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Rehabilitation of damaged RC exterior beam-column joint using various configurations of CFRP laminates subjected to cyclic excitations

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ABSTRACT

In this research, an investigational study on the use of CFRP laminates with 4 types of configurations (Series-A: laminated with confinement wrap, Series-B: single flat & L wrap, Series-C: confinement wrap, and Series-D: double flat & confinement wrap) to repair partially damaged reinforced cement composite column-beam joints is presented. The project's primary goal was to examine how retrofitting configurations affected the behaviour of repaired RC column-beam junctions when subjected to cyclic loads (FL + RL). To examine the effectiveness of repairs for enhancing the stiffness, strength capacity, and behaviour of damaged RC joints (Partially – 25%, 50%, and 75%), seventeen samples were fabricated and investigated. Cyclic loading was used to test the control specimen all the way to failure. Sixteen samples were subjected to a load level that was around 75% of the projected pre-failure load (26 kN) under seismic condition. The maximum load, ductility index, and load versus displacement were all used to analyse the data. Also, CFRP debonding and the failure modes due to fracture pattern were observed. The findings highlighted the significance of repairing and improving joint performance. All repaired joints have increased strength that is virtually as strong as the beam-column joint's actual shear strength. As a result, compared to the reference specimen, the Series-D joints had a substantially greater strength capacity (30.77%).

Keywords: Retrofitting; Beam-column joint; CFRP; Cyclic load.

1. INTRODUCTION

The connections between column and beam [1], known as column-beam joints, are critical components of RC (Reinforced Concrete) constructions [2]. Many criteria influence the performance of RC column-beam junctions, including reinforcement details [3], concrete strength [4], and relative stiffness between column and beam [5]. Actually, only the upright load is taken into account. Due to the failure of the diagonal fracture here, which causes the building to collapse, this joint is the most important part of the structure during an earthquake [6]. As a result, such joints require special consideration in order to retrofit the damaged joints to increase their capacity. Because of its high-stiffness-to-weight ratios and high strength-to-weight, FRP (Fibre Reinforced Polymer) is now preferred for reinforcing and retrofitting RC structural parts [7–9]. A column, beam, joint, or wall strengthened with CFRP loaded out-of-plane/in-plane may fail in a variety of ways. Debonding has a role in some of these modes. Cement composite crushing with or without yielding of steel bars, tension failure of CFRP (Carbon Fibre Reinforced Polymer) encloses with shear failure, and yielding steel which happens if the shear capacity is achieved earlier than any sort of flexural failure are examples of the latter [10]. Initiation of debonding typically occurs at stress-concentrated areas of the cement composite CFRP sheets interface [11–13]. This comprises the edges of the cement composite or cement composite cover peeling off and the adhesive, either entirely or in parts. So, in order to utilize the strengthening or repairing to its maximum capacity without debonding failure, it is crucial to develop insight and knowledge of how it should be done [14, 15]. Numerous research projects have studied the joints between RC beams and columns.

BEYDOKHTY and SHARIATMADAR [16] investigated the retrofitted column-beam joint in 2 phases (damaged phase and retrofitted phase) by CFRP composites [17] by cyclic loading. Plastic rotation and ductility ratio was reduced during their investigations. The size effect of repaired RC column-beam connections exposed to displacement-control cyclic stress was examined in an experimental investigation by CHOUDHURY *et al.* [18]. In all of the situations looked at, they discovered that the investigational outcomes closely supported

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the size impact law suggested by others. Also, the maximum load-carrying capacity for samples with retrofits increased from 5.29% to 26.92% [19, 20]. Exterior column-beam joints can be greatly strengthened by FRP-laminates, according to large-scale experimental research. Pimanmas and chaimahawan [21] looked over into the beam-column junction specimens' shear strength and found that an expansion joint is an efficient way to lessen the amount of shear stress that is transmitted to the joint panel. Wide loops show that energy dissipation can also dramatically increase [22]. Brittle shear failure in beam joint is replaced by substantially ductile flexural failure. The plastic hinge is relocated from the column surface to the enlargement's edge. PARVIN and WU [23] developed a strengthening method for outer column-beam connections based on carbon fibre-reinforced polymer laminates that are adhesively bonded and wrapped with CFRP strips fastened into beam perforations. To rise the ultimate strength and stiffness of strengthened column-beam junctions, several ferro-cement combinations were used [24–26]. Under cyclic loads, the experimental behaviour of retrofitted external RC column-beam joints with curbs and steel props has been investigated. YU *et al.* [27] tested internal column-beam couplings with transverse beams and slabs using outwardly bonded L-shaped FRP laminates in repair [28]. The application of a thin jacket on exterior joints was also studied by KARAYANNIS and SIRKELIS [29]. A 20 mm thick jacket was then placed over the broken joints, which were enclosed in various densities of 5.5 mm plain rebar that wasn't anchored [30]. In the specimens, they discovered that the joint's capacity had increased. An analytical study on the exterior column-beam joint was conducted by BINDHU *et al.* [31]. using a finite element model. They discovered that adding more inclined reinforcement bars enhanced the joints' earthquake performance. In the outer column-beam connection, KYTINOU *et al.* [32] inspected the impact of diagonal bars as shear reinforcement under cyclic excitations. Vertical bars, diagonal bars, stirrups, and combinations of them were employed to provide various shear-reinforcement profiles for the joint. They discovered that specimens with joint stirrups and crossed inclined bars displayed improved reaction and performance. It was crucial for the joint's safety that crossed bars and stirrups be used together [33]. Compared to specimens without stirrups, stirrups not only increased the joint's shear strength but also prevented the bending anchoring of the bars from deforming due to the concrete covering peeling off at the joint area's rear. In order to explore the idea of moving the positioning of the plastic hinge away from the face of the column, MAHINI *et al.* [34] looked into the efficacy of web-bonded CFRP on the capacity to absorb the energy of reinforced concrete joints. Also used in concrete joints are various retrofitting techniques including epoxy injection and the use of concrete masonry units [35]. COTSOVOS [36] investigated the yield close predictions of the behaviour of a two-story frame under static and dynamic loading. Using this model cracking in the intersection of beam-column has a major result in the comprehensive structural behaviour. Finally, practical analysis established on the assumption of stiffened joints ensures that will not defend code précised margins of safety and structural behavioural requirements [37–40].

SAGHAFI and GOLAFSHAR [41] work used experimental research to extract the joint behaviour in relation to the slab and transverse beam influence. Four concrete external beam-column joints that are experimentally built and loaded repeatedly are made for this purpose. The results of the retrofitted joint behaviour demonstrate no strength loss, stable cyclic behaviour, reduced pinching effects, and improved cyclic behaviour due to a change in the failure mechanism from shear failure of the joints to the production of flexural plastic hinges in the beam [42, 43]. BOURGET *et al.* [44] prepared the closed stirrup which made of prefabricated CFRP L-shaped laminates and a CFRP rope as a closure. Due to its minimal surface preparation requirements and lack of mechanical anchoring, this application method offers a long-lasting and economical option. Additionally, in seismic zones where transverse reinforcement must be closed for containment reasons, this is a feasible solution [45]. On full-size RC T-beams with three different internal transverse steel ratios, laboratory testing was conducted. There are few experimental investigations that examine the cyclic behaviour of RC beam-to-column joints that have experienced inner heat damage. MURAD and ALSEID [46] studied, eight interior RC beam-to-column joints that had been heat-damaged by being exposed to 900 °C for three hours are investigated experimentally for their cyclic behaviour. According to test results, CFRP ropes significantly improved the lateral strength, drift ratio, and ductility of heat-damaged joint specimens, respectively, by up to 50%, 98%, and 53%.

A current assessment of the efficiency of fibre-reinforced polymer retrofitting of column-beam joints revealed that limited cyclic excitations studies had been carried out on reinforced concrete elements retrofitted with fibre-reinforced polymer plates and explained the behaviour of repaired joints [47]. Thus, a deeper understanding of the behaviour of retrofitted joints under cyclic excitations was required. Also, it was important to build up an investigational setup that considers the numerous factors that influenced how retrofitted joints with CFRP behaved when subjected to cyclic loading with various configurations. In light of this, it will be investigated how various configurations, such as the arrangement of the CFRP laminates on the joint in terms of alignment and direction, affect the functionality of the retrofitted RC joints made of CFRP. Also, this research will concentrate on comprehending and postponing the debonding and failure pattern of CFRP laminates, thus boosting the strength of the column-beam joint.

2. MATERIALS AND SPECIMEN PREPARATION

In the Mahendra College of Engineering's Civil Engineering Department's Structural lab, 17 numbers of exterior (T-Shaped) RC column-beam junction specimens are developed, cast, and built [48]. All the specimens were cast horizontally by means of steel moulds constructed and prepared to allow for proper concrete placement. Furthermore, examples were designed in accordance with ACI318-011 and IS13920: 2016, which have the same geometry, characteristics, and reinforcement features [49–52]. To depict a poorly detailed exterior join, the joints were constructed with insufficient strength. The beams are 630 mm long with a 150 × 230 mm cross-section. All examples of the columns have a 290 × 150 mm cross-section. Figure 1 depicts a model of the exterior column-beam joint [53]. The longitudinally deformed steel bars in beams were made up of bottom bars measuring 3 numbers of 12 mm diameter and top bars measuring 3 numbers of 12 mm diameter. Stirrups were defined as 8 mm polished steel bars spaced 50 mm apart. Regarding columns, 8 numbers of 12 mm distorted bars with 8 mm ties spaced 50 mm apart are employed as longitudinal reinforcements. The same standard concrete mixture created using the IS10269:2019 mix-design technique was used to cast each specimen. In order to create the concrete mix, Ordinary Portland Cement 53 grade confirming to IS2269: 2006, CA (Coarse Aggregate) with a maximum aggregate size of 20 mm, M-Sand as FA (Fine Aggregate) conforming to Zone-II, and water with 6.75pH level as confirming to IS456:2000 was employed [54–56]. The proportions of the concrete mixture utilized to cast different examples were 0.45w/c. R&D Adhesive were used to connect the RC member and CFRP laminates. Using test cubes measuring 150 mm × 150 mm × 150 mm, a 28-day compressive strength of 20MPa was discovered for each batch of concrete. Specimen details are shown in Table 1.

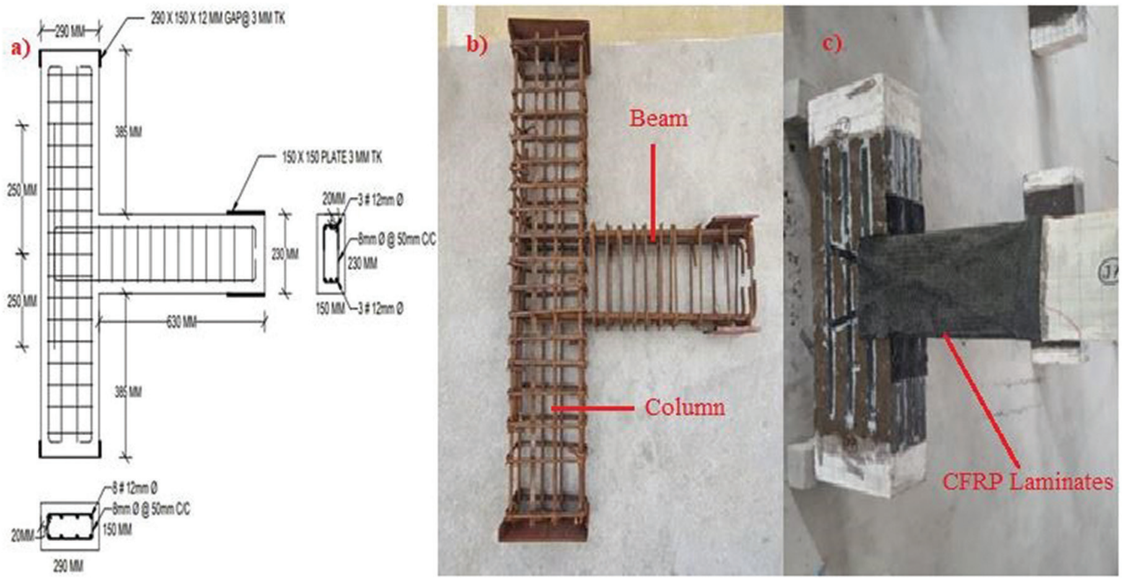

Figure 1: Beam-column joint a) Ductile detailing b) Reinforcement arrangement c) Retrofitted beam-column.

Table 1: Specimen index.

DAMAGE INDEX %	RETROFITTING BY CFRF TYPES			
	SERIES-A	SERIES-B	SERIES-C	SERIES-D
	LAMINATE WITH CONFINEMENT WRAP	SINGLE FLAT & L WRAP	CONFINEMENT WRAP	DOUBLE FLAT & CONFINEMENT WRAP
0	BCJ1	BCJ2	BCJ3	BCJ4
25	BCJ5	BCJ6	BCJ7	BCJ8
50	BCJ9	BCJ10	BCJ11	BCJ12
75	BCJ13	BCJ14	BCJ15	BCJ16

3. METHODS AND METHODOLOGY

3.1. Experimental techniques

In accordance with what was suggested in the literature and as depicted in Figure 1(a), a scale that was adequate was chosen: one-third of the prototype connections. In addition, the area of the loading frame (LF) at the structural laboratory of the Mahendra College of Engineering has limited space. The vertical cyclic load was applied at the top edge of the beam [57]. The goal of the current inquiry was to portray the most direct circumstance. As stated in the ACI code, adding an axial compression load to a compression member will increase the cement composite's resistance to shear in the joint zone. As a result, the vertical load was not taken into account in this investigation. A hydraulic actuator with a capacity of 250 kN in compression and 150 kN in tension was used to apply the cyclic loading while employing a load-controlling approach (2 kN per step). Figure 2 illustrates the cyclic load set-up in LF. The ends of the beams included hinge supports to imitate lateral movement [58]. Three steel plates (300 mm × 200 mm × 25 mm)-one plate at the bottom, one plate at the top of the column, and another one at the end of the beam to make up the hinge supports. The hydraulic jack plate was attached corner of the beam and fixed to LF. A hinge at the bottom of the compression member provided stability and allowed for rotation only at the connection where no movement in any other path was permitted. At the tip of the beam, the vertical displacement was measured using LVDT (Linear Variable Differential-displacement Transducers). One of the 17 column-beam joints was utilized as a control (reference) column-beam and tested until it failed in order to compare its performance to that of the retrofitted column-beam joints with CFRP plates. Similar to the control beam, the other sixteen beams were preloaded to a maximum of about 25%, 50%, and 75% (damage index) of the control specimen's ultimate failure load (Pu = 26 kN). Since it was difficult to foresee the whole load, it was vital to keep the specimen from completely failing. Preloading at this amount was designed to induce severe damage and numerous cracks, but a not complete failure [59]. The specimen was therefore simple to handle, fix, and retest. Investigated were various retrofitting arrangements.

3.2. Methodology

In the first stage, the specimen was assessed at 0% damage index with four different configurations namely laminated with confinement wrap, single flat & L wrap, confinement wrap, and double flat & confinement wrap of the extreme control load as established by examining the reference sample (controlled specimen). The joint was then retrofitted with various CFRP plates that were glued to the surface of the reinforced concrete section using a specific bonding at the scratched region of the column-beam junction using various plate conformations after the joint had been repaired using a unique cement mortar. The specimens were retested in the second stage with cyclic loading all the way to failure.

The CFRP laminates have a width of 500 mm and thickness of 0.250 mm, an elastic modulus of elasticity = 235–245GPa, and an elongation at rupture = 1.8%. Delaying debonding may be the guiding principle of retrofitting procedure. Debonding is a significant problem when RC members are externally retrofitted with FRP composites. The surface of the sample is grounded and then vacuum-cleaned to establish a strong adhesion

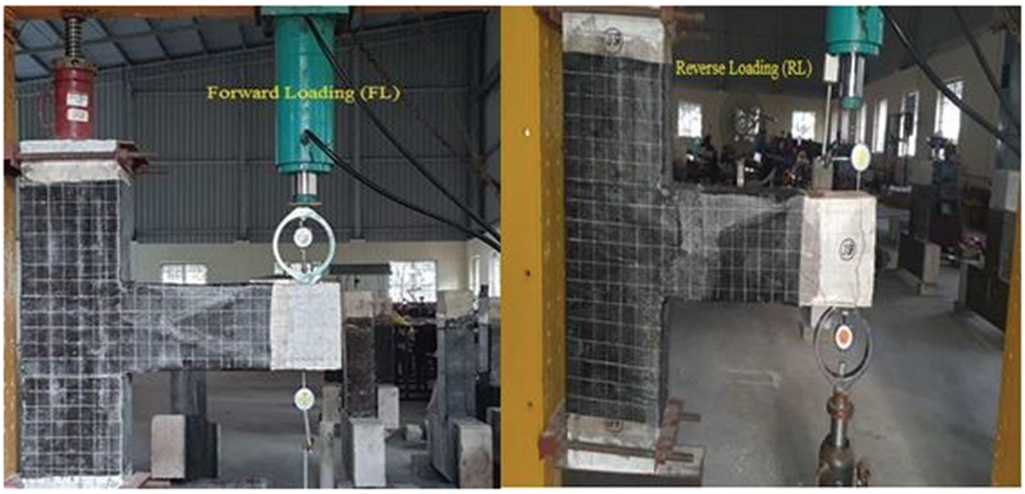

Figure 2: Cyclic load set-up.

between the repaired beam and the CFRP laminate. Using the commercial epoxy resin, the Carbon Fibre Reinforced Polymers laminate is attached to the cleaned outward on one face of the fractured cement composite beam. To establish a strong adhesion on the initial face, the same operation was performed on the reverse side of the fractured beam column after an additional 24 hours.

4. RESULTS AND DISCUSSION

4.1. Beam-colum joint with various configurations of CFRP

Several configurations were looked at in accordance with the results of the control specimen's deficiencies. The recommended strategies in the current study attempted to increase specimen strength and decrease damage-related cracks. The examples of the column-beam joints were divided into four sets, each with a different suggested rehabilitation. The Series-A specimens served as the starting point for the recommended arrangements, which attempted to stop the spread of diagonal cracks. The specimens in laminate with confinement wrap were assigned the designations BCJ1, BCJ5, BCJ9, and BCJ13 for the ductility index 0%, 25%, 50%, and 75% respectively, i.e., B for a beam, C for a column, and J for the joint. The Series-B specimens with a single flat & L wrap were assigned the designations BCJ2, BCJ6, BCJ10, and BCJ14 for the ductility index 0%, 25%, 50%, and 75% respectively. The Series-C specimens with confinement wrap were assigned the designations BCJ3, BCJ7, BCJ11, and BCJ15 for the ductility index 0%, 25%, 50%, and 75% respectively. The Series-D specimens with a double flat & confinement wrap were assigned the designations BCJ4, BCJ8, BCJ12, and BCJ16 for the ductility index 0%, 25%, 50%, and 75% respectively. The schematic view of laminated with confinement wrap, single flat & L wrap, confinement wrap, and double flat & confinement wrap in column-beam joints is shown in Figure 3 to Figure 7. The series-A specimen with two parallel plates; all other specimens have them (two layers in the perpendicular direction and one layer in one direction). Series-D has extra inclined plates of CFRP. Series-D CFRP (BCJ4, BCJ8, BCJ12, and BCJ16) was added to cover that corner in order to stop the diagonal cracks that developed at the end of the junction and contributed to Series-A, Series-B, and Series-C. Series-D specimens have comparable ornamentation, but the angle among the plates is different. The CFRP system of Series-A was made up of 2 plates: a discontinuous bottom layer and a continuous top layer on a one-layer plate with a length of 450 mm perpendicular to a two layer plate with a length of 250 mm. the Series-B, on the other hand, features a continuous 250 mm long one-layer plate that is inclined to a 250 mm long one-layer plate. Two CFRP plates, each 250 mm long and angled towards a single, continuous 730 mm long CFRP plate, made up the layout. As a result, Series-D is comparable to other series except that it has an inclined plate.

4.2. Hysteresis responses for the cyclic loading

Figure 3 displays the load vs the displacement for various configurations of CFRP. The control sample had the lowest strength capacity and stiffness, as stated. All of the samples were able to recover from and outperform their initial load strength capacity in comparison to the control specimen (CN). According to the findings shown in Figure 3, elastic behaviour predominated before the emergence of the first cracks at 10 kN, the second crack

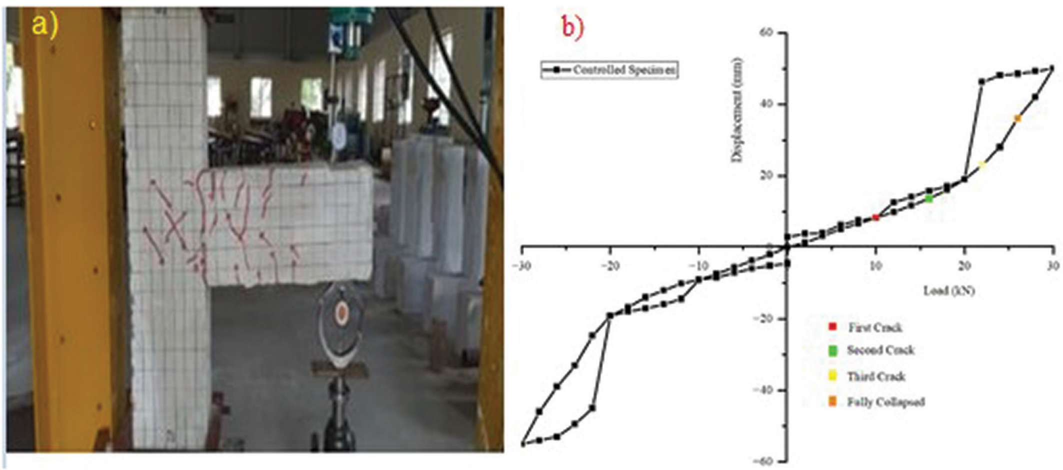

Figure 3: Load-displacement behaviour of the retrofitted beam-column joint a) Controlled specimen b) hysteresis response of the controlled specimen.

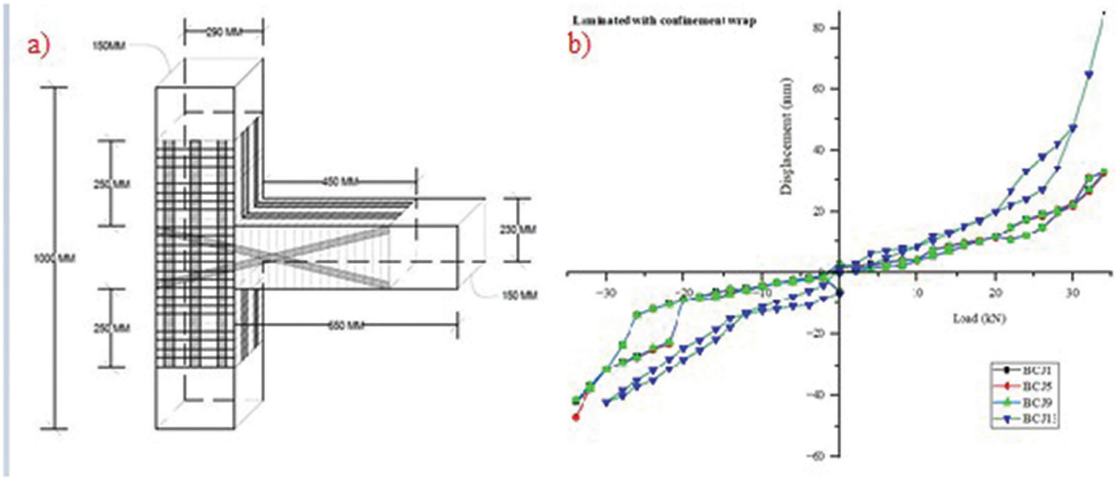

Figure 4: Load-displacement behaviour of the retrofitted beam-column joint a) Series-A configuration b) hysteresis response of Series-A specimen.

was at 16 kN and the third crack was at 22 kN during forward loading. The controlled specimen has a maximum load-carrying capacity of 26 kN. Table 2 depicts the failure loads of all the specimens including conventional concrete beams-column joints.

While applying forward loading (FL), the series-A specimens of designations BCJ1, BCJ5, BCJ9, and BCJ13 having the maximum deflections of 33 mm, 32.2 mm, 33.0 mm, 47.20 mm, respectively and in the reverse loading (RL) BCJ1, BCJ5, BCJ9, and BCJ13 having 42 mm, 41.0 mm, 41.5 mm, 42.2 mm. During FL, series-B produced 35 mm, 39 mm, 23.6 mm, 26.20 mm for BCJ2, BCJ6, BCJ10, BCJ14, respectively. While in the reverse loading (RL), BCJ2, BCJ6, BCJ10, BCJ14 have displacements of 37 mm, 38 mm, 38.5 mm, 42 mm. While applying forward loading (FL), the series-C specimens of designations BCJ3, BCJ7, BCJ11, and BCJ15 had the maximum deflections of 24.5 mm, 30.2 mm, 34.5 mm, 45.0 mm, respectively, and in RL BCJ3, BCJ7, BCJ11, and BCJ15 having 35.1 mm, 45.1 mm, 37.0 mm, 49.0 mm. Further, it was evident that, depending on the retrofitting arrangement employing CFRP plates, each repaired joint increased its load-carrying capability relative to the control specimens by a different proportion. The specimens Series-D BCJ4 (28 kN), BCJ8 (28 kN), BCJ12 (28 kN), and BCJ16 (28 kN), which include horizontal and vertical CFRP laminates configurations with inclined plates, showed the biggest increase in capacity compared to control specimen (CN).

According to ACI 318-11, the predicted strength capacity was roughly similar to the column-beam junction shear strength (65.6 kN). Retrofit diagonal plates prevented debonding from occurring under loads below the joint's shear strength capability, which led to the failure of a junction. In this series, it is noticed that the use of inclined plates with horizontal and vertical plates (Series-D) simply has a larger load-carrying capacity. As an outcome, the shear zone in the beam-column junction was strengthened further, delaying the onset of cracks and the debonding failure of Carbon Fibre Reinforced Polymers laminates. Figure 4 shows the load versus displacement envelope curves for the samples in Series-A. The specimen's load-carrying capability was enhanced compared to controlled specimens by the employment of CFRP laminates. The stiffness and load capacities of CN were, however, significantly impacted by the configuration of the CFRP plates. Figure 5 to Figure 7 depict the load displacement of Series-B, Series-C, and Series-D. The zone of the loop was stable during the elastic stage under both push and pull loads. Thereafter, as the range of the loop owing to each loading cycle rapidly expanded, the cracking stage began, resulting in the specimen's loss of stiffness. In comparison to the control sample, the curves clearly show how different plate layouts improve the behaviour of the specimens in terms of stiffness and load. As seen in Figure 5 to Figure 7, the repaired samples Series-A, Series-B, Series-C, and Series-D improved load-carrying capacity.

More strength was provided by the Series-D joint configuration than by other series. This suggests that adding layers will increase the strength capacity, but that they won't have an unintended, reversible effect. When compared to the one-layer plate specimen Series - A to C, the introduction of a double-layer plate in BCJ4, BCJ8, BCJ12, and BCJ16 (Series-D) increase the specimen's ability to support a load. The decrease in plate thickness other than Series-D, which led to a prior debonding of the corresponding Carbon Fibre Reinforced Polymer laminates due to an increase in eccentricity, may be responsible for this drop. This was the outcome of the shear-load transmission at the inter surface amongst the CFRP laminates and the associated reinforced

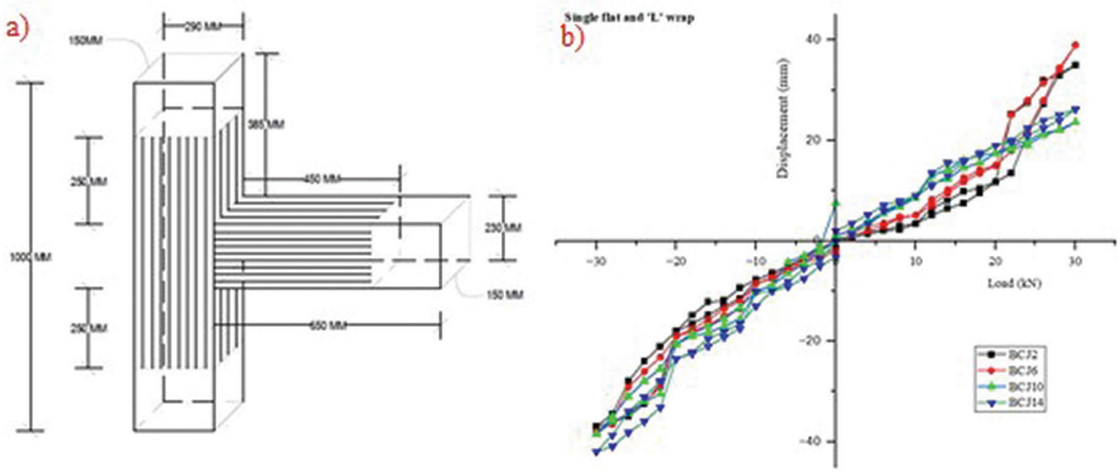

Figure 5: Load-displacement behaviour of the retrofitted beam-column joint a) Series-B configuration b) hysteresis response of Series-B specimen.

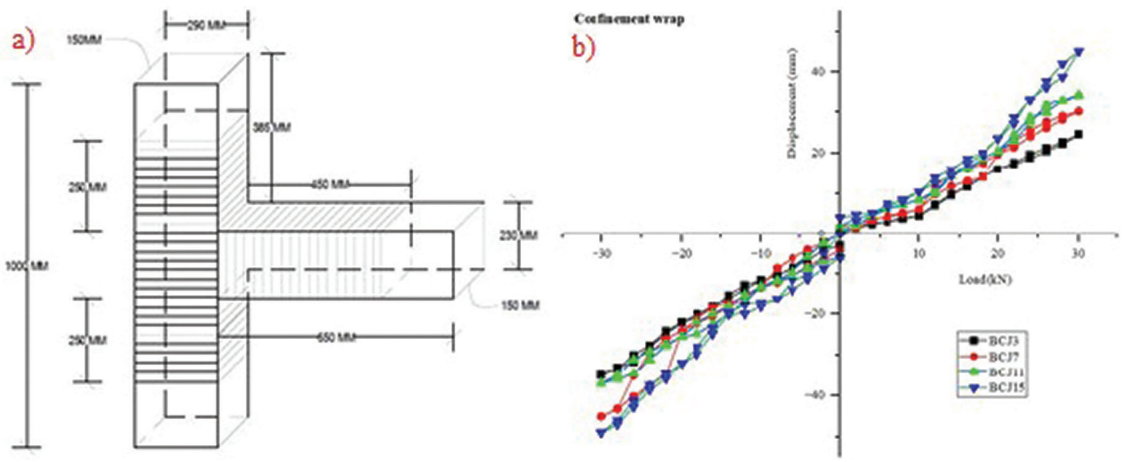

Figure 6: Load-displacement behaviour of the retrofitted beam-column joint a) Series-C configuration b) hysteresis response of Series-C specimen.

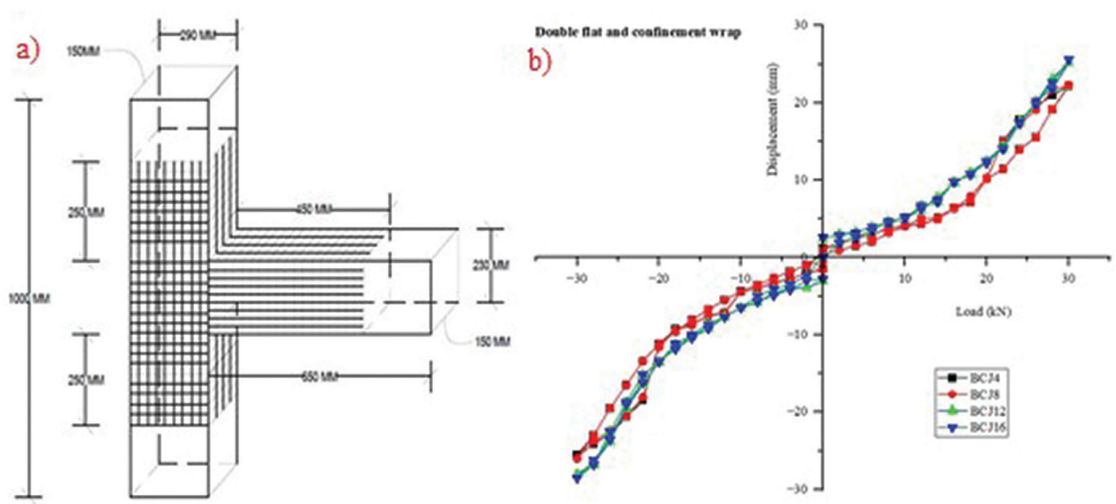

Figure 7: Load-displacement behaviour of the retrofitted beam-column joint. a) Series-D configuration b) hysteresis response of Series-D specimen.

Table 2: Failure loads of all the specimens.

BEAM ID	DAMAGE INDEX	FULLY COLLAPSED LOAD (kN)	
		FORWARD LOADING	REVERSE LOADING
Conventional Beam	0%	36.10	39.00
BCJ1	0%	33.00	42.00
BCJ5	25%	32.20	41.00
BCJ9	50%	33.00	41.50
BCJ13	75%	64.70	42.20
BCJ2	0%	35.00	37.00
BCJ6	25%	39.00	38.00
BCJ10	50%	23.60	38.50
BCJ14	75%	26.20	42.00
BCJ3	0%	24.50	35.10
BCJ7	25%	30.20	45.10
BCJ11	50%	34.50	37.00
BCJ15	75%	45.00	49.00
BCJ4	0%	22.16	25.50
BCJ8	25%	22.30	26.00
BCJ12	50%	25.20	28.00
BCJ16	75%	25.60	28.50

Figure 8: a) Applications of CFRP b) Failure mode of beam column joint.

concrete joint, which led to the shear-lag phenomena. In both positive and negative loading, specimen BCJ4, BCJ8, BCJ12, and BCJ16 capacity was greater than that of the control specimen. When a double layer with confinement wrap of Carbon Fibre reinforced Polymer laminates is used, the maximum load is increased, but when one layer wrap was used, the specimen is shown to be able to sustain a lesser load. Figure 8 depicts the CFRP application in damaged structure and failure mode of beam column joint.

The ratio of the yield drift to the ultimate drift is known as the ductility index. To idealize the real load-displacement curvature, a bilinear curvature was utilized in order to estimate the yield displacement. The accepted method set the starting yield point on the actual load-displacement curve at 0.6 of the ultimate load (f_u). At the origin, the initial segment of the bilinear curvature passed via the point of ($0.6f_u$) up to (f_u), where the yield displacement was defined. The second part of the bilinear model was created by extending the curve horizontally straight. As a result, the yield drift ratio that was obtained matched the yield displacement to specimen height ratio. The efficacy of the CFRP plate designs was assessed in this investigation using the ductility index. Eventually shows that the retrofitted beam-column joint had more ductility index. With a forward load (FL) of 30 kN and a reverse load (RL) of 30 kN, joint series-D had the greatest value (l = 2.60 mm) and hence the highest load-carrying capacity. In contrast, the control specimen (CN), which had FL = 30 kN and RL = 30 kN strengths, had the lowest value of l = 2.85 mm. The CN-specimen had the lowest initial crack load ever measured (10 kN), while Series-A was 11.5 kN. The area under the whole load-displacement envelopes was used to compute the total amount of energy that cyclic loading had dissipated in the joints between beams and columns. As shown in Figure 7(b), this region represented the energy that the specimens could expend before the system started to lose stability. The control joint (CN), according to the results, had the least amount of lost energy, while specimens BCJ4, BCJ8, BCJ12, and BCJ16 had the most. Also, it should be observed that joints in Series-D had substantially more dissipated energy than joints in Series-A, Series-B, and Series-C.

5. CONCLUSIONS

The investigational work of 17 reinforced concrete beam-column joints that were loaded cyclically was presented in this study. The first joint served as a control specimen, with the remaining joints being somewhat injured (preloaded up to 75% of the control specimen's ultimate load) and subsequently repaired using CFRP laminate systems. Here are a few inferences that can be made:

1. With the help of CFRP laminates, joints were able to carry more weight more effectively, however in retrofitted joints, debonding of the CFRP plates took the place of diagonal cracks as the mode of failure. When compared to the control specimen, the load-carrying capacity of the modified joints significantly increased by 15.38% to 30.77%.
2. The control specimen failed due to the appearance of diagonal cracks in the joint since there was shear reinforcement. Because of this, this specimen was far more resistant to failure than the repaired joints. The different retrofitted joints started out stiffer than the control specimen. When compared to laminate with confinement, Single flat & L wrap, and confinement wrap, double flat-confinement wrap makes more stiffness to structures.
3. The specimens BCJ3, BCJ7, BCJ11, and BCJ15 were found to have the highest strengths (Series-C). The key reason for this improvement was the simultaneous use of vertical and horizontal CFRP laminates, which protected the corners of the joint, which are where cracks first start to form. Thus, this prevented the diagonal cracks from growing. Similar behaviour was also seen by the joint BCJ4, BCJ8, BCJ12, and BCJ16 (Series-D), which further increased load-carrying capability by covering the joint corners with diagonal plates (Double Flat and confinement wrap). BCJ4, BCJ8, BCJ12, and BCJ16 displayed the highest joint ductility indices.

6. ACKNOWLEDGMENT

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