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RESEARCH ARTICLE Open Access

Innovative Analytical Approach For Evaluating The Performance Of Strengthened Edge RC Beam-Column Joints

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Abstract: Beam-column joints (BCJs) are important in reinforced concrete (RC) constructions because they have a big effect on how loads are transferred and how stable the structure is, especially when it is under uniaxial monotonic loading. Many older RC structures have poorly detailed joints, which makes them likely to break. Using the Strut-and-Tie Model (STM), which has been verified by numerical modelling, this study looks at how strengthened and unstrengthened exterior BCJs behave. Four samples: BCJ-1 (a control that met ACI 352-02), BCJ-2 (a joint that wasn't strong enough), BCJ-3 (a junction that was strengthened with CFRP), and BCJ-4 (a joint that was strengthened with a steel plate). Sta4CAD V14 and the Moment Distribution Method have been used to perform a sub-frame analysis and find the joint forces and inflection points. Results showed that CFRP and steel plate strengthening significantly enhanced joint performance in terms of shear strength, moment capacity, and strut width. CFRP sheets improved force transfer and stiffness due to effective confinement, while steel plates enhanced shear resistance and moment redistribution.CFRP provided superior energy dissipation, though steel plates offered advantages in durability and constructability. A finite element model employing STM principles was also used to evaluate strengthening efficiency. The findings highlight the critical impact of retrofit methods on joint behavior and offer practical insights for developing effective, economical strengthening strategies for RC joints under monotonic loads.

Keywords: *Beam Column Joints; RC; RC Joint Strengthening; Strut and Tie Model; CFRP Strengthening; Steel Plate Strengthening; Analytical Modeling.*

1. Introduction

A number of previous studies have focused on the significance of beam-column joints in RC structures, in terms of their effects on overall structural behavior and failure mechanisms [5, 4]. These joints primarily resist shear through two mechanisms: (a) the diagonal strut mechanism, in which the joint is in compression and acts as a compressed concrete strut; and (b) the truss mechanism, in which reinforcement bars contribute to shear resistance [7]. Nevertheless, a number of RC structures were reported with insufficient joint detailing because of outdated design practices, which results in their premature failure prior to the formation of plastic hinges in the beams [6]. These inadequate joints should be reinforced in order to increase their load capacity and general structural stability. There are several retrofitting methods used, such as concrete jacketing, steel plate retrofitting, and fiber-reinforced polymer (FRP) applications; these have their advantages and drawbacks [8].

To investigate the structural performance and strengthening efficiency for the preliminary design goal, four exterior BCJ specimens (BCJ-1, BCJ-2, BCJ-3, BCJ-4) were investigated in this study. BCJ-1 was created as a comparator/reference model by adapting the general principles of ACI 352R-02 to the specific conditions and objectives of this study, ensuring it provided a realistic baseline for assessing the proposed strengthening techniques [1]. The poor joint with low reinforcement (BCJ-2) failed prematurely with inferior ductility under load. BCJ-3 was improved with the addition of CFRP sheets at the joint to enhance its vibration performance, and BCJ-4 had steel plates attached at the joint.

Selected strengthening measures were chosen according to their prospects for increasing shear resistance, energy dissipation, and suppressing the brittle mode of failure, along with favoring feasibility in practice [12, 9].

The unique aspect of this study is the analysis of strengthened beam-column joints, combining CFRP and steel plate strengthening by including their contributions in the basic equations of analysis. In contrast to earlier efforts that mainly concentrated on experimental observations, this study establishes an analytical model that accounts for the material properties and mechanical roles of strengthening additives. The research presents a more accurate and predictive methodology for analyzing the effectiveness of retrofits, in which CFRP and steel plate parameters are incorporated into calculations of joint shear resistance. The proposed analytical approach not only contributes to the comprehension of retrofitted joints but also provides engineers with useful rational design guidelines in the search for more efficient and cost-effective means of strengthening deficient beam-column joints.

1.1 Research Significance

While the ACI code provides clear guidelines for the strengthening of beams and columns, it lacks any specific provisions for the analysis and design of strengthened beam-column joints. In practice, this often leads to a critical oversight—strengthening the beam or column while leaving the joint vulnerable. This research addresses that gap by investigating the behavior of joints strengthened with CFRP sheets and steel plates, and by developing an analytical model that incorporates the contribution of these materials into joint shear resistance calculations. The study aims to provide a rational basis for future design guidelines and promote the inclusion of joint strengthening in structural standards, enhancing the safety and performance of retrofitted RC frames.

2. Research Methodology

2.1 Analytical Approach

The researchers employed an analytical process utilizing the space truss model to assess the conduct of exterior beam-column joints under various strengthened states. This investigation delved into the force transference mechanisms, compressed area proportions, stress dispersal, and modes of failure using the STM technique when alternative strengthening techniques were applied, such as carbon fiber reinforced polymer and steel panels fixed with bolts. The analytical process facilitates a deep exploration of the load transmission path while also determining the effectiveness of the strengthening methods explored, presenting insightful findings for structural enhancement ventures.

2.2 Material Properties

The mechanical properties of the materials used in this study are summarized in Table 1.

Table 1: Mechanical Properties of Materials Used in the Study

Material	Diameter/ Thickness	f'_c(MPa)	f_y(MPa)	f_u (MPa)	E_c (GPa)
Concrete	–	20	–	–	21.019
Steel Reinforcement	12 mm	–	420	620	200
CFRP Sheets	0.167mm	–	–	4900	235
Steel Plates	10 mm	–	248	400	200
Bolts	16 mm	–	400	517	200

2.3 Geometric Properties

Four beam-column junction (BCJ) samples were taken from the fourth floor of a five-story reinforced concrete structure for this investigation. Each beam spans 7.5 meters on both sides of the column. Sta4CAD V14 software has been used to model the building's structure and see how the joints were affected by the interior forces. Also, the Moment Distribution Method was used to do a sub-frame analysis to find the spots along the beams where they bend. These spots were very important for figuring out the areas of negative moment so that the joint behavior under real-world loading circumstances could be shown accurately. Even though the approach uses reduced modelling assumptions, it gives a good idea of how beams and columns interact with one another. The beams that were part of the analysis were 400 × 600 mm, and the columns were 500 × 500 mm in cross-section.

The study used four beam-column junction (BCJ) samples taken from a five-story structure. The chosen joints are on the fourth level, where the beam is 7.5m long on each side.

2.4 Beam Column Joint Samples

The study examines four different beam-column joint (BCJ) configurations:

1. BCJ-1 (Control Sample): Designed following ACI 352-02, representing a conventionally detailed joint without strengthening.
2. BCJ-2 (Designed to Fail at the Joint): Modified with increased moment capacity to induce failure at the joint, simulating a weak joint condition.
3. BCJ-3 (CFRP Strengthened): Same as BCJ-2, but strengthened using CFRP sheets to evaluate the effect of fiber reinforcement on joint performance.
4. BCJ-4 (Steel Plate and Bolt Strengthened): Same as BCJ-2, but strengthened with steel plates and bolts, assessing the role of steel confinement in improving joint behavior.

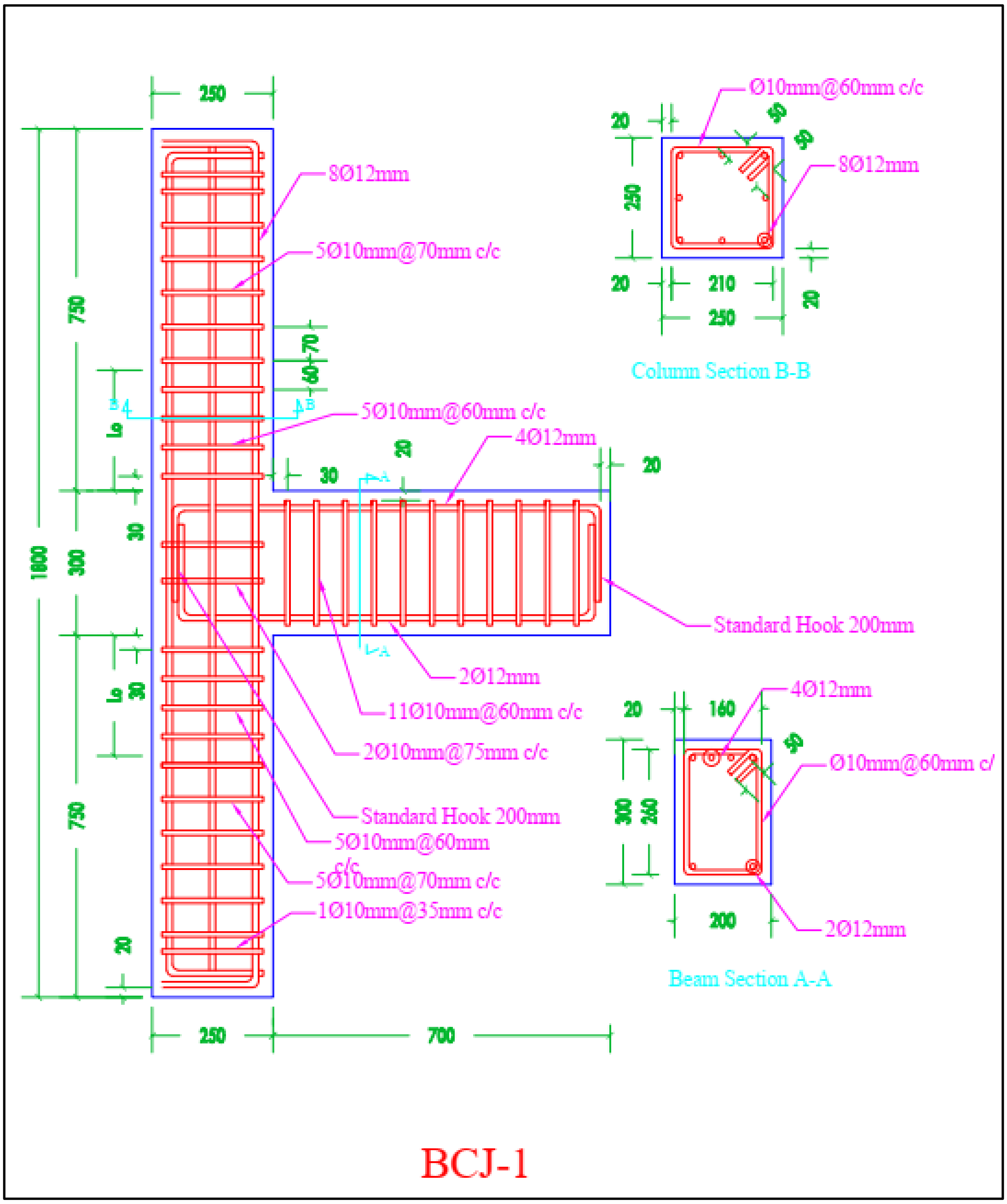

Figure 1: Reinforcement Detail of BCJ-1 Sample

2.5 Loading and Boundary Conditions

The beam-column joint specimens were subjected to a combination of vertical and lateral loading to simulate realistic in-service structural behavior. A concentrated load was applied at the free end of the beam to generate bending and shear forces within the joint region. Simultaneously, an axial load was imposed on the top of the column to replicate the effects of gravity loading from the upper stories. For boundary conditions, the column was assumed to be pinned at both the top and bottom ends, reflecting realistic support constraints typically found in structural systems. This loading arrangement enabled a comprehensive evaluation of the internal force distribution, shear transfer mechanisms, and the influence of strengthening interventions on the overall joint performance.

2.6 Calculation

- **BCJ-1 (Control Sample)**

Designed following ACI 352-02, representing a conventionally detailed joint without strengthening, and analyzed by the strut-and-tie model as below:

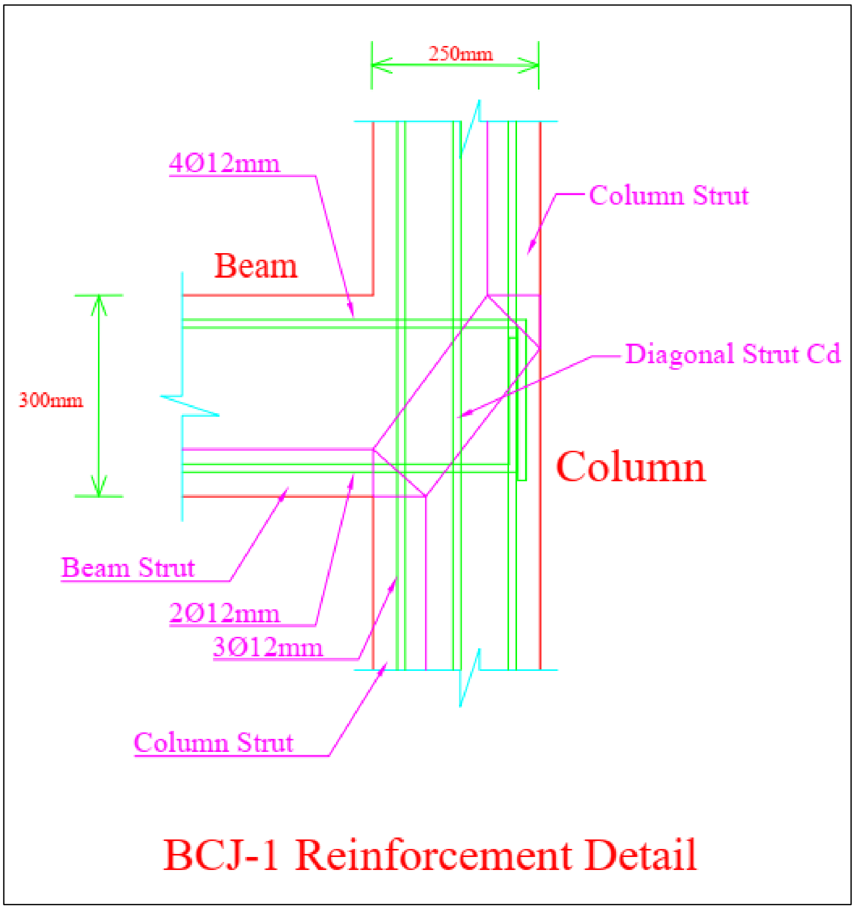

Figure 2: Reinforcement Detail of Beam-Column Joint-1

(1) $$d_c = h_c - cover - d_{b,tie} - d_{b,main}/2$$

(2) $$A_s = 4Ø12mm = 4x113 = 452mm^2$$

Upon assuming the beam tension reinforcement yields the tension force of the beam:

(3) $$T_b = 420x452 = 189.8kN$$

The compression of the beam:

(4) $$C_b = 0.85f_c'\beta_s w_{cb} b$$

Though the strut C_bHe prismatic strut is acting at node 2, the C-C-T node, and it is better to take the β_s equal to $\beta_n$of node 2, which is 0.8.

Then

(5) $$w_{cb} = \frac{189.8x10^3}{0.85x20x0.8x200} = 69.79mm$$

The beam lever arm

(6) $$Z_b = d_b - 0.5w_{cb} = 229mm$$

The nominal Moment of the beam

(7) $$M_{bn=}189.84x229 = 43.49\ kN.m$$

The nominal Moment of the Column

(8) $$M_{cn} = 0.50M_{bn=}21.74\ kN.m$$

The column reinforcement on either side is located at 36mm from the outer edge of the column; therefore, the width of either C_c or T_c can be taken 2x36=72mm.

Since the applied load on the column is N=100kN.

In most References, this equation is also used for calculating the compression of the column. C_c or a_c

(9) $$a_c = (0.25 + 0.85\frac{N}{A_g f_c'})h_c = 79.5mm$$

Giving lever arm

(10) $$Z_c = d_c - 0.5a_c = 174mm$$

The width of the:

(11) $$T_b = 2(h - d) = 72mm$$

As for the width of the strut w_{cb} or C_bIt has been calculated as before.

The geometrical relation illustrated for

(12) $$C_c = T_c = \frac{M_c}{Z_c} = 124.7kN$$

The angle of the strut at the joint

(13) $$\theta = \tan^{-1}\frac{Z_b}{Z_c} = 52.7°$$

The force in the diagonal strut is

(14) $$C_d = \frac{T_b}{\cos\theta} = 313kN$$

The effective concrete strength of the nodes and the struts.

Node-1: is a C-T-T Node thus

(15) $$f_{ce}^{n} = 0.85f_c'\beta_n = 0.85x20x0.6 = 10.2MPa$$

Node-2: is a C-C-T Node thus

(16) $$f_{ce}^{n} = 0.85 f_c' \beta_n = 0.85x20x0.8 = 13.6MPa$$

Struts $C_b$and $C_c$are prismatic struts; thus

(17) $$f_{ce}^{s} = 0.85 f_c' \beta_s = 0.85x20x1.0 = 17MPa$$

Struts $C_d It\ It\ It\ It$ a Bottle-shaped stress field, thus.

(18) $$f_{ce}^{s} = 0.85 f_c' \beta_s = 0.85x20x0.75 = 12.75MPa$$

If transverse reinforcement to resist lateral tension is provided, otherwise (i.e., transverse reinforcement not provided)

(19) $$f_{ce}^{s} = 0.85 f_c' \beta_s = 0.85x20x0.6 = 10.2MPa$$

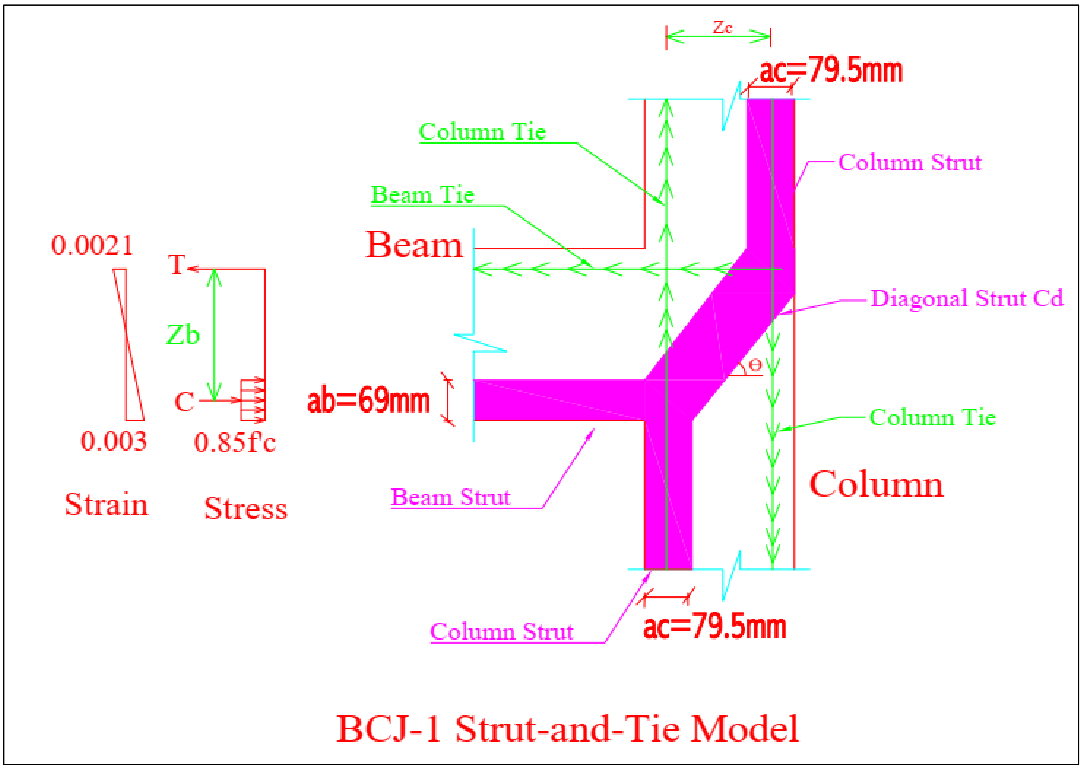

Figure 3: Strut-and-Tie Model of Beam-Column Joint-1

Node-1: is a C-T-T Node

The nominal Strength of the strut C_c is C_{cn}

(20) $$C_{cn} = 10.2x79.5x225 = 188.4kN$$
(21) $$C_{cn} = 188.4kN > C_c = 124.7kN \dots \dots \dots OK$$

The width of the strut C_dAt node 1:

(22) $$W_{cd}^{1} = 79.5 \sin\theta + 79.5 \cos\theta = 111.4mm$$

The nominal strength of the Strut C_d without ties at the joint

(23) $C_{dn} = 10.2x111.4x225 = 255.6kN$
(24) $C_{dn} = 255.6kN < C_d = 313kN \dots\dots\dots..Not\ \ OK$

The nominal strength of the Strut C_dWith ties at the joint

(25) $C_{dn} = 12.75x111.4x225 = 319.58kN$
(26) $C_{dn} = 319.58kN > C_d = 313kN \dots\dots\dots\ \ OK$

Node-2: is a C-C-T Node

The nominal Strength of the strut C_c is C_{cn}

(27) $C_{cn} = 13.6x79.5x225 = 243.2kN$
(28) $C_{cn} = 243.2kN > C_c = 124.7kN \dots\dots\dots..OK$

The nominal Strength of the strut C_b is C_{bn}

(29) $C_{bn} = 13.6x69.7x225 = 213.5kN$
(30) $C_{bn} = 213.5kN > C_b = 189.84kN \dots\dots\dots..OK$

The width of the strut C_dAt node 2:

(31) $W_{cd}^2 = 79.5 \sin\theta + 79.5 \cos\theta = 105.5mm$

The nominal strength of the Strut C_d without ties at the joint

(32) $C_{dn} = 10.2x105.5x225 = 242.1kN$
(33) $C_{dn} = 242.1kN < C_d = 313.5kN \dots\dots\dots..Not\ \ OK$

The nominal strength of the Strut C_dWith ties at the joint

(34) $C_{dn} = 12.75x105.5x225 = 303kN$
(35) $C_{dn} = 303kN < C_d = 313kN \dots\dots\dots\ \ it\ can\ be\ considered\ OK$

From the previous results, all were ok according to the design, which was done based on ACI 352-02, which means the joint did not fail under the applied load because it was designed according to ACI.

The remained samples have been designed to fail in joint and strengthened by CFRP and steel plates to increase it is capacity to resist the applied load.

The same procedure has been repeated for BCJ-3 and BCJ-4, with the contribution of CFRP sheets and steel plates incorporated into the strut-and-tie model through the modified strut forces. The total strut force was calculated using the STM equation $(T_r + T_f = C_b + C_s)\ and\ (T_r + T_{plate} = C_b + C_s + C_{plate})$. The results reflecting the strengthening effects are presented and discussed in the Results and Discussion section.

2.7 Validation Strategy

The accuracy of the proposed analytical method is validated by comparing its predictions with experimental data and recent research findings. The validation process is structured around key performance parameters to ensure the reliability and robustness of the methodology.

2.8 Failure Modes

The analytical model's predictions of failure modes, such as diagonal cracking, joint shear failure, and concrete crushing, were compared to the observed experimental results to assess its accuracy. It is vital to fully describe these failure modes [11] in order to effectively predict the behavior of CFRP-strengthened RC joints under applied loads.

2.9 Load core strength and resistance to shear are quite similar.

There is a close link between shear strength and load-carrying capacity. The predicted shear strengths of the joints were compared with experimental results to validate the analytical model. This validation is particularly important for assessing the safety and performance of RC joints reinforced with CFRP sheets or steel plates [2].

2.10 Energy dissipation and ductility improvement

The effectiveness of the model in depicting energy dissipation under cyclic loading was evaluated. The beam-column joints exhibited significantly increased flexibility and energy absorption when steel plates and angles were applied, providing clear evidence of improved seismic performance [10].

2.11 Impact of Adding More Strength

The suggested solution takes into consideration how CFRP confinement and steel plate stiffening work together to make the shear strength of a junction stronger. The trial results demonstrated that the hybrid strengthening strategy performed effectively in both peak stress scenarios and when the structure was carrying its full-service load [2].

2.12 How Accurate Is the Strut-and-Tie Model?

The Strut-and-Tie Model (STM) that was suggested correctly indicated how internal forces flowed in the experimental data. The model was good at predicting how joints would react, especially when the PHM reinforcing design was used. It could accomplish this for things like the breadth of the strut and the specifications of the reinforcement [10].

3. Results and Discussion Analysis

On the basis of moment capacity, strut shape, and diagonal force, four beam-column joint (BCJ) specimens were compared, paying attention to strengthening method influences. An unstrengthened control specimen, BCJ-1, was designed according to ACI 352 and had 53.19 kN·m moment capacity, an angle of 52.74°, and 313.58 kN of diagonal force in the strut. The configuration served as a baseline and exhibited negligible shear capacity. Without joint strengthening, BCJ-2 was designed to possess beam moment capacity increased by 50% (75.32 kN·m), which created a larger strut width and higher diagonal force (558.7 kN). Due to its poor shear capacity, it failed brittlely, which highlights the role of joint reinforcing.

BCJ-3, which was reinforced with CFRP sheets, had the most effect on how well the joints worked. The specimen had a diagonal force of 1299.8 kN, strut widths that were wider at the top (339 mm) and narrower at the bottom (210 mm), and a moment capacity of 90.38 kN·m. The CFRP worked well to improve confinement and force redistribution. BCJ-4, which had steel plates added to it, also became a lot stronger. The moment capacity was maximum at 107.57 kN·m with a diagonal force of 1000 kN. This was the highest of all the samples. Even though the diagonal force was smaller than BCJ-3, the steel plates successfully limited strut movement, which made the joints work better. Both CFRP and steel plate strengthening made BCJs much stronger overall. Steel plates had the best moment resistance, while CFRP had the best strut confinement and load redistribution.

Based on the STM analysis, the plastic hinge location varied among the specimens. For BCJ-1, the hinge formed in the beam region due to flexural yielding. In BCJ-2, failure was concentrated in the joint core, indicating shear-dominated behavior. For BCJ-3 and BCJ-4, the observed behavior reflected a combined mechanism, where both joint shear and beam flexure contributed to the formation of the hinge, influenced by the presence of CFRP and steel plate strengthening, respectively.

Table 2: Summary of Key Results for BCJ Samples

BCJ Sample	Top Strut Width (mm)	Bottom Strut Width (mm)	Strut Angle (°)	Diagonal Strut Force (kN)	Top Strut Strength (kN)	Bottom Strut Strength (kN)	Moment Capacity (kN·m)	Moment Capacity at Face of Column (kN·m)
BCJ-1	111.1	105.5	52.74	313.58	319.58	302.65	43	43
BCJ-2	112.34	153.17	47.2	558.7	257.82	351.52	75.32	75
BCJ-3	339	210	66	1299.8	778	481.95	75.32	90.38
BCJ-4	271	184.86	63	1000	621	424	75.32	107.57

Table 3: Comparison of Strut Force and Strength Increases (%)

Comparison	Diagonal Strut Force (kN)	% Increase	Top Strut Strength (kN)	% Increase	Bottom Strut Strength (kN)	% Increase
BCJ-2 vs BCJ-1	558.7 vs 313.58	+78.1%	257.82 vs 319.58	-19.3%	351.52 vs 302.65	+16.1%
BCJ-3 vs BCJ-1	1299.8 vs 313.58	+315%	778 vs 319.58	+143%	481.95 vs 302.65	+59.3%
BCJ-3 vs BCJ-2	1299.8 vs 558.7	+133%	778 vs 257.82	+201.6%	481.95 vs 351.52	+37.1%
BCJ-4 vs BCJ-1	1000 vs 313.58	+219%	621 vs 319.58	+94%	424 vs 302.65	+40.1%
BCJ-4 vs BCJ-2	1000 vs 558.7	+79%	621 vs 257.82	+140.8%	424 vs 351.52	+20.6%

4. Conclusion

The study found that both CFRP sheets and steel plate strengthening techniques greatly improve the structural performance of reinforced concrete beam-column junctions, although each has its own set of benefits. CFRP strengthening made the diagonal strut force go up the most, and it also made the confinement, stiffness, and force redistribution better. But using it requires careful thought about ductility, as the quick strain buildup might make it act brittle. Steel plate strengthening, on the other hand, gave the structure the largest flexural capacity and successfully stopped diagonal strut deformation, which made it stronger against shear and moment.

The results also show that raising the beam moment capacity without properly reinforcing the joints, as seen in BCJ-2, might cause brittle joint failures since the shear capacity is not enough. So, to make sure that joints behave safely and reliably, it is important to take a balanced approach when designing both moment and shear capabilities. The Strut-and-Tie Model's analytical approach did a good job of showing how alternative strengthening schemes improved performance and how loads were transferred. These findings are very helpful for improving retrofit procedures for RC joints, especially in buildings that are exposed to seismic or steady lateral stresses.

Author's Contribution

Conceptualization, Methodology, and Modeling were led by Hussein Safeen Al-Bustany, and supervision was provided by Salahuddin Abdulrahman Ahmed.

Conflict of Interest

There is no conflict of interest for this paper.

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