RC) structures, which allow the execution of the electromechanical plumbing system. Using opening through the beam web, leads to a substantial reduction in the cost. In addition, the opening locations are decided by the electromechanical plumbing design, irrelevant of the structural aspect. Which could lead to situation where opening are nearby beam-column joints at the plastic hinge zone. The recommended design philosophy is “strong column - weak beam”, which ensure the formation of the plastic hinge in the beam, rather than in the column. However, a nearby web opening could significantly affect the behavior of the beam-column joint. Due to the severity of the Beam-Column joint, its behavior has been the subject of several research studies [1-3]. RC Beam-Column joint failure may lead to a catastrophic collapse of structures [4-7] due to large deformation. Failure of Beam-Column joints is due to various factors such as poor reinforcement detailing, construction defects, insufficiency of both reinforcement ratio, and transverse reinforcement [8-9]. Many researchers investigate the seismic behavior of different types of Beam-Column joints to investigate their structural behavior and examine several techniques to improve their response [10-13].

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Transverse openings through beams are often required based on the mechanical, electric, and plumbing layout. These openings could be located close to the supports while having different sizes and shapes. The behavior of beams with web openings under flexure, shear or combined shear and flexure has been investigating by researchers for many decades [14-19]. Recently, the effect of web opening on the behavior of Prestressed Concrete (PC) Beams as well as beams under torsion were investigated by many researchers [20-21]. Findings from previous studies on the effect of opening on beams reached the following conclusions [22]:

- Opening Dimensions (either length or height) and location compared to support greatly affect the Beam-Column joint.
- For openings located at the pure moment zones, it leads to a reduction in beam ultimate strength as well as cracking moment and stiffness. The amount of reduction depends on the previous parameters.
- For opening located near support, the mode of failure is the same as that of a solid beam and the failure line always passes through the center of the opening. Besides horizontal reinforcement above and below the opening and vertical stirrups by its sides, short stirrups in the members both above and below the opening are necessary to eliminate the weakness due to the provision of the openings.
- For opening located in a combined bending and shear zone, the upper and lower chord bend in double curvature with contra flexure points located at their midspan. The total shear force may be distributed between the upper and lower chords according to their flexural stiffness.
- More recently, the effect of beam web nearby opening on the behavior of unreinforced concrete beam-column joints was investigated practice [30]. The main purpose of this study is to examine the effect of having additional reinforcements on the behavior of Beam-Column joints with a nearby opening on. Nine Beam-Column joins were tested under cyclic loading. Four without additional reinforcements and five with additional reinforcements.

Research Significance and Previous Work

Most designer engineers permit the embedment of small pipes, provided some additional reinforcement is used around the periphery of the opening. However, when large openings are encountered, particularly in reinforced or pre-stressed concrete members, they show a general reluctance to deal with them because adequate technical information is not readily available. Although they contain detailed treatment of openings in floor slabs, there is a lack of specific guidelines in building codes of practice for opening in beam webs, in particular those nearby beam column joints [23, 24], As a result, designs are frequently based on intuition, which may lead to disastrous consequences or unjustified additional costs.

Methodology

The beam-column joints were tested under a rigid steel frame. The beam-column joints considered in the experimental program represent a large-scale model of exterior beam-column joints extending between the inflection points of a ductile moment resisting frame subjected to seismic action, as shown in Fig. 1. The test frame consisted of four columns post-tensioned to the laboratory strong floor and braced with tie rods to ensure rigidity. Figure 2a shows the elevation of the loading set-up. The reactions of loads which were applied to column and beam end were taken by a stiff steel beam supported on the main girders The column top and bottom ends were clamped by system of steel plates and rollers and anchored to two stiff steel beams using eight threaded high strength tie rods. The top steel beam lay on two concrete blocks and tied to the test frame columns while the bottom steel beam was well anchored to the laboratory strong floor using two 40 mm diameter anchors. The column axial load and the beam cyclic load were applied by two independent loading systems. Fig. 2b shows the details of instrumentation and of loading arrangements. This system allowed transmitting the cyclic vertical load to the beam tip while maintaining its freedom to rotate. In order to simulate the case of seismic action, beam-column joints were loaded by applying a constant compressive axial load (15% of the column ultimate load sustained by concrete, about 50% of column-balanced load) on the columns while the free end of the beams was subjected to displacement-controlled reversed increasing cyclic load.

Experimental program

Material properties

Table (1) shows the properties of the steel reinforcement used. The bars used for reinforcement were 8 mm, 10 mm, 12 mm and 16mm diameter. The same concrete mix was used for all beam-column joint. Compression testing of cubes was conducted. A 28 days compressive strength was recorded value of 26±0.62 MPa.

Table (1): Properties of Reinforcement Steel Bar.

Bar diameter (mm)	Yield strength (MPa)	Ultimate strength (MPa)	Elongation (%)
8	282	413	26.18
12	386	570	21.30
16	384	570	20.90

Test specimen preparation

The experimental program included testing of nine beam-column joints. All beam-column joints consisted of beam had a (T-cross section) total depth of 400 mm, flange thickness of 60 mm, flange width of 350 mm, and web width of 150 mm and 1500mm clear span from the column face as shown in fig. 3. The main column had a rectangular cross section of 350 mm depth, 250 mm width, and 2000 mm clear height. Column longitudinal reinforcements are 8D16 and ties D8 @ 100 mm cc., while the beam longitudinal reinforcements are 3D16 and stirrups D8 @ 120 mm cc. A typical RC beam column joint with opening is shown in fig 3a. Three RC beam column joints (J1, J1R, and J1R*), which have a square opening (170 mm X 170 mm) located at clear distances 170 mm from the column face. Two RC beam column joints (J2 and J2R), which have a square opening (170 mm X 170 mm) located at clear distances 340 mm from the column face. Two RC beam column joints (J3, and J3R), which has a rectangular opening (170 mm X 340 mm) located at clear distances 170 mm from the column face. Two RC beam column joints (J4, and J4R), which has a rectangular opening (170 mm X 340 mm) located at clear distances 340 mm from the column face. Further details are tabulated in Table (2). Beam-column joints J1, J2, J3, and J4 have no additional steel reinforcements around the opening, while J1R, J1R*, J2R, J3R, and J4R have additional steel reinforcements around the opening.

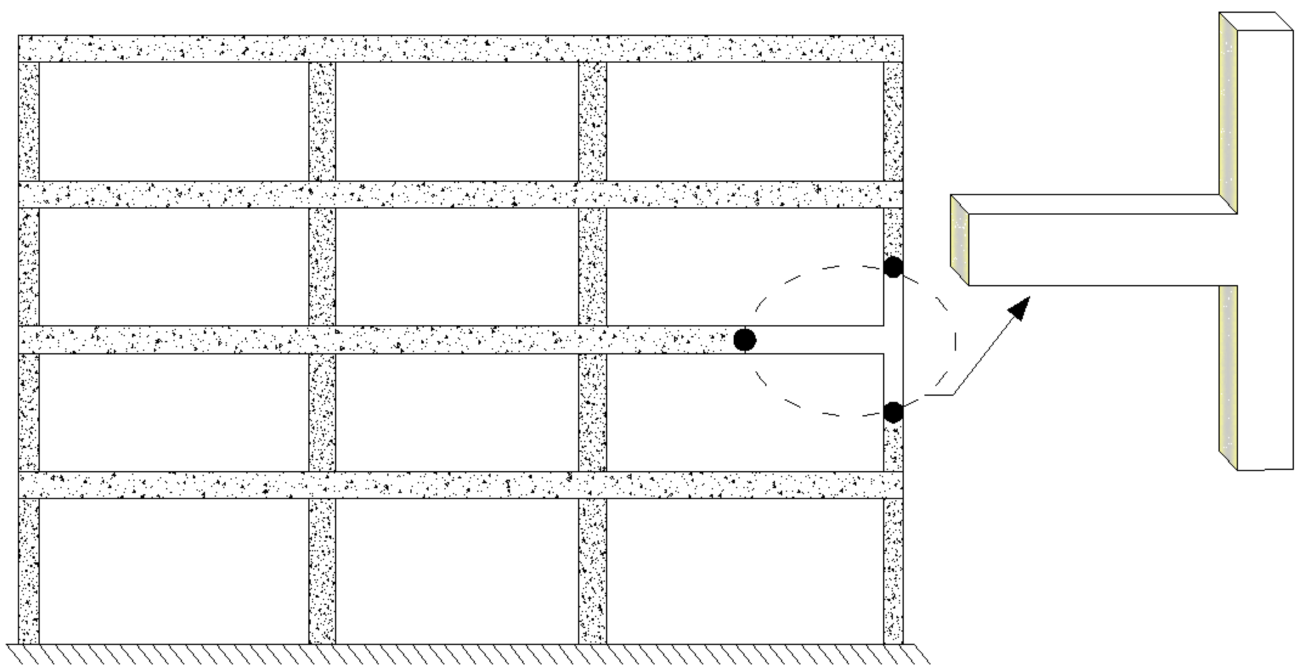
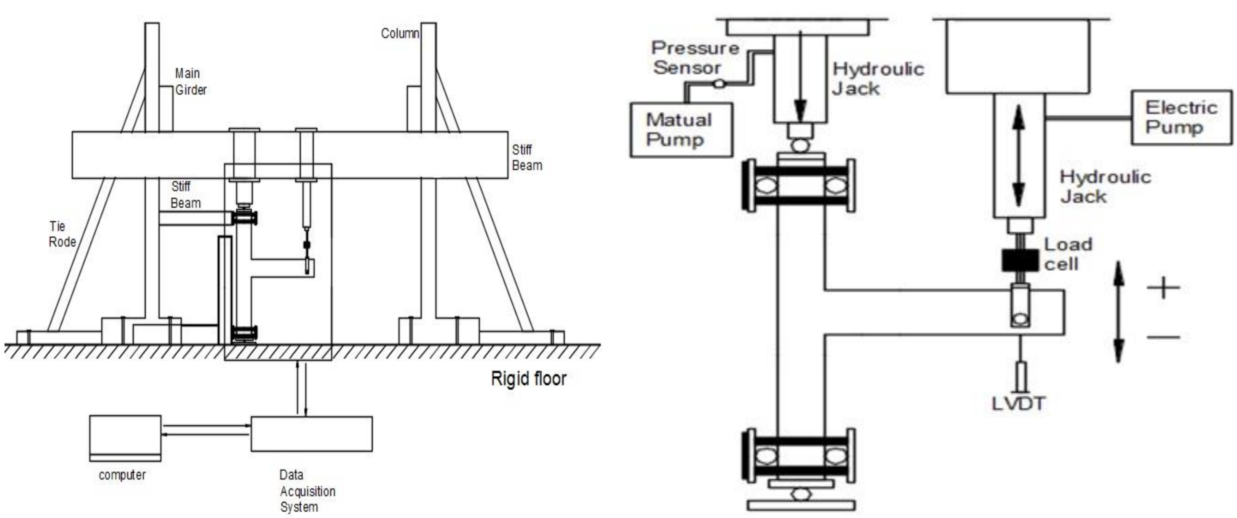


Fig. 1 Test specimen prototype



(a) (b)

Fig. 2 schematic diagram for Load setup; a) Elevation; b) Instrumentation.

Table (2) Details of all tested beam-column joints.

Joint	Relative Opening Height $\mathbf{H_o}$/d	Relative Opening Length $\mathbf{L_o}$/d	Opening Proximity to Support S/d	Rft at Top &Bottom of Opening	Rft at Right &Left of Opening
J1	0.50	0.50	0.50	-	-
J2	0.50	0.50	1.00	-	-
J3	0.50	1.00	0.50	-	-
J4	0.50	1.00	1.00	-	-
J1R	0.50	0.50	0.50	3 D16	3 D 16
J2R	0.50	0.50	1.00	3D16	3D16
J3R	0.50	1.00	0.50	3D16	3D16
J4R	0.50	1.00	1.00	3D16	3D16
J1R*	0.50	0.50	0.50	3D16 diagonal	3D16 diagonal

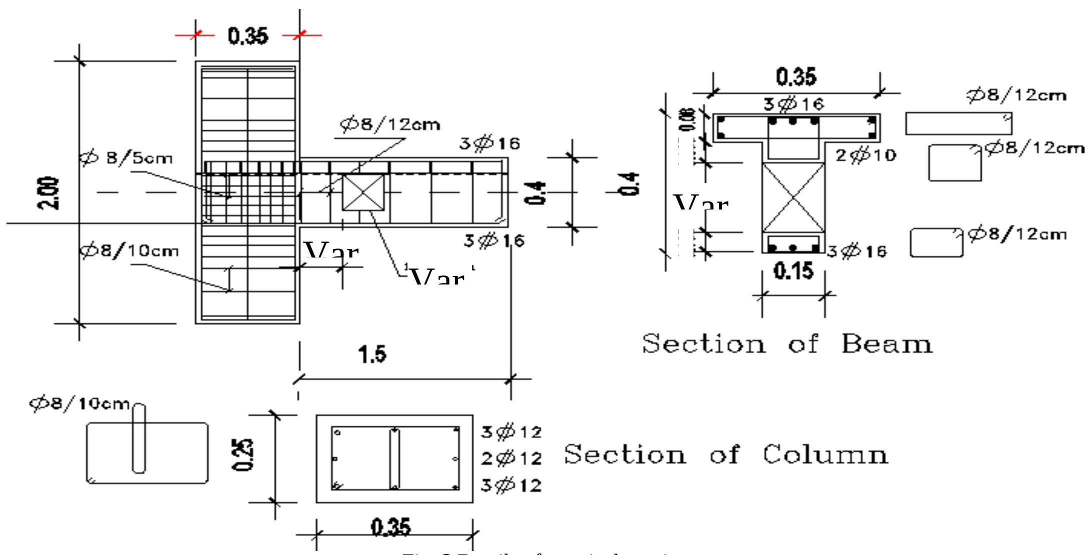


Fig. 3 Details of a typical specimen.

Test procedure and measurements

The beam-column joints were tested under quasi-static displacement control technique. At the beginning of each test the procedure was as follows: 1) The beam-column joint was installed in the test frame, which allowed for minor adjustments; 2) The column top and bottom ends were clamped by system of steel plates and rollers and anchored to the two stiff steel beams; 3) Vertical and horizontal loading systems were positioned; and 4) The data acquisition system continuously recorded readings from the load cells and the LVDTs. Electrical strain gauges, of 10-mm gauge length, were used to measure strain in stirrups and steel longitudinal reinforcements. LVDT was attached to the beam bottom tip at a point 250-mm from the beam end, as shown in Fig. 2b, to obtain the beam tip deflection.

EXPERIMENTAL RESULTS AND ANALYSIS

The successful performance of beam-column joints under seismic action has to satisfy adequate stiffness degradation, energy dissipation, load-displacement envelope, and ductility. The seismic response is complicated compared to static response. The differences among the performances of the joints cannot be assessed by direct comparisons of their load-displacement envelopes only. Accordingly, this section presents analyses of the test results to clarify the variations in stiffness, energy dissipation, and load-displacement envelope of the tested beam-column joints.

Cracking Patterns and Failure Modes

The measured loads were plotted against the associated applied beam tip displacements at different levels of loading. In addition, Table (3) shows the applied load and displacement at first onset of cracking, ultimate and failure. In addition, Figs. (4-7) show the cracking pattern and failure mode of all tested beam-column joints. For all beam-column joints, the first onset of diagonal cracks was initiated far from the opening location. Later, vertical cracks were initiated beneath the opening. Eventually, cracks propagated and spread around the opening location. In addition, minor cracks were initiated at the intersection between beam and column. Moreover, major cracks were initiated and spread across the concrete beam flange at the opening location. Finally, failure occurred accompanied by excessive concrete spalling, and rebar buckling. Where the opening section lost the ability to transfer any loading. For Beam-column joints J1R and J1R*, the cracking load improved by 16% and 21%, respectively, compared to that of J1. While the ultimate load improved by 13% and 28%, for J1R and J1R*, respectively, compared to that of J1. And the ductility improved by 50% and 31% for J1R and J1R*, respectively, compared to that of J1. For Beam-column joints J2R, the cracking load improved by 12%, compared to that of J2. While the ultimate load improved by 1% for J2R compared to that of J2. And the ductility improved by 70% for J2R compared to that of J2. For Beam-column joints J3R, the cracking load improved by 19%, compared to that of J3. While the ultimate load improved by 19% for J3R compared to that of J3. And the ductility improved by 21% for J3R compared to that of J3. For Beam-column joints J4R, the cracking load improved by 18%, compared to that of J4. While the ultimate load improved by 11% for J4R compared to that of J4. And the ductility improved by 21% for J4R compared to that of J4. It is clear that using additional opening reinforcements significantly improved the strength and ductility for all opening configurations.

Stiffness Degradation

We determined the stiffness at each displacement at cyclic load history for all tested the beam-column joints as shown in figs. 8(a-e). The stiffness degradation through loading cycles is a good measure for the decay of the structural resistance to the seismic load. Stiffness loss increases at a varying rate with the increase in the peak displacement as indicated by the reductions in the slopes of the load-displacement hysteresis loops. The stiffness of the beam-column joint at a certain displacement level was taken as the average of the stiffness in both the positive and negative loading directions. The stiffness was calculated as the ratio of the peak load of the loop to the associated displacement. The degradation of the stiffness at ultimate load level was evaluated using the stiffness degradation rate KDR.

$$KDR = \frac{(K_o - K_u)}{K_o} \tag{1}$$

where Ko and Ku are the flexural stiffness of the beam-column joints at initial and at ultimate level, respectively. Table (4) presents the values of the stiffness degradation rates for all beam-column joints. The stiffness degradation at ultimate load of the beam-column joint (J1) was 33.96 % and 59 % lower than that of beam-column joints (J1R1 and J1R*). The initial stiffness of the beam-column joint (J2) was 24.66 % lower than the beam-column joint (J2R). The stiffness degradation at ultimate load of the beam-column joint (J2) was 16.19 % lower than the beam-column joint (J2R). The stiffness degradation at ultimate load of the beam-column joint (J3) was 27.28 % lower than the beam-column joint (J3R). The stiffness degradation at ultimate load of the beam-column joint (J4) was 19.74 % lower than the beam-column joint (J4R). Using additional reinforcements have lowered the stiffness degradation significantly.

Load-Displacement Envelope

The measured loads were plotted against the associated applied beam tip displacements at different levels of loading. At different levels of loading, the measured loads were plotted against beam displacements. Figs 9(a-e) present the experimental load-deflection envelope for all beam-column joints. It is clear that using additional reinforcements for beam joints increased the load deflection envelope compared to those without ones.

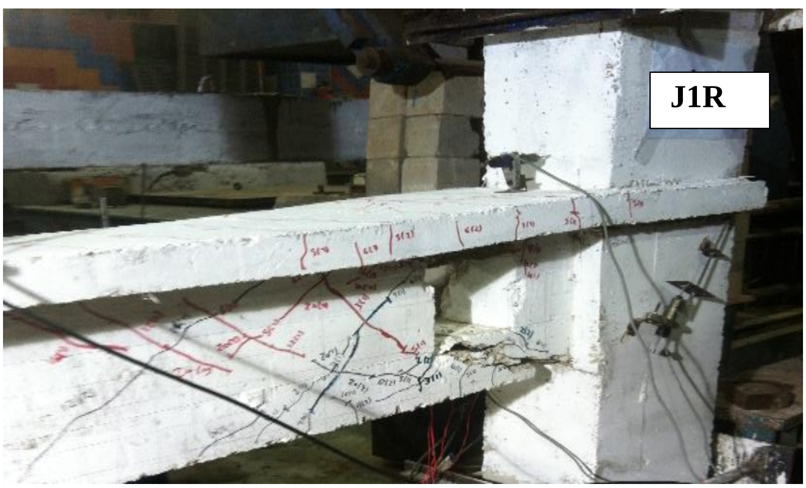
Energy Dissipation

Under severe earthquakes, beam-column joints suffer from large inelastic deformations. The ability of dissipating the inelastic deformation energy is one of the significant factors for evaluating the performance of beam-column joints subjected to seismic action. The energy dissipated by the beam-column joint during an individual cycle, *Ei*, is the area enclosed within the load-displacement hysteresis loop. Then the total energy dissipated was estimated as the sum of the areas of the loops throughout the test, which was estimated by numerical integration of the recorded load times the displacement. Figs 10(a-e) show the dissipated energy during for all beam-column joints. Many measures were proposed to compare the energy characteristics under seismic loading such as “energy dissipation index" and “energy index". In the current study, “the normalized energy index "I_{EN} was adopted as reliable and comprehensive measure. It has the advantage of including the effect of actual displacement, stiffness and energy for each cycle. As a result, this index is sensitive in assessing any variations in the seismic performance of beam-column joints. The normalized energy index, I_{EN}, is expressed as follows:

$$I_{EN} = \frac{1}{P_u \Delta_y} \sum_{i=1}^{m} E_i \left(\frac{K_i}{K_y} \right) \left(\frac{\Delta_i}{\Delta_y} \right)^2 \tag{2}$$

where E_i, is the energy dissipated during the i^{th} cycle, Δy is the yield displacement of the beam-column joint, Pu is the ultimate load, Ky is the stiffness corresponding to the yield displacement and Δi is the peak displacement of the i^{th} cycle and Ki is the corresponding stiffness. The energy index is accumulated until cycle number "m” where the loop peak load dropped to 85% of its ultimate value. Under seismic excitation, beam-column joints experienced large inelastic deformations. The ability to dissipate this inelastic deformation energy is a major factor for evaluating the beam -column performance during seismic action. The presence of web openings in beams leads to a reduction in beam ultimate strength as well as cumulative energy and inertia of section. Table (5) shows the cumulative energy at ultimate and 24 mm displacement. The beam-column joints (J1R and J1R*) dissipated more energy by value of 5.05% and 13.17 %, respectively compared to that of beam-column joint (J1). The beam-column joint (J2R) dissipated more energy value of 14.44 % compared to the beam-column joint (J2). The beam-column joint (J3R) dissipated more energy value of 42 % compared to the beam-column joint (J3). The beam-column joint (J4R) dissipated more energy value of 44.11 % compared to the beam-column joint (J4). Adding additional reinforcements for the nearby opening improved the energy dissipation of the beam-column joint by 5.05% up to 44.11%.

(a)



(b)

(c)

Fig. 4 Cracking pattern of Specimen; a) J1; b) J1R and c) J1R*.

Table (3) Experimental results.

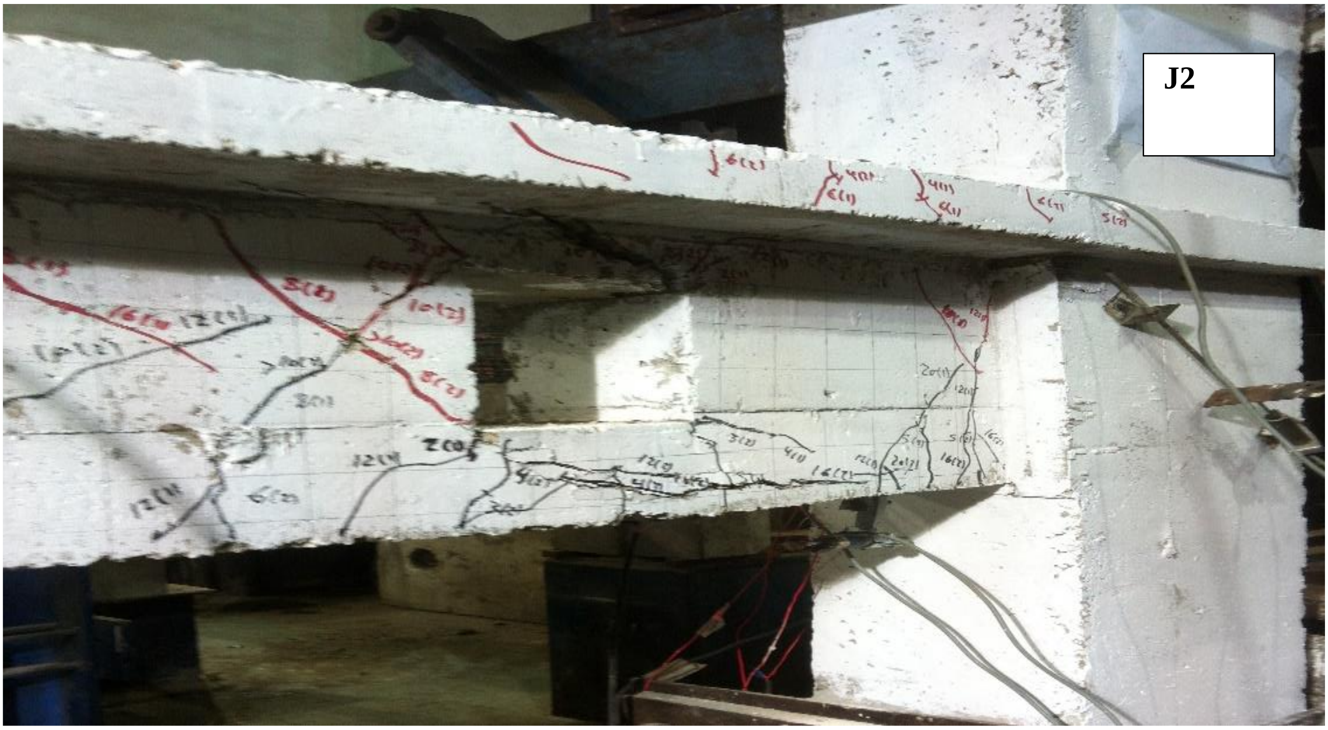
Beam-column joint	Cracking P (kN)	Cracking Δ (mm)	Ultimate P (kN)	Ultimate Δ (mm)	Failure P (kN)	Failure Δ (mm)
J1	22	2.26	69	16.6	53.6	25.1
J2	24.	2.25	80	17	48.2	25.1
J3	20.	2.30	58	16.5	47.8	37.9
J4	21	2.25	64	16.5	37.0	30.2
J1R	26	2.39	78	16.5	42.3	37.7
J2R	27	2.30	80	16.8	57.5	42.7
J3R	24	2.43	69	15.3	52.5	29.9
J4R	25	2.34	71	17.3	43.8	36.6
J1R*	27	2.30	89	17.0	50.5	33.1

Table (4) Stiffness degradation for all beam-column joints.

Beam-column joint	K_o (kN/mm)	KDR (%)
J1	11.34	59.27
J2	12.13	65.37
J3	10.69	57.85
J4	8.68	63.2
J1R	14.84	4.46
J2R	16.10	4.88
J3R	13.16	4.40
J4R	15.15	4.61
J1R*	18.01	5.05

Table (5) Cumulative Energy for all beam-column joints.

Beam-column joint	Cumulative Energy at Ultimate (kN.m)	Cumulative Energy at Displacement 24mm (kN.m)
J1	4.80	9.90
J2	5.10	9.70
J3	3.80	6.40
J4	4.10	6.80
J1R	6.20	10.40
J2R	7.60	11.10
J3R	5.80	9.10
J4R	6.80	9.80
J1R*	7.70	11.60



(a)

(b)

Fig. 5 Cracking pattern of Specimen; a) J2 and b) J2R

(a)

(b)

Fig. 6 Cracking pattern of Specimen; a) J3 and b) J3R.

(a)

(b)

Fig. 7 Cracking pattern of Specimen; a) J4 and b) J4R

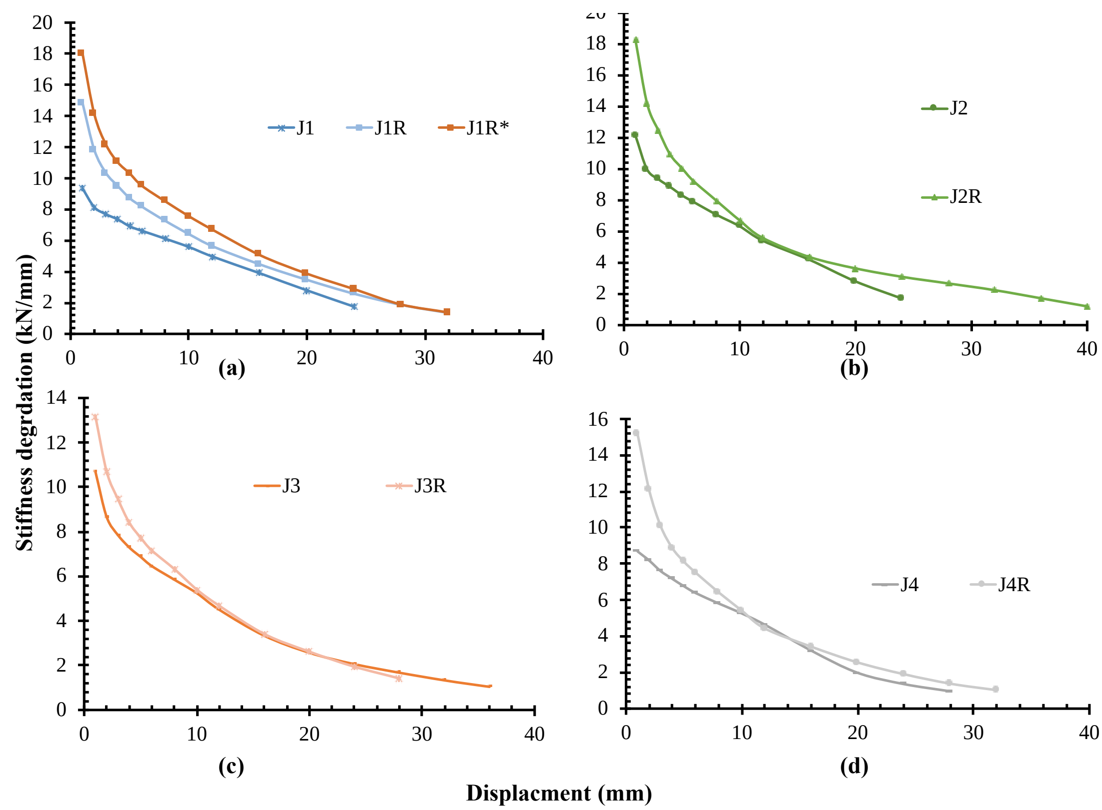


Fig. 8 Stiffness degradation for beam-column joints a) J1, J1R and J1R*; b) J2 and J2R; c) J3 and J3R; d) J4 and J4R.

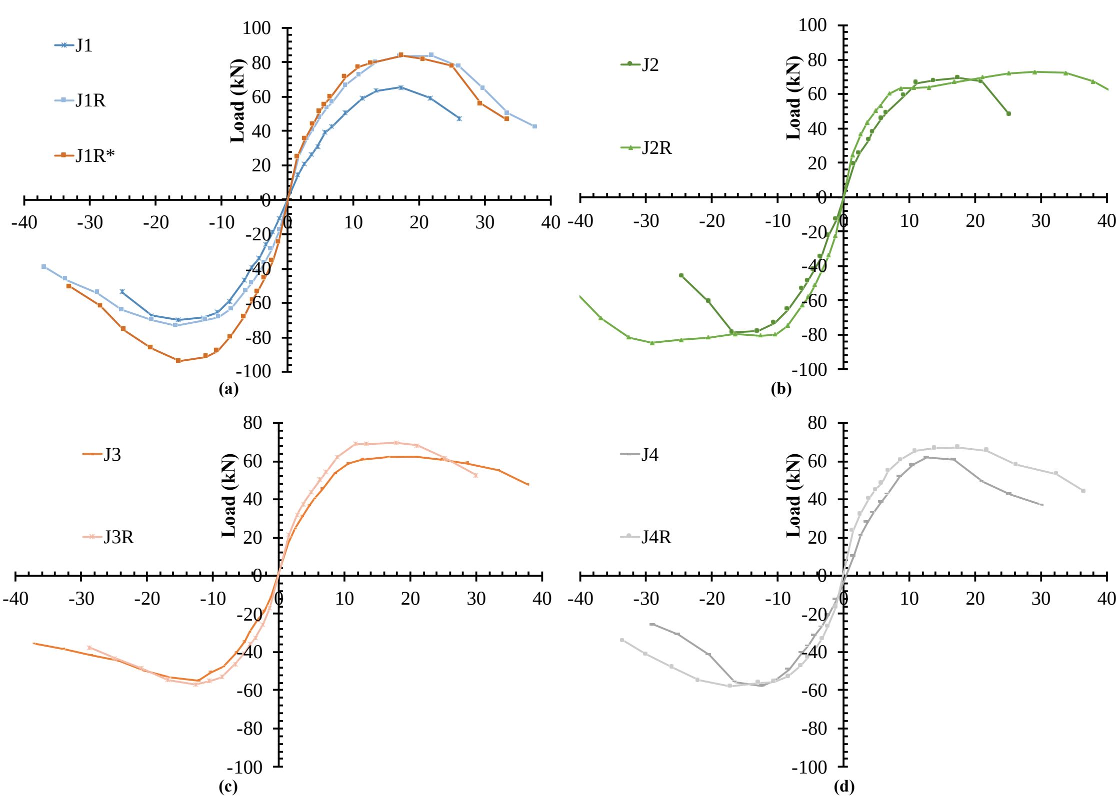


Fig. 9 Load-displacement envelope for beam-column joints a) J1, J1R and J1R*; b) J2 and J2R; c) J3 and J3R; d) J4 and J4R

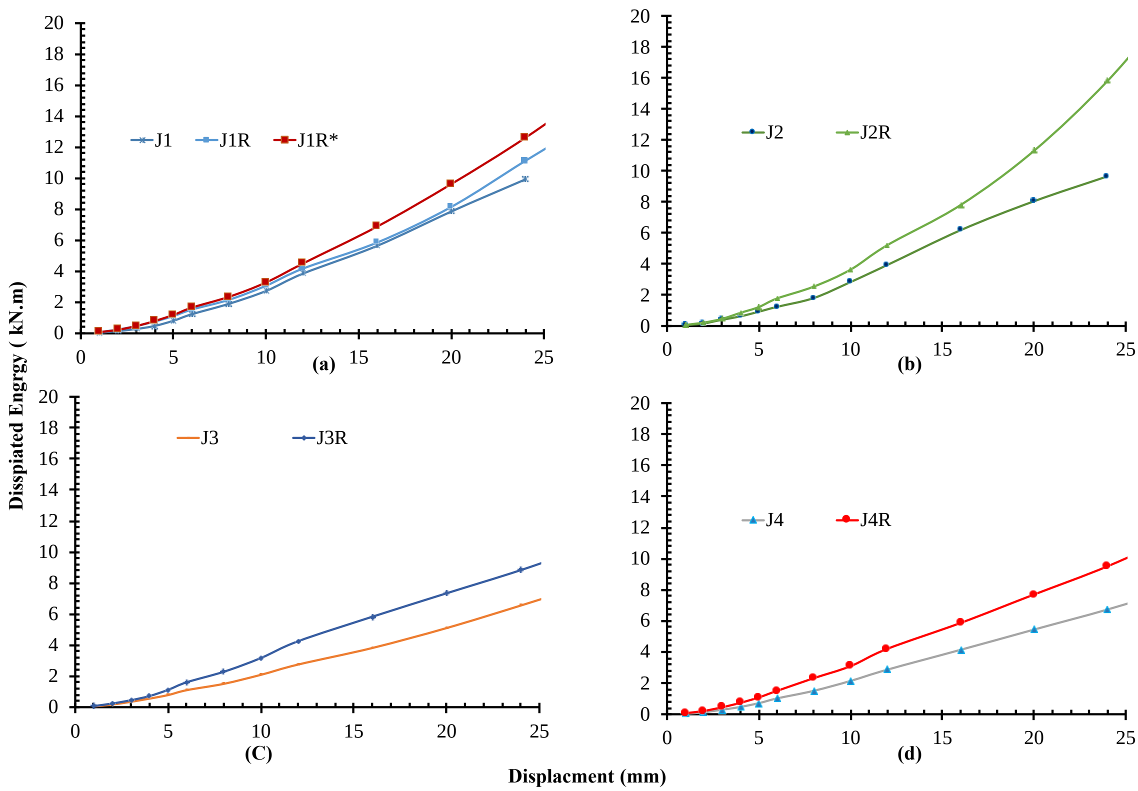


Fig. 10 Energy dissipated for beam-column joints a) J1, J1R and J1R*; b) J2 and J2R; c) J3 and J3R; d) J4 and J4R.

CONCLUSIONS

A total of nine full-scale beam column joints with unreinforced and reinforced were constructed and tested under cyclic loading and the following was concluded:

- All beam-column joints failed when the opening cross section reached maximum capacity, which was accompanied by excessive concrete spalling, and rebar buckling.
- The cracking and ultimate strength as well as the ductility of the beam-column joints with reinforced openings was significantly improved by a value up to 21, 28, 50%, respectively, compared to beam column-joints with unreinforced openings.
- The stiffness degradation for the beam-column joints with reinforced openings was significantly lowered by a value up to 59% compared to beam column-joints with unreinforced openings.
- The load-displacement envelope for the beam-column joints with reinforced openings was increased significantly compared to beam column-joints with unreinforced openings.
- The dissipated energy for the beam-column joints with reinforced openings increased significantly by a value up to 44% compared to beam column-joints with unreinforced openings.
- Using diagonal reinforcement for the opening improved failure load, ductility, stiffness degradation, load displacement envelope, and dissipated energy more than using straight reinforcement.

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