SEISMIC RETROFITTING OF BEAM COLUMN JOINTS USING CFRP NITOWRAP METHOD

K. Ravichandran, A.K. Prsadkrishnan, S. Christian Johnson

[1] Associate Professor, Department of Civil and Structural Engineering, Annamalai University, Cuddalore, Tamil Nadu 608001, India

[2] Research Scholar, Department of Civil and Structural Engineering, Annamalai University, Cuddalore, Tamil Nadu 608001, India

[3] Professor, Department of Civil Engineering, Erode Sengunthar Engineering College, Perundurai, Erode, Tamilnadu 638054, India

Email : ravichandrank.annamalaiuniv@gmail.com

Abstract

Beams and columns are the important structural elements in any framed structure, and the joints that connect beams and columns have to be designed appropriately since they are the main component that transfers the internal forces. The failure of the entire structure has happened mainly due to the poor performance of the beam-column joints, which lie along the path of load transfer, and hence their design is considered crucial in any moment frames for external strengthening of the beam-column joints subjected to the cyclic loading conditions. The construction sector has a unique place for the use of FRP composites as an efficient alternative for reinforcing and repairing these parts. In the past, several repair and strengthening techniques have been created to strengthen existing structures and restore their strength and usefulness. In this study, there were six examples refitted using different techniques, two control specimens, and eight full-scale beam-column joints. In various configuration procedures, CFRP sheets were applied to the joints. In the present study, the columns were subjected to axial loading, and controlled displacements were applied to the cyclic load in the beam. The outcome demonstrates that the retrofitted beam-column connections exhibit enhanced strength, stiffness, energy dissipation, and composite behavior until breakdown.

Keywords: Beam column joint, energy dissipation, composite action, retrofitting, cyclic load, Hysteretic curves.

1. Introduction

In earthquake-prone areas, the column and beam connections are a crucial element in RC structural frames that are designed to resist moments. Buildings made of reinforced concrete can collapse as a result of earthquakes, which can cause property damage and human casualties (Ghaderi Barmi *et al.* 2023). The majority of the buildings can withstand small to large earthquake loads. When exposed to seismic loads, the beam-column connections are a crucial part of RC frames because any failures there will result in damage to the entire structure (Sorace *et al.* 2023). Due to a bending moment with an opposing sign, the joint core develops horizontal and vertical joint shear stresses on either side of the member. With this kind of stress, the joint section is crushed and has lateral resistance to brittle shear failure (Bruschi and Quaglini 2022). By fortifying the joint, it is necessary to mitigate brittle failure. The brittle failure in the joint and the destruction caused by strong earthquakes causes RC buildings to collapse (Pohoryles *et al.* 2021). Pre-seismic loads are taken into consideration when designing the existing concrete beam-column joint. When an earthquake strikes, buildings that were built with the vertical acting as gravity load but without taking earthquake probabilities into consideration, they fall (Hareen and Mohan 2022). Weak-column/strong-beam mechanisms develop when a structure fails completely as a result of an insufficient strength and transfer of loads around the connections of beam-column. The failure due to shear at the joints and beams and bar slides could all be to blame for the collapse (Takase and Yamada 2022). The composite materials made of fibres are thought to be well suited for the fabrication of composites and produce laminates with stiffness and strength greater than those of three-dimensional FRP structures due to their peculiar mono dimensional geometry (Hassan *et al.* 2021, Colajanni and Pagnotta 2022). The reason for this is that mono-dimensional configurations have a lower defect density than three-dimensional members. By adding a single or multiple layers of laminates, fabric, or sheets as an outside reinforcement to the tension side of the part that needs strengthening, flexural strengthening with FRP materials can be accomplished. Greater ductility is ensured in FRP enhanced members when a breakdown occurs as a result of concrete crushing. Due to their outstanding strength as well as their high Young's modulus of elasticity, carbon fibres are employed because of their excellent performance (Ozturk *et al.* 2023). In comparison to glass and aramid fibres, they feature brittle failure behaviour, comparatively low energy absorption, and higher failure strengths (Zhou *et al.* 2020). Carbon fibres exhibit a modest drop in tensile strength over time while being less susceptible to creep, rupture, and fatigue (Guo *et al.* 2023). Carbon Fibre Reinforced Polymers is the common name for FRP composites made of carbon fibre (CFRP). Although CFRP is currently an expensive composite material, it is exceptionally strong and lightweight. In this field, CFRP can be applied to repairing wrecked buildings or retrofitting an existing structure to make it stronger. In place of steel reinforcement, it can be used as an alternative reinforcement (Huang *et al.* 2022). Typically, CFRP has a significant impact on strength and an insignificant rise in stiffness. This is due to the material's normal strength and lack of stiffness in this application (Al-Abdwais and Al-Mahaidi 2022). Wrapping around sections can also improve a section's ductility by significantly reducing its susceptibility to collapse under seismic loading. Wrapping columns in these FRPs has allowed for a larger axial capacity. Two methods are generally utilised to strengthen beams (George *et al.* 2022). The first step is to attach FRP plates, fabrics, and sheets to the tension face of beams. As a result, the beam's stiffness, deflection capacity, and strength all rise. The sides of the beams can also be covered with FRP plates, textiles, or sheets to boost the shear strength (Lim *et al.* 2022, Hung *et al.* 2023). To achieve greater strength, building columns might be encased in FRP. The method prevents the column from expanding laterally. In order to retrofit and restore these reinforced concrete beams and columns, the use of FRP is crucial (Milev *et al.* 2022). The yield load and post-elastic stiffness of the strengthened beams were both significantly boosted by the CFRP's presence (Yazdani *et al.* 2018). The RC structures that are already existing, the CFRP reinforcements in the form of external bonding agents are practical structural strengthening solutions (Colomb *et al.* 2008, Ilia and Mostofinejad 2019). However, the strength due to bonding between FRP systems and the concrete substrates limits the highest FRP tensile stress that can be used in accordance with this technique (Seo *et al.* 2013, Bazli *et al.* 2023).

1.1 State of Art

Retrofitting beam-column connections has involved the use of a variety of FRP materials, including carbon fibre-reinforced polymer (Oskouei 2010, Eslami and Ronagh 2014, Yurdakul and Avşar 2015), glass fibre-reinforced polymer (El-Amoury and Ghobarah 2002, Agarwal *et al.* 2014), aramid fibre-reinforced polymer (Granata and Parvin 2001), FRP hybrid composite (Mosallam *et al.* 2019), quasi-isotropic laminate (Mosallam 2000), and sprayed FRP (Yang *et al.* 2018). Due to its excellent mechanical qualities, CFRP, one of these composite materials, is the most popular. The efficient CFRP to retrofit the RC bridge piers seismically can reduce the damage from impact load. The inhibition of the shear mechanism offers a variety of positive outcomes, including an improvement in energy dissipation capacity due to increased ductility and a reduced peak displacements (Zhou *et al.* 2021). RC constructions deteriorate over time for a variety of reasons, but the corrosion of reinforced rebar is the main cause, according to literatures (Elghazy *et al.* 2018, Nguyen and Castel 2020). A considerable improvement in the bearing capacity of the connections with greater ductility and less energy dissipation was seen when CFRP composites were installed using the grooving technique. The lack of seismic features, lateral reinforcements, and inadequate strength against shear forces in the connection zone cause the concrete beam-column joint specimen to pinch and have low energy dissipation (Wang *et al.* 2021). The use of CFRP sheets that are L-shaped at the beam-column corners as an externally wrap and CFRP strengthening of both the beam-column finish zones for passive strengthening of an exterior RC beam-column joint was found to be futile because the shear failure near the joints still increased and only a marginal improvement in the dissipation of energy in the joints was observed (Wang *et al.* 2019). This was demonstrated by the EBROG approach in conjunction with CFRP anchorage systems. The X-shaped CFRP pattern performed significantly better than the T and L-shaped ones, despite the fact that all strengthening schemes increased the lateral strength and ductility of the specimens (Le-Trung *et al.* 2010). Multiple strengthening strategies was found that by installing FRP strips in the joint area as a retrofit, the shear damage could be kept to a minimum (Parvin *et al.* 2010). L-shaped strips and 45°-oriented strips arranged in two layers were used to reinforce the CFRP near the joint region. The outcomes demonstrated an improvement in the specimens' ductility and maximum lateral load at all three stress levels (Singh *et al.* 2018). While the failure mode in the retrofitted joints shifted from diagonal cracks to debonding of CFRP-plates, the adoption of CFRP-plates greatly improved the load-bearing ability of joints. The modified joints' load-carrying capabilities were dramatically increased by 64% to 148% over the control specimen (Obaidat *et al.* 2019). Along with contributing to the effectiveness of CFRP, the glued segmental circular concrete covers performed admirably in conjunction with the pre-existing concrete at the joint to withstand shear loads. The improved circular section's wrapped CFRPs lessen the chance that they will come unglued from the concrete surface. The rigidity of the horizontal CFRPs surrounding the joints should be enhanced to improve performance (Hadi and Tran 2014). Greater lateral displacement, higher load capacity, faster energy dissipation, higher displacement ductility, and a slower rate of secant stiffness degradation were all improvements in the cyclic behavior of heat-damaged RC beam-column joints reinforced with CFRP sheets. The effectiveness of CFRP sheets also improves with the severity of heat damage. All of the externally strengthened specimens underwent surface preparation and grooving prior to CFRP installation in order to guard against potential de-bonding of the CFRP. Despite the effectiveness of the shear retrofit concept for 3D outside connections, those strengthened with a combination of spike anchors and CFRP sheets functioned better than those strengthened purely with CFRP sheets (Farhang *et al.* 2023).

As a result of inadequate design and details for the current loading conditions, the survey of existing construction found that upgrading of structures is required. The constructions determined to be in inadequate seismic conditions are also included. In this research, the findings of an experimental investigation that aimed to provide a new efficient FRP retrofit method for RC exterior beam-column joints are presented. The goal of the current study was to create an innovative, affordable, and practically workable retrofit solution for **exterior beam-column connections under cyclic**

loading. The purpose of this investigation is to examine the potential benefits of enveloping CFRP to enhance the cyclic response and strength characteristics of reinforced concrete beam-column joints. In addition, an experimental program is used to assess the stiffness, energy dissipation, and failure modes of the externally wrapped beam column joints utilizing CFRP.

2. Materials

In this study, CFRP is used in place of the many other repair techniques and materials because FRP bonding has found widespread use. A carbon fibre composite wrapping method called Nitowrap EP (CF) uses Nitowrap (CF) along with an epoxy sealer/primer called Nitowrap 30 and a high-built epoxy saturant called Nitowrap 410. In the event that structures are exposed to the atmosphere, a polyurethane top coat of Nitowrap 512 protects the system. A carbon fibre composite system called Nitowrap EP (CF) is used to strengthen columns and beams of load-bearing structures, especially when shear strength and deformation properties need to be improved. Table 1 lists the characteristics of the CFRP materials provided by the supplier. The junction between the beam and column was 200 x 200 mm in size. Eight specimens were cast, two of which were modelled after the control specimen and the remaining six after the CFRP bonding Table 2. A detailed external joint of an RC frame was represented by each specimen, which had equal dimensions and was reinforced in accordance with the recommendations of the IS 456-2000 code. The reinforcement consists of eight 8mm stirrups evenly spaced at 150 mm intervals in the column and beam, four 12 mm diameter rebars in the column, and two 12 mm diameter rebars on either side of the beam. The joint created in this work is shown with the reinforcing details in Figure 1.

Table 1 Technical Details of CFRP (provided by the manufacturer)

Orientation	Unidirectional
Weight	205 $\pm$ 5 g/m^2
Density	1.83 g/cc
Thickness	0.32 mm
Ultimate Elongation (%)	1.6
Tensile Strength	3550 N/mm^2
Tensile Modulus	29.5 x 10^3 N/mm^2

Table 2 Details of casted test specimens

S.No.	Specimen Designation	Retrofitting Methodologies
1	BCJ-A1	Control specimen
2	BCJ-A3	Control specimen
3	BCJ-C1	3 CFRP U-shaped strips in beam + 3 strips in each face of the column with 20% axial load.
4	BCJ-C2	4 CFRP U-shaped strips in beam + 4 strips in each face of the column with 20% axial load.
5	BCJ-C3	3 CFRP U-shaped strips in beam + 3 strips in each face of the column with 30% axial load.
6	BCJ-C4	4 CFRP U-shaped strips in beam + 4 strips in each face of the column with 30% axial load.
7	BCJ-C5	One layer each of CFRP, flexible sheet on both sides of the column, and U-shaped sheet on the beam, Wrapping one layer of 150-mm-wide sheet around the beam junction with a 30% axial load served as the anchorage.
8	BCJ-C6	On either side of the column, there are two layers of flexible sheeting, two layers of CFRP, and two layers of U-shaped sheeting, Wrapping one layer of 150-mm-wide sheet around the beam junction with a 30% axial load served as the anchorage.

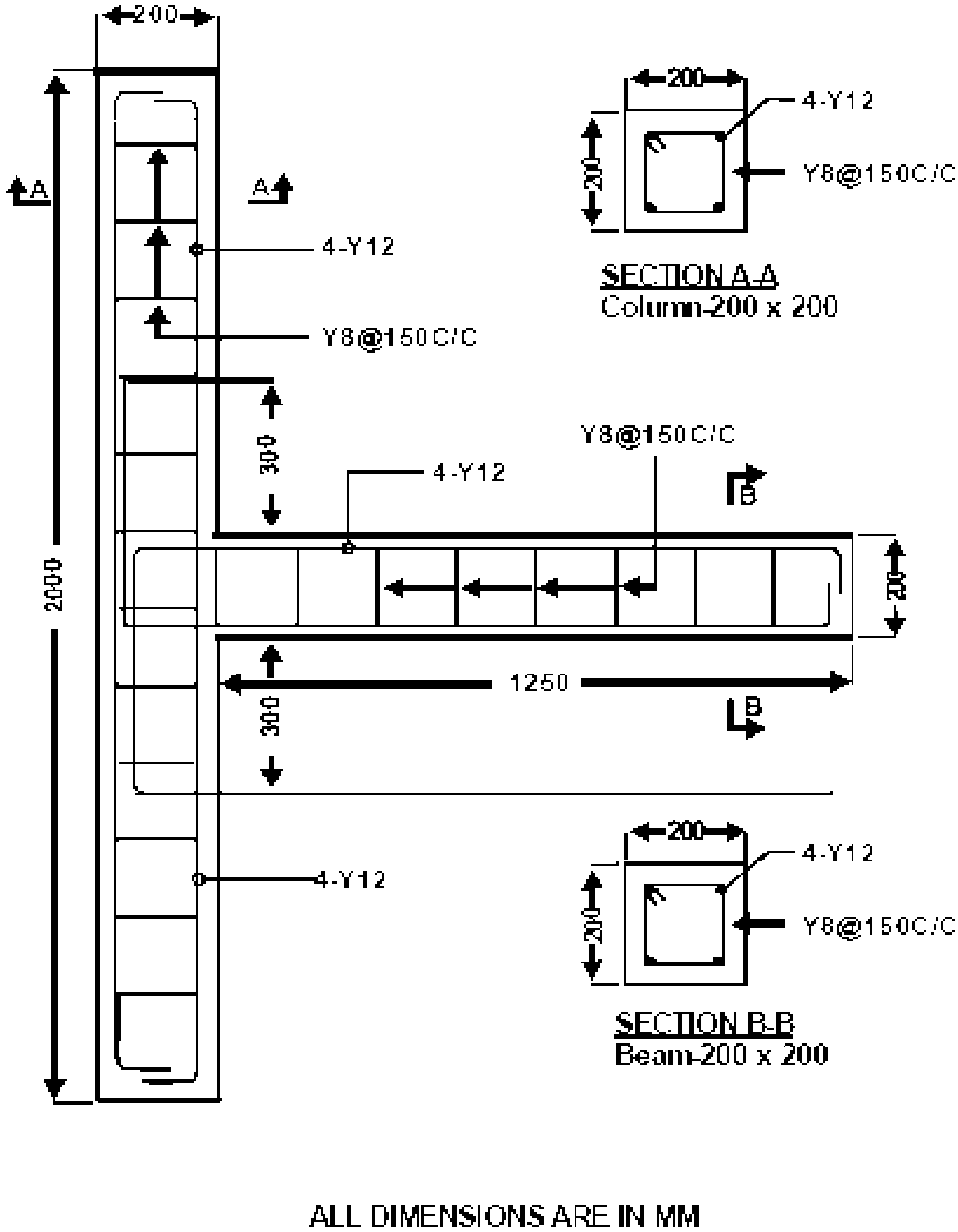

Figure 1 Details of beam column joint

2.1 Bonding of CFRP laminates

For pressing over the joint location, two layers of CFRP were offered, each layer having two CFRP shapes—one for the column portions and the other for the beam portions. As illustrated in Figure 2, a covering type of a single U-shaped mat of dimension 1530 x 230mm is placed horizontally after two numbers of 230 x 830mm CFRP mats are provided vertically in the column's opposing faces.

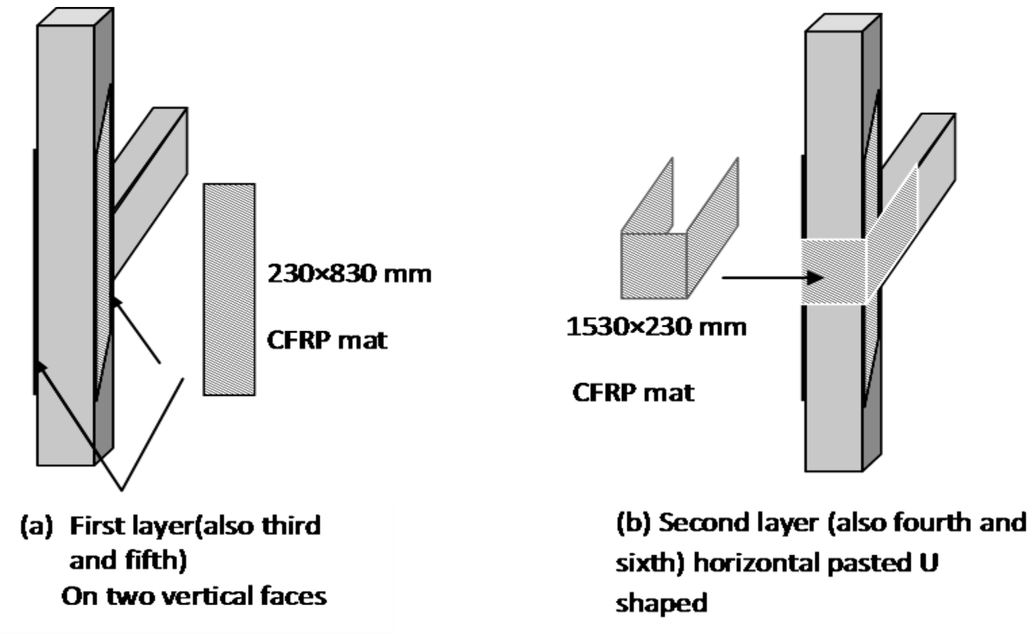

Figure 2 CFRP wrapping system

3. Testing Arrangement

Figure 3 depicts the test configuration's schematic view. Reverse cyclic loading and an axial load were applied to the joint assemblies. To simulate the impact of gravity on the column, a hydraulic jack (500 kN) was attached in the vertical position to the loading frame. In order to hold the specimen in place and imitate column axial load, varied axial loads of 20% and 30% of the column's axial potential were applied to the columns. Along with the peripheral hinges that are supported at the top and bottom of the column, two of the ends of the column received external axial hinge support. The beam part of the beam-column joint was subjected to a reverse cyclic load using a second hydraulic push and pull jack with a 500 kN capacity. The cyclic load application point was 50 mm from the free end of the beam and the displacement testing was done all the way to failure. For the test specimen, the push and pull displacement increment was 5 mm. For measuring the displacement at the point of loading, the specimens were equipped with a linear variable differential transducer with a range of 75 mm or less.

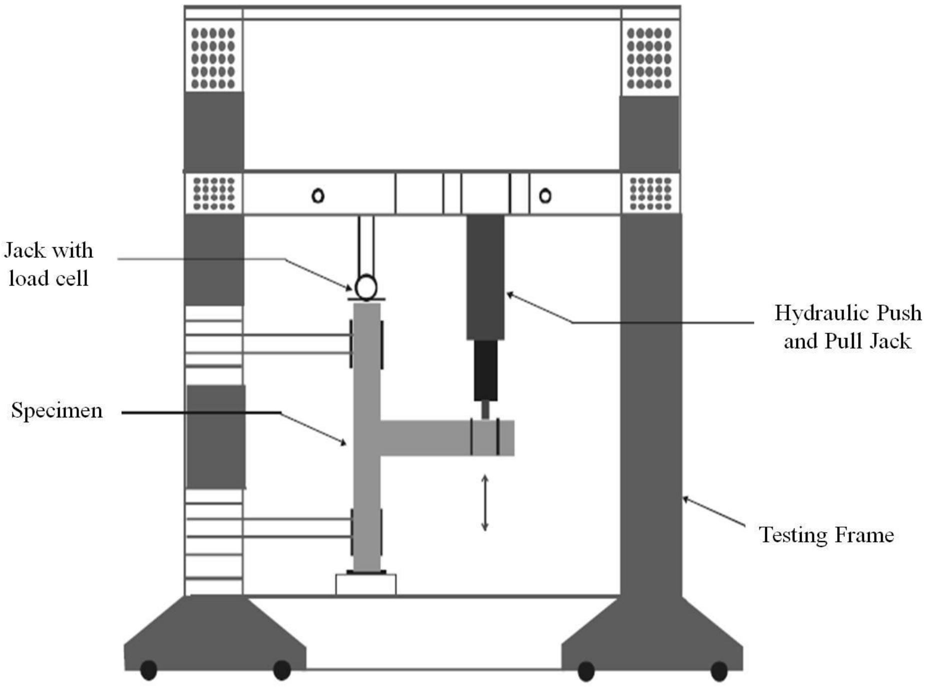

Figure 3 Test Arrangement – A Schematic View

4. Test results and discussion

4.1 Hysteretic responses at various axial capacity

During cyclic loading, the most crucial factor for evaluating the seismic performance of a structural component is the measurement of the hysteretic response of the beam-column joints with its force-displacements, as this factor reveals both the component's ability to dissipate energy and its ductility. As a result, Fig. 4(a–c) depicts the hysteretic response with the force-displacements for the control and retrofitted specimens, respectively, along with their corresponding envelope curves. The maximum load of about 23.5, 24.6, 24.2, 25.2, 24.8, 26.1, 31.8, 34.6 kN is observed for push for BCJ-A1, BCJ-A3, BCJ-C1, BCJ-C2, BCJ-C3, BCJ-C4, BCJ-C5, BCJ-C6 samples, whereas their maximum pull load values was observed to be 17.8, 18.4, 18.2, 19.5, 18.7, 20.4, 26.7, 32.4 kN, respectively. The developed sample's failure is mostly found at 30 and 35 mm displacement in which BCJ-A1, BCJ-C1, BCJ-C3 fails at 30 mm and BCJ-A3, BCJ-C2, BCJ-C4, BCJ-C5, BCJ-C6 fails at 35 mm. Among the results presented, BCJ-A1, BCJ-A3 represents controlled specimens, BCJ-C1, BCJ-C3 are 20% axially loaded, BCJ-C2, BCJ-C4, BCJ-C5, BCJ-C6 are 30% axially loaded. The energy dissipation and the hysteresis behaviour along with the stiffness degradation are measured and in both the push and pull directions, a positive displacement indicates a movement. The CFRP confinement procedure adapted to the beam end is also anticipated to have boosted concrete strength. CFRP sheets at the beam column corners along the beam axis acted as extra flexural reinforcement. Following the yield load, all specimens showed the ductile failure due to the yielding of the steel reinforcements present in the beam end into the joint region. However, the presence of CFRP in the specimens resulted in additional strength gains following the yielding of the steel reinforcement and reduced yield penetration by reducing bond degradation that occurred in the interface of the beam ends and the steel reinforcements. In comparison to their matching control specimens, the hysteric response loop of the columns retrofitted using CFRP are larger and highly stable with no evident weakening or loss in stiffness.

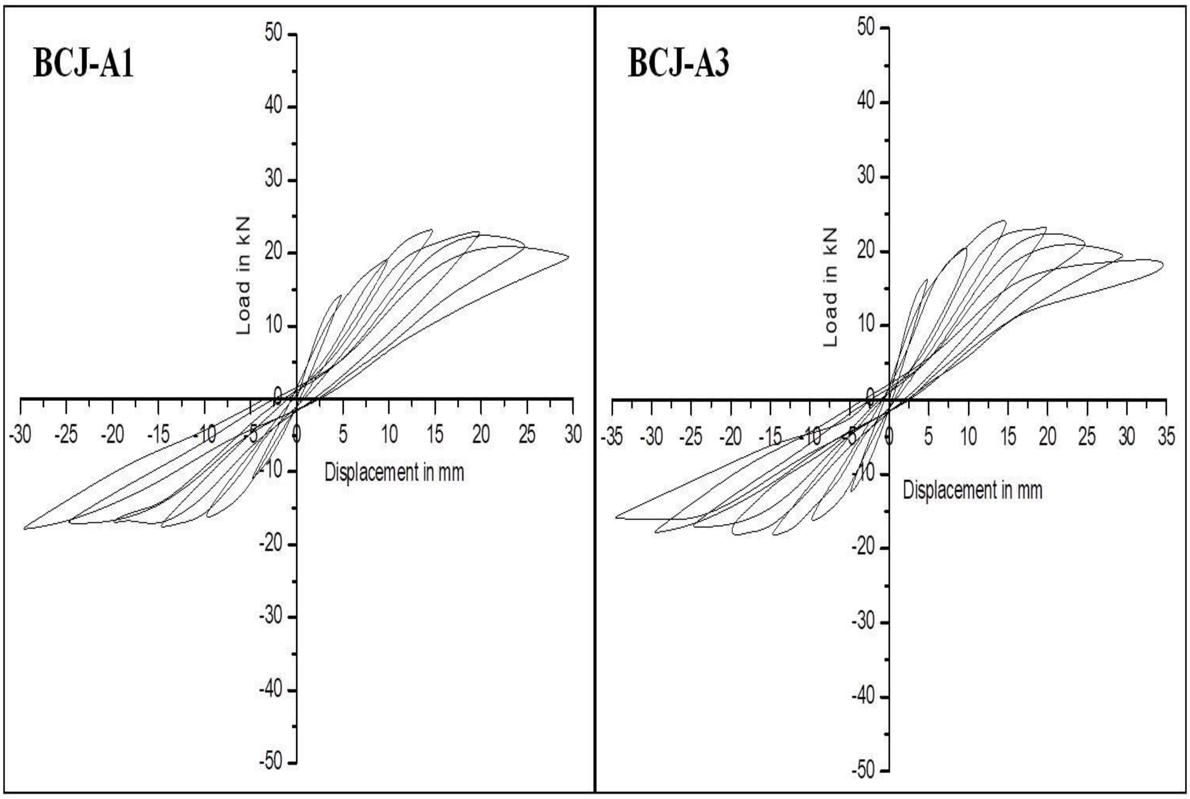

Figure 4(a) Hysteretic response of controlled samples

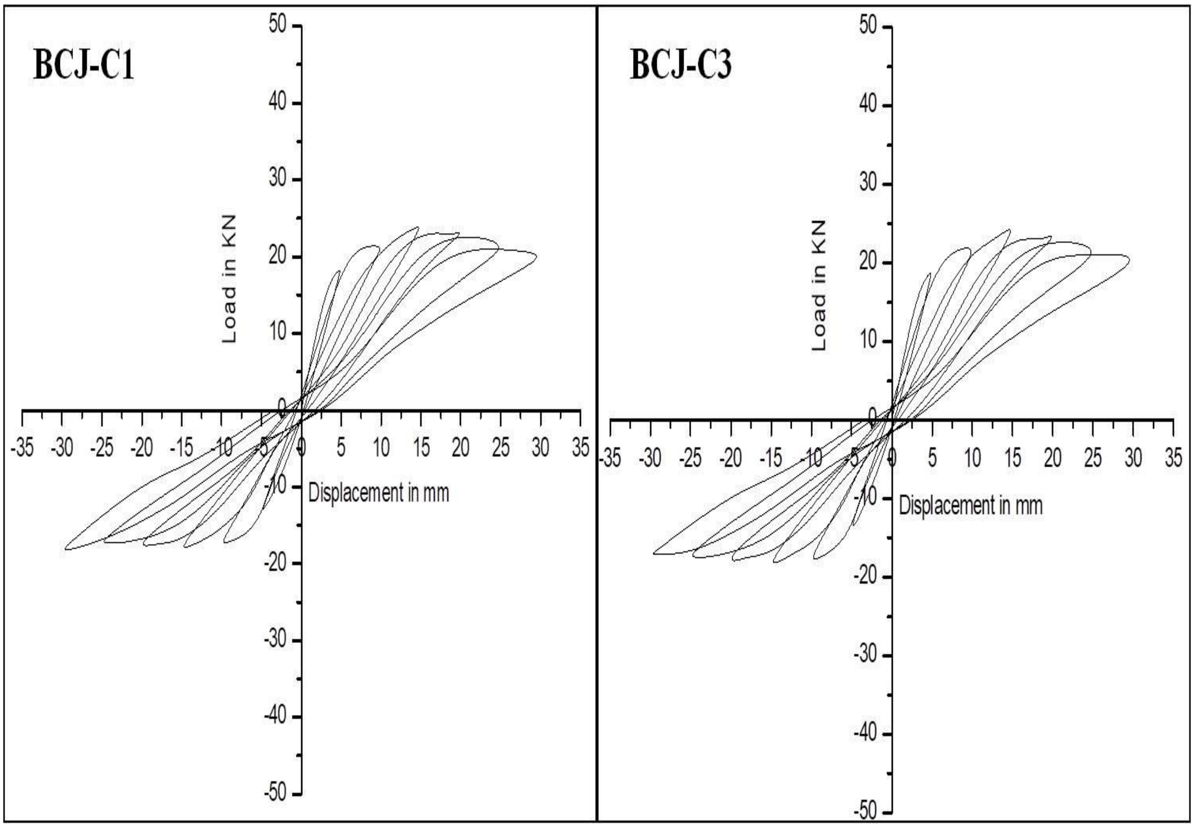

Figure 4(b) Hysteretic response of CFRP retrofitted sample with 20% axial load

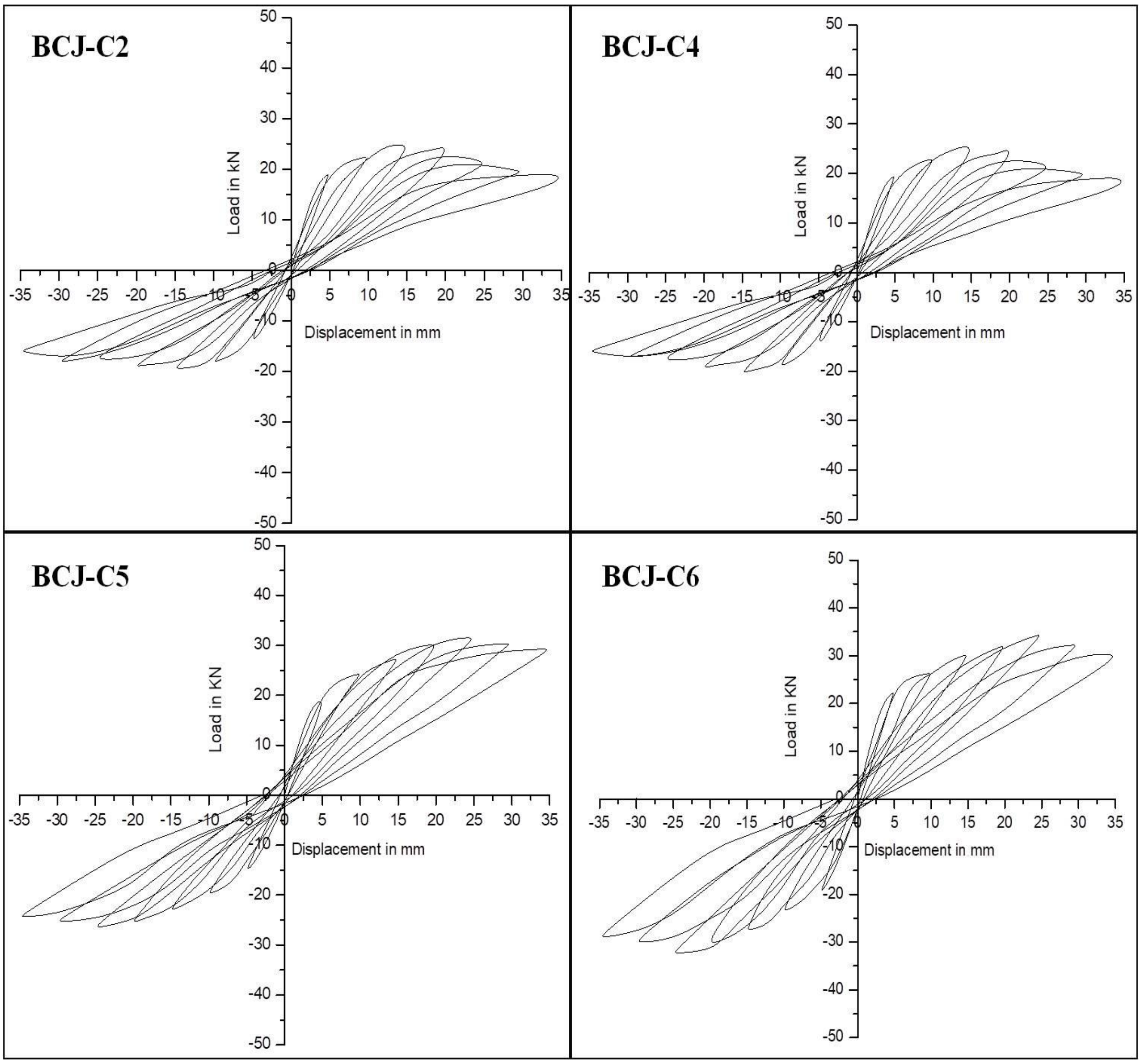

Figure 4(c) Hysteretic response of CFRP retrofitted sample with 30% axial load

4.2 Cumulative energy dissipation

One of the most crucial factors in determining how well a component performs under simulated seismic loading is its ability to dissipate energy. This is determined primarily by the rates at which a component's stiffness and strength degrade over the course of successive cycles of hysteresis response. The capacity of a structure to disperse energy determines whether it will survive an earthquake. The summation of the energy lost during the displacement test at each cycle provides the cumulative energy dissipation for structural members under cyclic loads which indicate the regions that is bound by the hysteric loop. The cumulative energy dissipation of the control beam-column and the CFRP wrapped beam-columns are presented in Fig. 5.

The slip that occurred between the CFRP wraps and the concrete in combination with the deformation (plastic) of the reinforcements in the concrete are the main causes of energy dissipation. For the samples BCJ-A1, BCJ-A3, BCJ-C1, BCJ-C2, BCJ-C3, BCJ-C4, BCJ-C5, and BCJ-C6, the total cumulative energy dissipation was 823.38, 1102.22, 1034.89, 1257.2, 1240.3, 1463.02, 1574.73, and 1728.64 kN mm, respectively. When compared to specimens with CFRP retrofits, the control specimens are determined to have the least energy dissipation. The CFRP that were aligned parallel to the axis of the column were unable to prevent joint shear failure, but they were able to minimize the formation, widening and number of the shear cracks that were parallel as a result of the tension stiffening effect, giving specimen BCJ-C1 a significantly lower energy dissipation capacity than BCJ-C3. Additionally, when comparing the 30% axially loaded specimens, BCJ-C2 had the lowest energy dissipation capacity, whereas BCJ-C6 provided the highest dissipation. Overall, the strength characteristics and the energy dissipation behaviour of the retrofitted beams were highly favourable and the strengthening strategy using CFRP along the beam axis proves to be the best option.

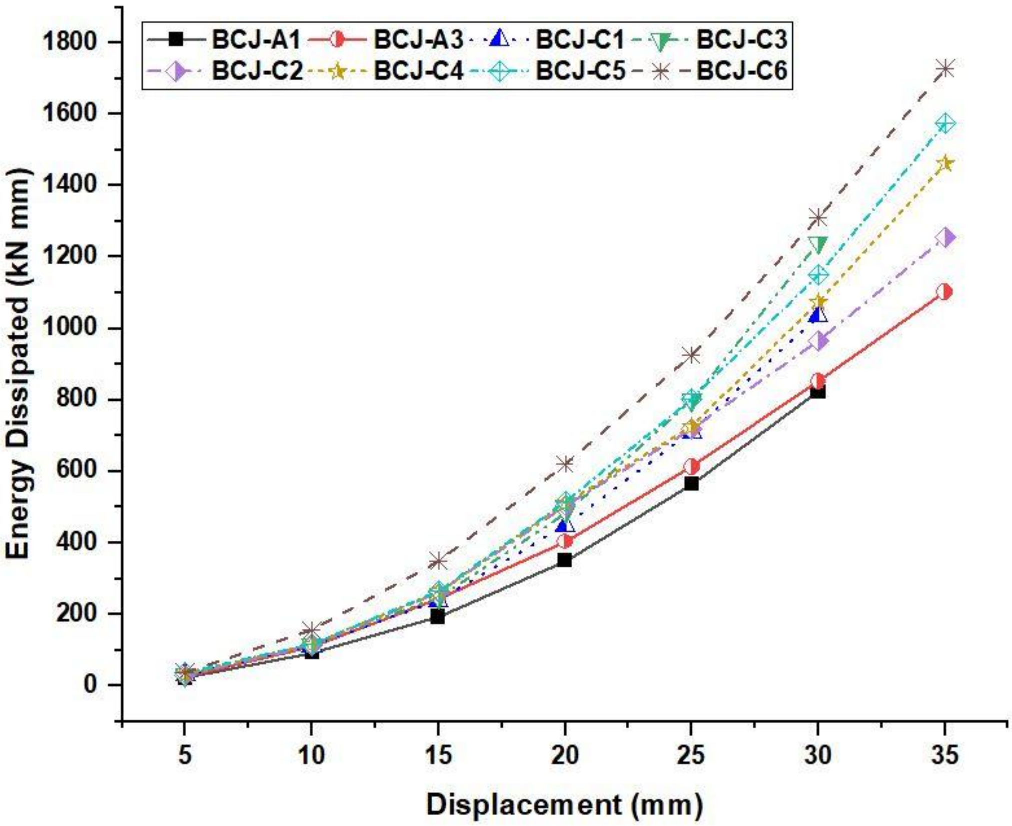

Figure 5 Cumulative Energy Dissipation of CFRP retrofitted specimens

4.3 Stiffness degradation

The slope of the line joining the peak-to-peak for each cycle served as an approximation of the cyclic stiffness at the beam-column joint, as illustrated in Fig. 6. The cracks formed due the flexure and shear that caused distortion of the connections in the panel and the deformation that has occurred in a non-linear manner in the concrete, loss of cover, and reinforcement slippage are all blamed for this degradation. The stiffness value (initial) of the retrofitted specimen BCJ-C6 in comparison to the control specimens (BCJ-A1 and BCJ-A3) showed the biggest increase of roughly 55.2% and 36.4%, respectively. The joint enlargement using CFRP is what causes the retrofitted specimens to have a higher starting stiffness. For the samples BCJ-A1, BCJ-A3, BCJ-C1, BCJ-C3, BCJ-C2, BCJ-C4, BCJ-C5, and BCJ-C6, the stiffness decreased from 2.9 to 0.65, 3.3 to 0.54, 3.7 to 0.68, 3.84 to 0.7, 3.84 to 0.64, 3.96 to 0.72, 4.16 to 0.84, and 4.5 to 0.87 kN mm, respectively. In comparison to their equivalent control specimens, the retrofitted specimens' initial stiffness is constant and their rate of cyclic stiffness degradation is reduced.

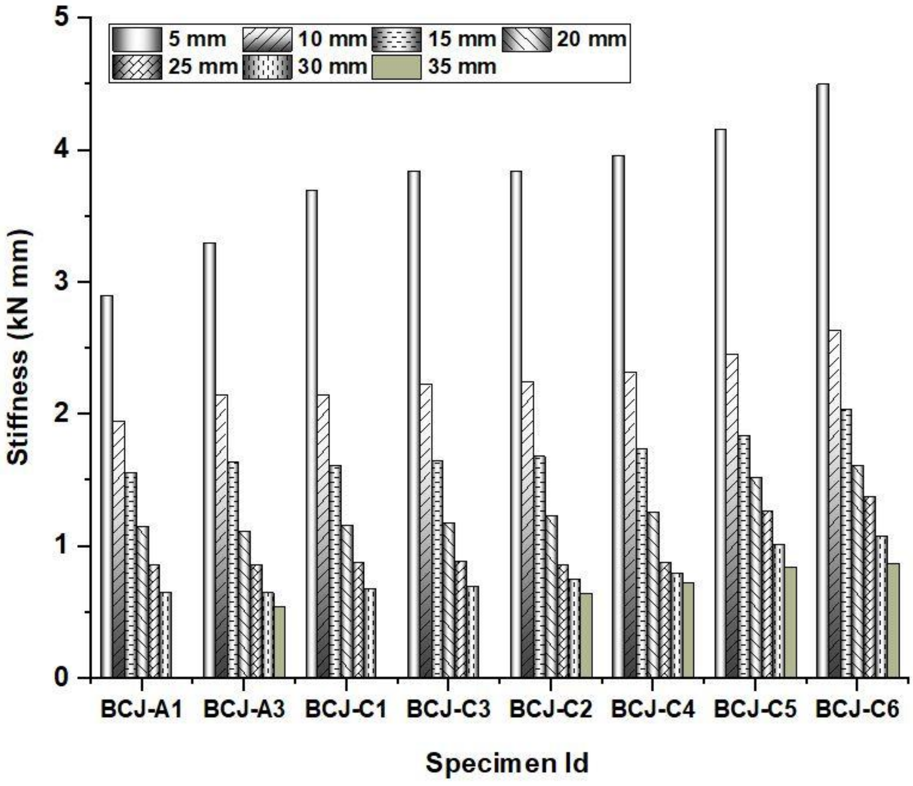

Figure 6 Stiffness of CFRP retrofitted specimens at various displacements

4.4 Crack patterns and failure modes

The fig shows the failure pattern of the beam-column connections, and the control specimen showed shear failure due to the absence of the external retrofitting systems. The control specimen also showed first crack formations, and the flexural cracks were formed near the connection, which further extended into the panels, further broadening the crack formations. The yielding of the steel was found on all the beam segments at the failure moment. The bonded strain gauges in the beam elements debonded after the permitted deflection was reached at the end of two cycles. The flexural cracks were also formed on the surface of the columns, which were a result of the failure of the lateral supports of the columns and shear failure of the joints that further extended into the joint zone after the control specimen broke. Furthermore, the increase in amplitude created more flexural cracks that extended further into the beam width during the experiment. The joint zone also showed cracks that developed on the top and bottom portions of the beam column connections. As the crack propagation increased, the CFRP fibers ruptured in a direction perpendicular to the shear crack formation. At higher axial load capacity during the final loading cycles, the rupture was critical, as observed in the joint zone on the column exterior spreading through the joint area. The concrete crushing has caused this rupture on the CFRP fibers due to the higher stress concentration on the fibers. However, no debonding failure was observed in the specimen, indicating the perfect bonding of the fibers with the column. The adopted methodology for the layering of the CFRP fibers in retrofitting showed efficient performance in enhancing the shear performance of the joints. Almost all the specimens retrofitted using CFRP showed no severe flexural damage, but the shear joints showed non-ductile behaviors. In CFRP retrofitted specimens, the cracks formed were minute and diagonal in the joint zone, and these cracks were temporary and invisible when the load was removed. With the extension of the cracks diagonally into the columns, the failure point shifted from the beam to the core of the connections as a result of the confinement by the CFRP wrapping. The confinement was essentially provided to achieve the strong connections that were only partially achieved in this study through the CFRP reinforcements in the edges of the members, thereby limiting the spread of the cracks into the joint region of the members and enhancing the ductility of the connections.

Figure 7(a) Crack patterns of control specimens

Figure 7(b) Crack patterns of 20% axially loaded CFRP retrofitted specimens

Figure 7(c) Crack patterns of 30% axially loaded CFRP retrofitted specimens

5. Conclusions

In order to evaluate the efficacy of CFRP seismic reinforcing methods, the findings of a well-planned experimental program using RC beam-column connections are provided in this work. The study aids in concentrating on how effectively the suggested rehabilitation plan provides a more flexible state for weak joints. The seismic behavior of the beam-column joints that is deficient to sustain seismic loads when compared to the conventional beam-column joint specimen for less dissipation of energy showing the efficiency of the proposed CFRP retrofitting scheme. All enhanced specimens experience greater mean peak loads in both pulling and pushing directions than the control specimen without CFRP reinforcements. The increased beginning stiffness of the retrofitted specimens is due to the joint expansion with CFRP. Overall, it appears that the strengthening technique using CFRP along the beam axis is the optimum choice for dissipating energy and strengthening of the joints. Regarding the case of non-ductile-strengthened beam-column connections, the absence of cumulative energy dissipation can be compensated for by strengthening CFRP.

Acknowledgement

None

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