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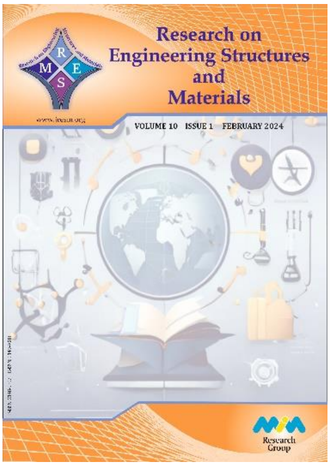

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Research Article

Comparative analysis of seismic resilience: conventional vs. rectangular spiral reinforcement in joints

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Abstract

Beam-column joints are recognized as critical weak points in reinforced concrete (RC) frames, particularly in seismic zones. This study evaluates the seismic performance of conventional stirrup reinforcement versus an innovative continuous rectangular spiral reinforcement under cyclic loading conditions. Four full-scale specimens were tested, including a control specimen with conventional stirrups designed per IS 456:2000 and three specimens with varying rectangular spiral reinforcement configurations. Fe-500 grade steel was employed for longitudinal reinforcement, and Fe-250 grade mild steel for transverse reinforcement. Key metrics, such as load-carrying capacity, energy dissipation, and ductility, were analyzed to assess performance. The results reveal a substantial improvement in the seismic behavior of specimens with rectangular spiral reinforcement. BCJ-3 demonstrated a peak load of 45 N, 50% higher than the control specimen (30kN), while BCJ-4 showed a 25% improvement. Energy dissipation per cycle for BCJ-3 reached 450kN-mm, 80% more than BCJ-1 (250kN-mm). Cumulative energy dissipation for BCJ-3 peaked at 2200kN-mm, surpassing BCJ-1 by 57% and BCJ-4 by 35%. Additionally, the rectangular spiral specimens exhibited enhanced crack control, distributing and managing cracks more effectively under cyclic loading, thereby improving structural durability and resilience. These findings underline the potential of rectangular spiral reinforcement to significantly enhance seismic safety and stability in RC structures. By offering superior energy dissipation, higher load-carrying capacity, and better crack management, this reinforcement approach provides a robust alternative to conventional stirrups. The study provides valuable insights for updating design codes and promoting advanced reinforcement strategies to improve the durability and seismic performance of RC structures in earthquake-prone regions.

1. Introduction

Beam-column joints are critical for the stability and safety of reinforced concrete frames, especially in seismic zones [1]. These intersections, subjected to complex forces during seismic events, directly influence the structural integrity [1–3]. Effective reinforcement is crucial to withstand seismic forces without catastrophic failure. While traditional methods, like vertical closed stirrups, provide basic reinforcement, they often lack the ductility and energy dissipation needed to manage seismic loads effectively [2]. Beam-column joints are classified into rigid, semi-rigid, and pinned types based on reinforcement configurations and loading conditions [3–5]. These classifications guide the development of advanced techniques by highlighting strengths and limitations in traditional approaches. However, challenges persist in designing joints with adequate energy dissipation [6,7] and crack control [8,9] under cyclic loading [10–13]. Conventional methods frequently result in

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insufficient performance, necessitating innovative solutions [14,15]. This study evaluates the performance of continuous rectangular spiral stirrups versus conventional methods, focusing on load-carrying capacity, energy dissipation, and ductility under cyclic loading. Insights gained could inform updates to seismic design codes, enhancing the resilience of reinforced concrete structures in earthquake-prone areas.

Beam-column joints transfer loads between beams and columns, enduring significant shear and moment demands during seismic events. Inadequate performance can result in structural failures, emphasizing the need for effective reinforcement [16,17]. While traditional methods like closed stirrups are widely used, they often fail to provide the uniformity and crack control needed under cyclic stress conditions [18–20]. Continuous rectangular spiral reinforcement has emerged as a promising alternative, offering enhanced strength, ductility, and energy dissipation. Studies indicate its effectiveness in improving seismic performance, making it a viable option for advancing design practices and structural resilience [21–25]. Despite advancements, conventional reinforcement methods often lack the ductility and energy dissipation required to ensure the safety of beam-column joints during seismic events. This study evaluates rectangular spiral stirrups as an alternative, examining their effectiveness in addressing these vulnerabilities.

This research aims to compare the seismic performance of beam-column joints reinforced with conventional stirrups and rectangular spiral stirrups. Key metrics include load-carrying capacity, energy dissipation, ductility, and crack development under cyclic loading. Insights will contribute to revising seismic design codes and enhancing reinforcement practices. By investigating the comparative performance of rectangular spiral reinforcement, this study addresses critical challenges in improving ductility and energy dissipation of beam-column joints. Findings could inform updates to seismic design codes, leading to safer and more resilient structures in seismic regions. Additionally, these insights may drive sustainable construction practices by reducing repair costs and enhancing structural longevity.

2. Literature Review

2.1. Classification of Beam-Column Connections in Reinforced Concrete Structures

Reinforced concrete moment-resisting frame structures typically feature three main categories of beam-column joints, as illustrated in Figure 1(a) and (b).

(a) Critical Beam-Column Joint Locations in Reinforced Framed Structures - Figure 1 (a) illustrates the various locations where beam-column joints are crucial in a reinforced concrete frame structure. It highlights typical areas within the structural framework where these joints are essential for maintaining structural integrity, including key positions where the joints are subjected to significant stresses.

(b) Classification of Beam-Column Joints According to ACI 352R-02 - Figure 1 (b) a classification of beam-column joints based on their locations and characteristics. It categorizes joints into:

- Interior Joints: Located within the interior of the structure, where beams connect to columns, typically subjected to complex loading conditions due to the convergence of multiple structural elements.
- Exterior Joints: Positioned at the outer edges of the structure, these joints are exposed to different environmental conditions and loading patterns compared to interior joints.

- Corner Joints: Found at the intersections of two or more structural elements at a corner of the frame, these joints often experience a combination of stresses from both adjacent beams and columns

Beam Beam-column joints in reinforced concrete structures can be categorized based on their location. According to ACI 352R-02[26], these joints are further classified into two types based on loading conditions:

- Type-1 Joints**-** Designed to meet ACI 318-02[27] strength requirements without specific ductility considerations. These joints are primarily intended to support gravity loads and typical wind forces.
- Type-2 Joints**-** Engineered to sustain consistent strength under reversals of structural deformation into the inelastic range. These joints are specifically designed to resist lateral loads due to earthquakes, explosions, and severe windstorms.

2.2. Common Challenges in Designing Beam-Column Joints

Designing beam-column joints in reinforced concrete structures presents several challenges. These joints play a crucial role in transferring forces between beams and columns, and their proper design is essential for structural safety and performance. Following are some common challenges faced during the design of beam-column joints:

2.2.1 Shear Strength and Ductility Modelling Procedure

Achieving an optimal balance between shear strength and ductility is challenging. Joints must be strong enough to resist shear forces but also ductile enough to absorb energy during seismic events. Ensuring that the joint remains stable under both service loads and extreme events (such as earthquakes) is critical.

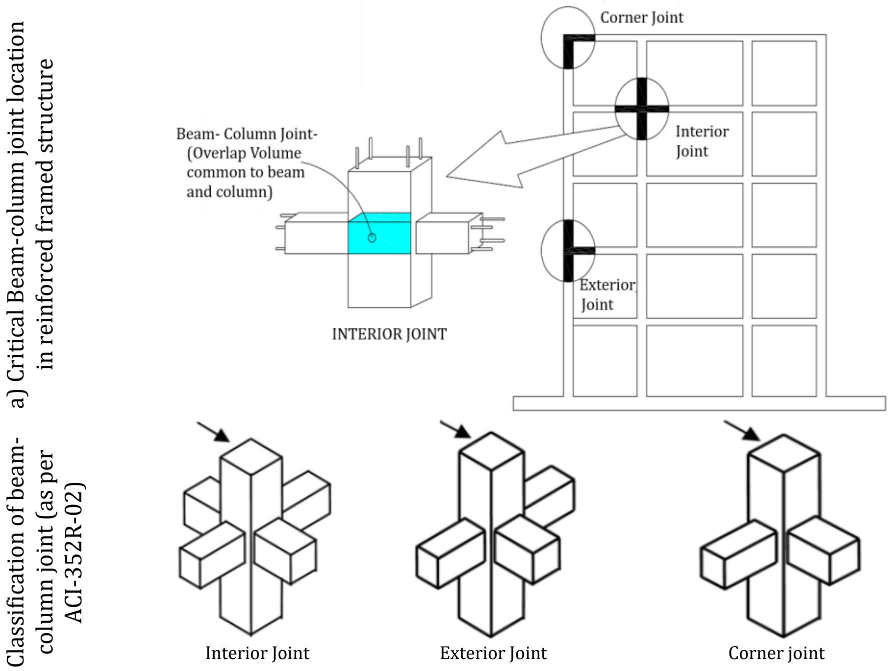


Fig. 1. (a) Critical Beam-column joint location in reinforced framed structure (b) classification of beam-column joint [23]

2.2.2 Reinforcement Congestion

Properly detailing reinforcement in the joint area can be difficult due to limited space. Reinforcement congestion can lead to poor concrete placement, inadequate consolidation, and compromised earthquake resistance. Designers must find a balance between providing sufficient reinforcement and avoiding congestion.

2.2.3 Anchorage Length and Development Length

Ensuring proper anchorage and development length of reinforcement bars in the joint area is essential. Inadequate anchorage length can lead to premature bar pull-out or bond failure. Designers must consider the effects of bar diameter, concrete cover, and bar spacing on anchorage and development length.

2.2.4 Concrete Placement and Consolidation

Properly placing and consolidating concrete in the joint area is challenging. Honeycombing, voids, and poor consolidation can weaken the joint. Special attention is needed during construction to ensure high-quality concrete placement.

2.2.5 Load Transfer Mechanism

Achieving the desired load transfer mechanism such as weak beam-strong column behavior is crucial. Designers must ensure that plastic hinges form away from the joint, preventing premature joint failure.

2.2.6 Seismic Consideration

Beam-column joints are particularly vulnerable during seismic events. Ensuring that joints remain ductile and can absorb energy is essential for overall structural performance.

2.2.7 Construction Quality Control

Challenges related to construction quality control can affect joint performance. Proper inspection, testing, and supervision during construction are necessary to avoid defects.

2.3. Seismic Performance of Reinforced Concrete Structures

Reinforced concrete structures are designed to withstand various loads, but their seismic performance is critical in earthquake-prone regions. During seismic events, these structures must endure dynamic forces that can induce significant lateral displacements and moments. Effective seismic design aims to enhance the structure's ability to absorb and dissipate seismic energy, thereby reducing the risk of damage or collapse [28]. Key aspects of seismic performance include ductility, which allows structures to deform without losing their load-carrying capacity, and energy dissipation, which helps in mitigating the effects of seismic forces. Evaluating and improving these characteristics are essential for ensuring the resilience of reinforced concrete structures under earthquake loading.

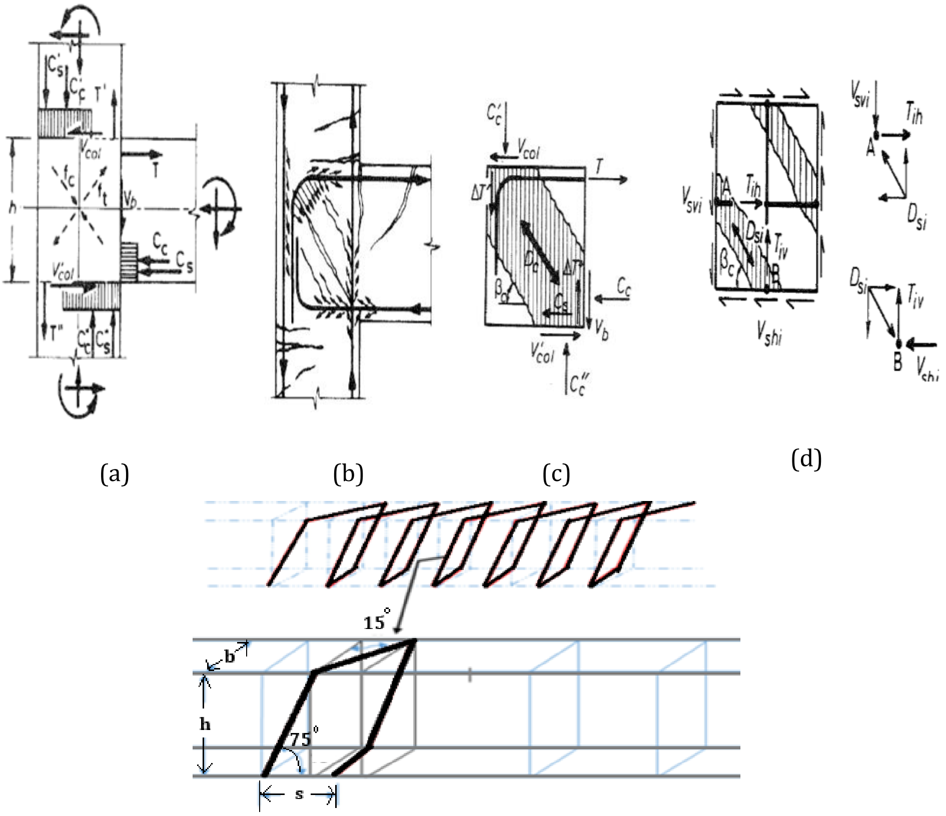
2.3.1 Forces Acting on Beam-Column Joints- Mechanism of Forces and Crack Developed in The Joint Core

The beam-column joint core is subjected to complex forces during seismic events, leading to the development of stresses and potential cracks. The mechanism of forces and crack development in the joint core involves the interaction between shear forces, flexural forces, and bond stresses. Internal forces are generated at the beam-column joint core of an exterior type when a plastic hinge develops in the beam due to earthquake loads, as depicted in Figure 2 (a) to (d). In Figure 2 (a), the tensile forces T, T’, T”, along with the compressive forces Cs, Cs’, Cs”, are introduced by the beam and column reinforcement into the concrete of the joint core. These forces interact within the joint, influencing its behavior under load. Figure 2 (b) illustrates how cracks typically develop at the intersection of the beam and column, propagating through the joint as the internal stresses exceed the tensile strength of the concrete. In Figure 2 (c), the concrete within the joint acts as a compression strut, resisting the internal forces and helping to maintain the stability of the joint. Finally, Figure 2 (d) shows the strut mechanism, where the diagonal struts within the joint core effectively transfer the loads, ensuring the joint remains stable even under high stress. Proper design and reinforcement are critical to prevent excessive cracking and to ensure the structural integrity of the joint under seismic conditions.

2.4. Reinforcement Techniques for Beam-Column Joints: Traditional and Innovative Approaches

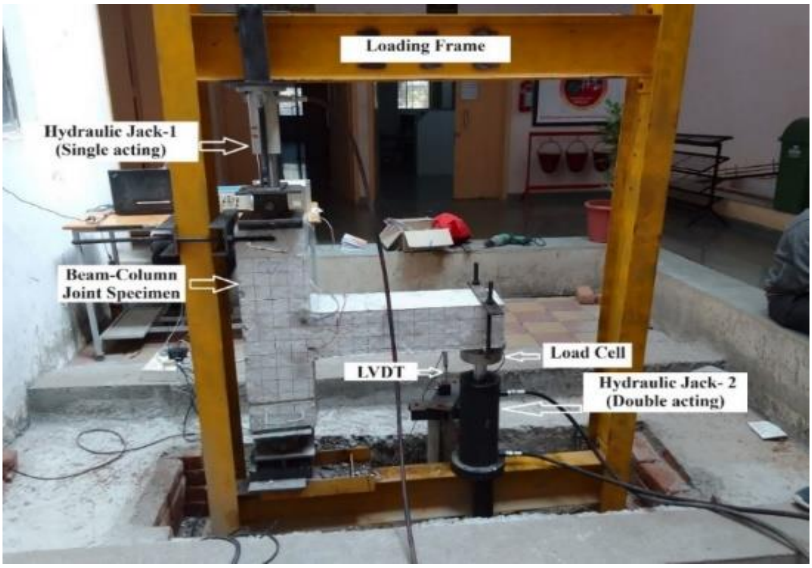
Beam-column joints are critical components of reinforced concrete frames, facilitating the transfer of forces between beams and columns. Conventional reinforcement techniques, such as vertical closed stirrups and standard shear reinforcement, are commonly employed to enhance the joint's capacity to resist axial and lateral loads. Vertical closed stirrups help confine concrete and resist shear forces, while conventional shear reinforcement provides additional strength. However, these methods often fall short in offering sufficient ductility and energy dissipation, which are vital for seismic resilience.

The limitations of traditional reinforcement, particularly regarding crack control and cyclic loading resistance, highlight the need for innovative solutions to improve the seismic performance of beam-column joints.



(a) (b) (c) (d)

(e)



(f)

Fig. 2. (a) Forces acting in the beam-column joint core (b) crack development in the joint core (c) concrete strut mechanism (d) strut mechanism [9](e) continuous rectangular spiral reinforcement (f) experimental setup for beam-column joint load testing

To address these challenges, rectangular spiral reinforcement has emerged as a promising alternative. As illustrated in Figure 2 (e), this approach uses continuous spirals arranged in a rectangular configuration, providing enhanced confinement of concrete. This innovative technique not only improves the overall strength and ductility of beam-column joints but also offers superior crack control and greater energy dissipation capacity compared to traditional methods. Studies have demonstrated that rectangular spiral reinforcement contributes to more uniform confinement and better resistance under cyclic loading, making it a viable option for improving seismic resilience in reinforced concrete structures.

2.5. Comparative Studies and Research Gaps

Comparative analyses of traditional and innovative reinforcement techniques are essential for evaluating their relative effectiveness in seismic applications. These studies typically assess critical performance metrics such as load-carrying capacity, energy dissipation, and ductility under simulated seismic loading. By juxtaposing conventional methods with advanced approaches like rectangular spiral reinforcement, researchers have gained valuable insights into their respective benefits and limitations. For instance, the uniform confinement provided by rectangular spirals, as evident in Figure 2 (e), has shown significant advantages over standard shear reinforcement in terms of crack control and energy absorption during seismic events.

Despite these advancements, several research gaps remain. Limited data exist on the long-term durability and performance of rectangular spiral reinforcement under realistic seismic conditions. Additionally, more studies are needed to evaluate the effectiveness of these techniques across diverse structural configurations and load scenarios. Addressing these gaps is crucial for refining the design and implementation of innovative reinforcement strategies.

2.6. Towards Improved Seismic Resilience

This study hypothesizes that rectangular spiral reinforcement will outperform conventional methods in key performance areas, including ductility, energy dissipation, and overall seismic resilience. As highlighted in Figure 2 (e), the innovative design of rectangular spirals offers significant potential to overcome the shortcomings of traditional reinforcement techniques. By bridging the identified research gaps and conducting comprehensive evaluations, the findings of this study aim to inform design codes and standards, ultimately enhancing the seismic resilience of reinforced concrete structures.

3. Experimental Program

3.1. Selection of Material

The materials in Table 1 used in this study were selected to meet the relevant Indian standards, ensuring the quality and consistency of the experimental outcomes. The concrete mix was designed with specific proportions: Cement was used at a quantity of 435.45 kg/m^3 to achieve a target compressive strength of 43 N/mm^2. The cement adhered to IS 269:2015 [29] (OPC-Ordinary Portland Cement) with a fineness of 8%, well within the standard limit of 10% residue on a 90 µm sieve. Its specific gravity was recorded at 3.15, and it demonstrated a consistency of 31%, indicating suitable workability. The chemical composition included 60-67% CaO, 17-25% SiO_2, 3-8% Al_2O_3, 0.1-6% Fe_2O_3, and 1-3% SO_3, with a loss on ignition below 5% as per IS 4031 guidelines. Fine aggregate used in the mix was Tapi river sand, which exhibited a specific gravity of 2.68 and a fineness modulus of 3.2. According to IS 383:2016[30], the fine aggregate was chemically inert, primarily composed of silica (SiO_2) with minor amounts of other minerals such as feldspar and mica. It had a bulk density of 1675 kg/m^3 and a silt content of 1%, which is below the 3% limit specified by IS 2386[31]. Coarse aggregate, downgraded to 20 mm, was selected for its suitability in concrete mixes, showing a specific gravity of 2.71 and a bulk density of 1650 kg/m^3. The coarse aggregate was composed of silica, alumina, iron oxide, and other minor oxides, and had a water absorption rate of 0.5%, which is below the maximum limit of 2% . The impact value was measured at 15%, well within the acceptable range of less than 30%. The water used in the mix had a pH of 6 and total dissolved solids (TDS) of 1268 mg/l, which is below the 2000 mg/l threshold. The water was free from organic matter, acids, and oils, and had a hardness less than 500 ppm and a chloride content below 500 mg/l, in accordance with IS 456:2000[32] and IS 3025[33] specifications. These properties ensured that the water did not adversely affect the quality of the concrete.

3.2. Specimen and Detailing

The experimental program for this study included four one-third scale exterior beam-column joint specimens designed to investigate the performance of various reinforcement techniques under seismic loading. These specimens were designed in accordance with IS 456:2000 (Plain and Reinforced Concrete) and detailed following the guidelines of IS 13920:1993 [36]. The concrete mix used was M25 grade, ensuring uniformity across all specimens. Specimen 1 served as the control and featured conventional reinforcement with vertical closed stirrups. Specimen 2 incorporated continuous rectangular spiral reinforcement in the beam, while conventional links were used in the column. Specimens 3 and 4 were similar to Specimen 2 in terms of reinforcement configuration but included different anchorage mechanisms in the joints facing the beam and column. All columns had a cross-sectional dimension of 170 mm × 220 mm and a height of 800 mm. The transverse beams were 170 mm × 170 mm in cross-section and 600 mm in span. After casting, the specimens were cured for 28 days using gunny bags to maintain adequate moisture, as shown in Figure 3. Testing was conducted using a controlled 100 kN hydraulic jack positioned vertically to apply axial force to the column, while Linear Variable Differential

Transducers (LVDTs) measured deflections at the beam's free end, located 600 mm from the beam-column intersection, as illustrated Figure 3. Figure 3 provides detailed cross-sectional dimensions and reinforcement configurations for both the control specimen and those with rectangular spiral reinforcement. All specimens employed high-strength Fe-500 steel bars for longitudinal reinforcement and plain mild steel (Fe-250 grade) for transverse reinforcement. For Specimen 1, the beam's tension reinforcement consisted of two 10 mm diameter bars, providing an area of 157 mm^2, exceeding the minimum required area of 69 mm^2. The beam's shear reinforcement consisted of two-legged vertical stirrups with an area of 56.52 mm^2, spaced at 100 mm centers, conforming to IS Code 456:2000. Column reinforcement included five 12 mm diameter bars, with a longitudinal area of 452 mm^2, surpassing the minimum requirement of 270 mm^2. Lateral ties in the column were spaced at 100 mm centers using 6 mm diameter bars.

Table 1. Material properties

Material	Physical Properties	Chemical Properties	IS Code Limitations
Cement	- Fineness: 8 %< 10% residue on 90 μm sieve	- Composition: 60-67% CaO, 17-25% SiO_2, 3-8% Al_2O_3, 0.1-6% Fe_2O_3, 1-3% SO_3	IS 269:2015 (Ordinary Portland Cement)
	- Specific Gravity: 3.15	- Loss on Ignition: < 5%	IS 4031: Methods of physical tests for hydraulic cement [34]
	- Consistency: 31 %		
	- Soundness: 8 mm < 10 mm		
Fine Aggregate	- Specific Gravity: 2.68	- Chemically inert, typically composed of silica (SiO_2) with small quantities of other minerals like feldspar and mica	IS 383:2016 (Coarse and Fine Aggregates for Concrete)
	- Fineness Modulus: 3.2		IS 2386: Methods of test for aggregates
	- Bulk Density: 1675 kg/m^3		
	- Silt Content: 1% < 3%		
Coarse Aggregate	- Specific Gravity: 2.71	- Consists of silica, alumina, iron oxide, and small amounts of other oxides	IS 383:2016
	- Bulk Density: 1650 kg/m^3	- Reactivity: Should be non-reactive with alkalis in cement	IS 2386: Methods of test for aggregates
	- Water Absorption: 0.5 % < 2%		
	- Impact Value: 15% < 30%		
Water	- pH: 6	- Should be free from organic matter, acids, oils, and other impurities	IS 456:2000 (Plain and Reinforced Concrete)
	- TDS: 1268 mg/l < 2000 mg/l	- Chloride content: < 500 mg/l	IS 3025: Methods of sampling and test (physical and chemical) for water and wastewater[35]
	- Hardness: < 500 ppm	- Sulphate content: < 400 mg/l	
	- Color: Clear, no visible impurities		

Specimens 2 to 4 utilized rectangular spiral reinforcement with an inclination angle of 75° for both beam and column reinforcement. The specifics of the spiral reinforcement configurations for these specimens are detailed in Table 1, showing variations in reinforcement patterns and anchorage methods to assess their impact on the seismic performance of the beam-column joints.

3.3. Experimental Program

Figure 2 (f) illustrates a reinforced concrete beam-column joint specimen undergoing a load test within a laboratory environment. The setup comprises the following components:

Loading Frame: A sturdy and rigid structure designed to apply controlled loads to the specimen. It supports the specimen and ensures that the applied forces are accurately transferred to the joint.

Hydraulic Jacks: These devices are employed to apply both vertical and horizontal loads to the specimen. Positioned on either side, the hydraulic jacks deliver precise and adjustable force.

Load Cell: A high-precision instrument installed in the load path to measure the force exerted on the specimen. It provides real-time data on the applied load, allowing for accurate assessment of the joint's performance.

Model Setting: The model was developed using finite element software tailored to simulate reinforced concrete behaviour under cyclic loading. Indian standards (IS 456:2000 and IS 13920:2016) were adhered to for material properties and loading configurations. The beam-column joint dimensions and reinforcement detailing reflect typical construction practices in India.

Boundary Conditions: Fixed supports were applied at the column ends to replicate in-situ conditions, while lateral and axial loads were applied at the beam ends to mimic seismic loading as per IS 1893:2016. The joints were restrained to prevent out-of-plane movements.

Parameters Used: Material properties such as M30-grade concrete and Fe-500 steel for longitudinal reinforcement were used, along with Fe-250 steel for transverse reinforcement. Loading protocols included incremental cyclic loading based on the displacement-controlled approach outlined in relevant Indian guidelines.

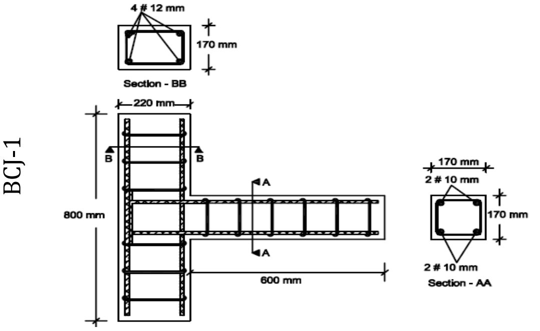
Linear Variable Differential Transformer (LVDT): An instrument used to measure the displacement and deformation of the specimen during testing. The LVDT is strategically placed to capture vertical and horizontal movements, supplying critical data on the deformation of the beam-column joint under load. The specimen is carefully positioned within the loading frame. This testing setup is designed to replicate real-world loading conditions, including gravity and lateral forces, to evaluate the joint's structural behaviour, such as load-carrying capacity, ductility, and energy dissipation. This experimental arrangement enables researchers to evaluate the effectiveness of different reinforcement strategies and configurations under controlled conditions, providing valuable insights into the behaviour of beam-column joints in practical applications. The Figure 3 provides a comparative analysis of different reinforcement types in concrete beams. It showcases four different beam configurations (BCJ1-BCJ4) with varying reinforcement patterns. The left side of the Figure 3 displays schematic drawings of the beam cross-sections and reinforcement details, specifying dimensions and types of steel used. The right side illustrates the actual physical construction of these beams, demonstrating the real-world implementation of the design. At the bottom of the image, a close-up of a rectangular spiral reinforcement is labelled "Rectangular Spiral Reinforcement," indicating the study's focus on evaluating the performance of different reinforcement types, particularly comparing rectangular spiral reinforcement to other configurations shown in the beams. The image visually represents a scientific investigation aimed at comparing the effectiveness of various reinforcement methods in concrete beams. It underscores the importance of these design considerations in ensuring the structural integrity and performance of concrete structures.

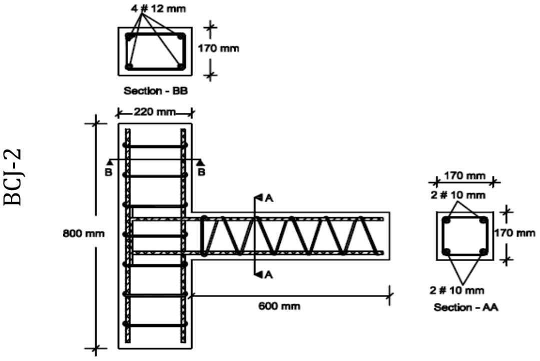
The beam-column joint specimens were subjected to double-acting cyclic loading (push and pull) to simulate seismic conditions. The testing involved a displacement-controlled protocol with increasing drift levels. The loading frequency was maintained at 0.1 Hz to replicate typical seismic excitation rates, and the displacement amplitude was incrementally increased until failure. This approach ensured a comprehensive evaluation of the specimens' behavior under realistic cyclic loading conditions, including load-carrying capacity, energy dissipation, and crack propagation patterns.

3.4. Fabrication of Specimens

Reinforcement Detailing: This section focuses on the meticulous process of reinforcement detailing, which is crucial for ensuring the structural integrity and performance of the concrete beam-column joints. The reinforcement detailing involves specifying the type, size, and placement of steel bars within the concrete matrix to achieve the desired strength and ductility. Detailed drawings are prepared to guide the construction process, showing the exact positioning of longitudinal and transverse reinforcement, including stirrups and ties.

Special attention is given to the anchorage length, spacing of bars, and the configuration of any additional reinforcement, such as rectangular spirals, to enhance the joint's capacity to resist seismic forces. Proper reinforcement detailing ensures that the concrete structure can effectively withstand various loads and stresses, contributing to its overall durability and safety.





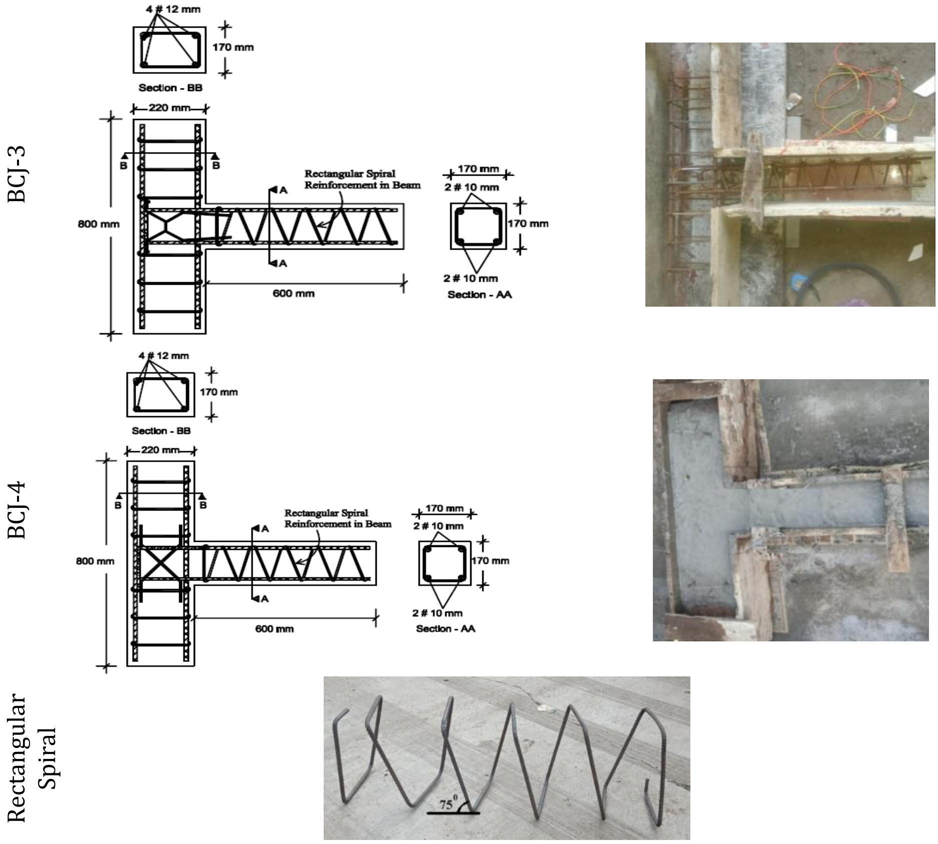


Fig. 3. Beam-column joint reinforcement details - rectangular spiral

Casting and Curing Process: This section describes the procedures for casting and curing the concrete beam-column joints, which are critical to achieving the desired material properties and structural performance. The casting process involves carefully placing the concrete mix into the formwork, ensuring uniform distribution and proper compaction to eliminate voids and achieve a dense, homogeneous structure. Once the concrete is cast, it undergoes a curing process, which is essential for the development of strength and durability. The curing process involves maintaining adequate moisture, temperature, and time conditions to allow the concrete to hydrate properly. Techniques such as water curing, using wet burlap, or applying curing compounds are employed to prevent moisture loss and promote optimal curing. Proper casting and curing practices are fundamental to the structural integrity and longevity of the reinforced concrete joints, ensuring they meet the design specifications and perform effectively under load conditions.

3.5. Testing Procedure

Test Setup and Loading Protocols: This section outlines the experimental setup and loading protocols used to evaluate the performance of reinforced concrete beam-column joints under simulated conditions. The test setup typically involves mounting the specimen within a rigid loading frame, designed to apply controlled loads that replicate the stresses experienced in real-world structural scenarios. The loading protocols are carefully defined to simulate various conditions, such as gravity loads, lateral forces, and cyclic loading, which are critical in assessing the joint's behavior under different stress regimes. The loading sequence, including the magnitude, direction, and rate of load application, is systematically planned to observe the specimen's response at different stages, from initial loading through to failure. This process ensures that the test accurately reflects the performance of the joint under realistic conditions, providing valuable insights into its load-carrying capacity, ductility, and overall structural behavior.

Instrumentation and Data Collection: This section describes the instrumentation and data collection methods used to monitor and record the response of the beam-column joint during testing. High-precision instruments, such as load cells, Linear Variable Differential Transformers (LVDTs), are strategically placed on the specimen to measure key parameters, including applied loads, displacements, and deformations. The data collected by these instruments is crucial for analyzing the performance of the joint, particularly in terms of its strength, stiffness, and energy dissipation capabilities. The instrumentation setup ensures that all relevant data is captured with high accuracy throughout the loading process, allowing for detailed analysis of the joint's behavior under different loading conditions. The data is typically recorded and processed using specialized software, enabling researchers to evaluate the effectiveness of various reinforcement strategies and compare the experimental results with theoretical predictions and design standards.

4. Results and Discussions

4.1. Experimental Results

4.1.1 Load- Deflection Behavior of All Specimen

The load-deflection curves are critical for understanding the performance of beam-column joints under cyclic loading, as they depict the relationship between the applied force and the resulting displacement. Throughout the experimental process, detailed observations were made regarding the displacement at the beam's unsupported end and the development of cracks. Two essential load values were recorded and tabulated: the load at which the initial crack appeared and the maximum load sustained by each specimen. These data points, presented in Table 2, provide insights into the structural behavior of the joints under stress.

Table 2. Experimental outcomes

Specimens	Cycle			Crack Load (KN)	Displacement (mm)	Peak Load (KN)	Maximum Displacement (mm)
BCJ-1	8 mm	Push	+	+2.851	+6.90	+11.80	+28.09
	8 mm	Pull	-	-2.804	-7.19	-18.90	-28.05
BCJ-2	4 mm	Push	+	+7.288	+4.35	+17.49	+28.08
	4 mm	Pull	-	-8.662	-3.97	-19.12	-28.03
BCJ-3	12 mm	Push	+	+3.668	+12.56	+17.33	40.00
	12 mm	Pull	-	-5.091	-6.93	-17.70	-40.20
BCJ-4	12 mm	Push	+	+4.071	+13.39	+9.486	+28.11
	12 mm	Pull	-	-5.30	-7.31	-8.05	-24.20

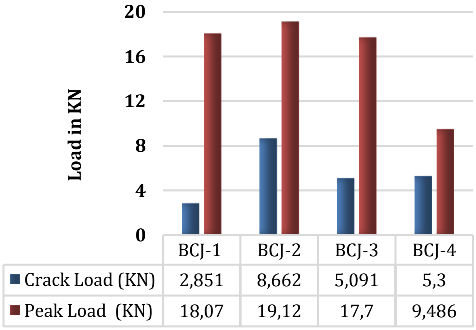
4.1.2 Initial Crack and Ultimate Load

Fig. 4 provides a comprehensive overview of the load-carrying capacity and load-deflection behavior for various cases. Figure 4 (a) compares the load-carrying capacities, showing how much load, different structures can support before failing. Figure 4 (b) to 4(e) illustrate the load-deflection behavior for different joints (BCJ1, BCJ2, BCJ3, and BCJ4), highlighting how each joint responds to applied loads and the corresponding deflection that occurs. Figure 4 (f) summarizes the overall load-deflection behavior, providing a general view of how all the cases perform under loading conditions. This collection of graphs is crucial for analyzing the structural performance and understanding the strength and flexibility of different joints the initial cracking load was identified from the load-deflection envelope curve at the point where the plot deviated from linearity. As shown in Table 2, specimens BCJ-1, BCJ-3, and BCJ-4 exhibited similar first crack loads, while BCJ-2 demonstrated the highest load capacity at the point of initial cracking. The load-carrying capacities were as follows:

- BCJ-1: Crack load of 2.804 kN and peak load of 18.9 kN.
- BCJ-2: Crack load of 8.662 kN. and peak load of 19.12 kN., indicating the highest performance among the specimens.
- BCJ-3: Crack load of 5.091 kN and peak load of 17.70 kN.
- BCJ-4: Crack load of 5.3 kN and peak load of 9.486 kN.

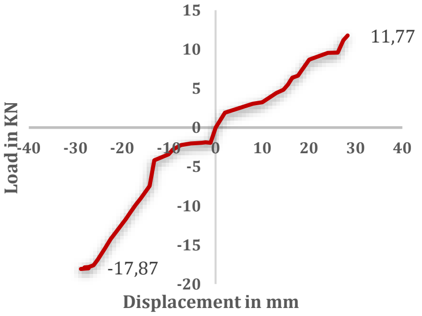
Load-Deflection Behavior - The load-deflection behavior of each specimen provides further insights into their performance under cyclic loading:

- BCJ-1: Exhibited a moderate load-deflection response, with deflections ranging from -30 mm to 40 mm. The load increased steadily up to approximately 15 kN before gradually declining.
- BCJ-2: Displayed a similar load-deflection behavior with a more pronounced load increase, peaking at around 18 kN, with deflections ranging from -30 mm to 40 mm.
- BCJ-3: Presented a distinctive load-deflection profile, with a larger deflection range from -45 mm to 50 mm and a load capacity that peaked at 20 kN before stabilizing. This indicates BCJ-3's ability to tolerate higher deflections.
- BCJ-4: Demonstrated early stiffness degradation, with a peak load capacity around 10 kN, followed by a rapid decline. The deflection range was from -20 mm to 40 mm, indicating lower stiffness and potentially different failure modes.

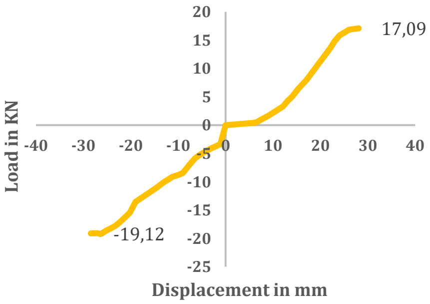


	BCJ-1	BCJ-2	BCJ-3	BCJ-4
■ Crack Load (KN)	2,851	8,662	5,091	5,3
■ Peak Load (KN)	18,07	19,12	17,7	9,486

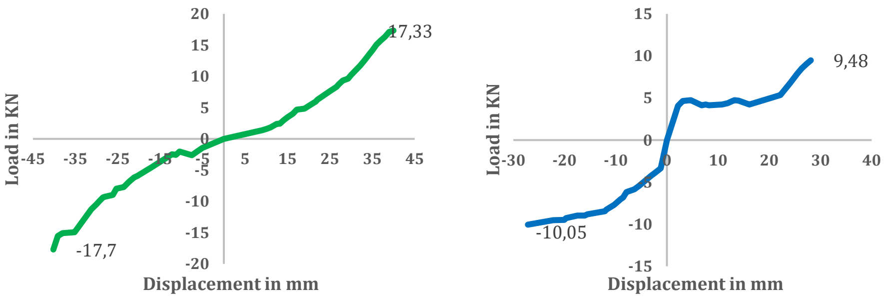
(a) Load carrying Capacity



(b) Load Deflection – BCJ-1

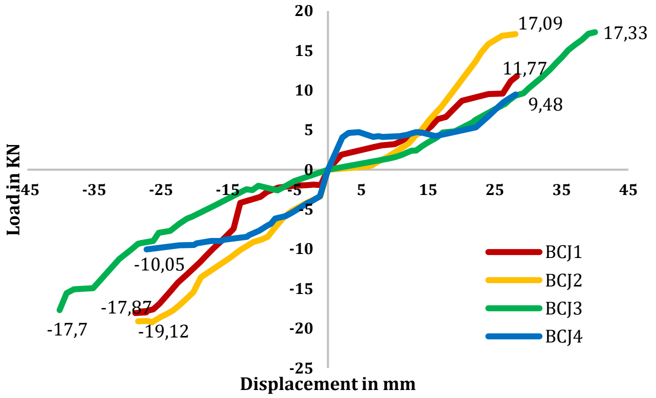


(c) Load Deflection – BCJ-2



(d) Load Deflection – BCJ-3

(e) Load Deflection – BCJ-4



(f) Load Deflection Behavior

Fig. 4. (a) Load carrying capacity of the joints (b) load-deflection - bcj1 (c) load-deflection – bcj2 (d) load-deflection – bcj3 (e) load-deflection – bcj4 (f) load- deflection behavior of joints

4.1.3 Comparative Load-Deflection Behavior

A comparative analysis of the load-deflection behavior reveals that BCJ-3 offers the highest deflection tolerance, though BCJ-2 and BCJ-1 maintain higher load capacities. BCJ-4, despite its lower load capacity, exhibited significant deflection, suggesting reduced stiffness and a different structural response. Among the specimens, BCJ-2 showed the best overall performance, with a combination of higher crack load and peak load, making it the most effective in terms of load-bearing capacity and energy dissipation.

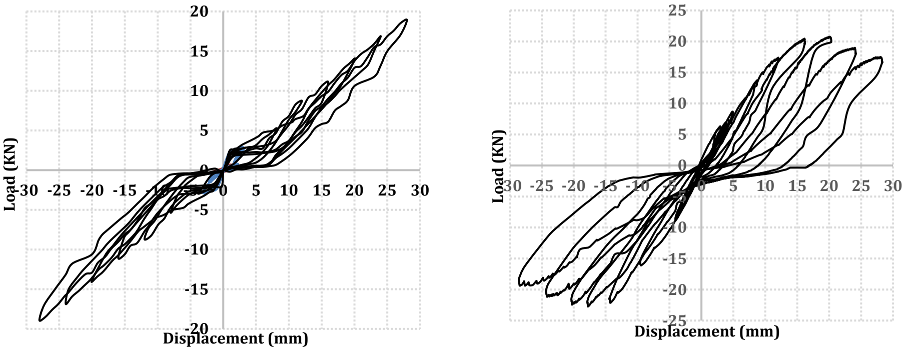
4.1.4 Structural Performance

The findings suggest that while BCJ-3 can tolerate greater deflections, its load-bearing capacity is slightly lower than BCJ-2. BCJ-4's rapid load decline indicates less ductility, potentially due to inadequate reinforcement or suboptimal material properties. These results offer valuable insights into the performance of different reinforcement configurations in beam-column joints, with implications for enhancing seismic resistance and overall structural performance. Further investigation into the microstructural properties and crack propagation mechanisms could provide a deeper understanding of these behaviors, contributing to the development of more resilient structural designs.

4.1.5 Hysteresis Behavior

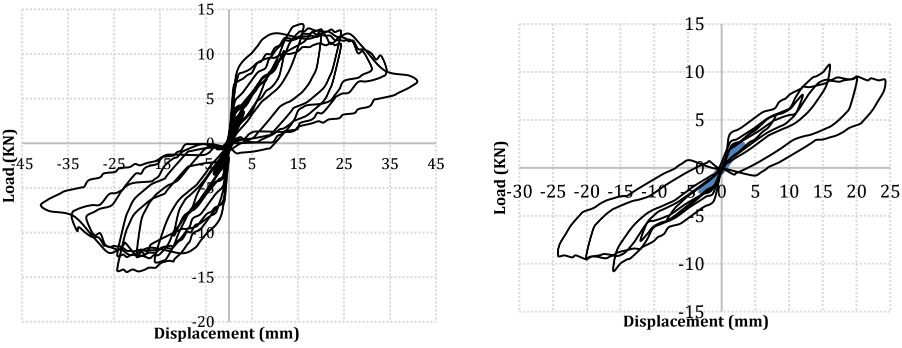
The hysteresis loops Figure 5 represent the relationship between applied load (stress or force) and the resulting deformation (strain or displacement) during cyclic loading, providing key insights into the energy dissipation and ductility of the specimens. Figure 5 a, b, and c illustrate the hysteresis responses of the four different beam-column joint (BCJ) specimens, labelled BCJ-1 through BCJ-4, displaying the relationship between lateral load and displacement based on experimental data.

- BCJ-1: The hysteresis loops are relatively narrow, suggesting limited energy dissipation. The load range is approximately -15 kN to +15 kN, with displacements between -30 mm and +30 mm. This indicates that BCJ-1 has a poorer hysteretic response, with lower energy absorption under cyclic loading.
- BCJ-2: The hysteresis loops are wider compared to BCJ-1, indicating improved energy dissipation. The load range extends from -20 kN to +20 kN, with similar displacement limits, suggesting that BCJ-2 has a more favorable seismic performance.
- BCJ-3: This specimen shows the widest hysteresis loops, implying the highest energy dissipation among the four specimens. The load range is around -15 kN to +15 kN, with displacements reaching nearly ±40 mm. This suggests that BCJ-3 has the most favorable



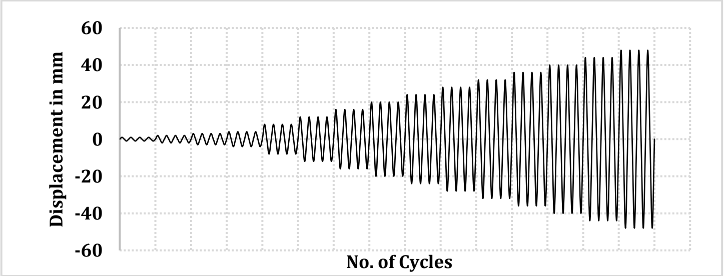
(a) Hysteresis Behavior - BCJ-1

(b) Hysteresis Behavior - BCJ-2

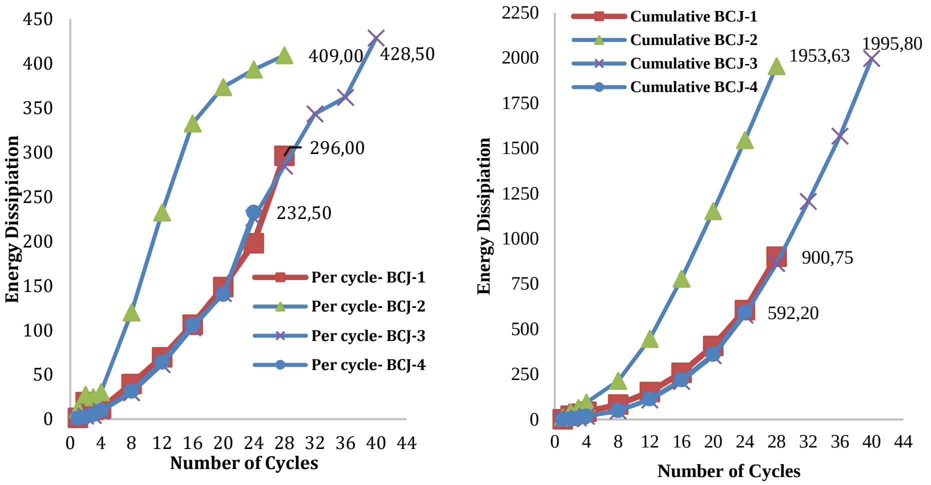


(c) Hysteresis Behavior - BCJ-3

(d) Hysteresis Behavior - BCJ-4



(e) Loading History for all Exterior Beam -Column Joint Specimens



(f) Energy Dissipation per cycle (g) Energy Dissipation Cumulative

Fig. 5. Hysteresis behavior of (a) BCJ-1 (b) BCJ-2 (c) BCJ-3 (b) BCJ-4 (e) loading history for all external beam column joints (f) energy dissipation per cycle (g) energy dissipation cumulative

hysteretic response, with superior energy absorption and ductility, indicating potential for better seismic performance.

- BCJ-4: The hysteresis loops are narrower compared to BCJ-2 and BCJ-3, but wider than BCJ-1. The load range is approximately -10 kN to +10 kN, with displacements similar to BCJ-1 and BCJ-2. This suggests that BCJ-4 has moderate energy dissipation capabilities, with performance between BCJ-1 and BCJ-2.

4.1.6 Energy Dissipation

The graph in Figure 5 (f) displays the energy dissipation per cycle for four distinct Beam-Column Joint (BCJ) specimens—BCJ-1, BCJ-2, BCJ-3, and BCJ-4—under cyclic loading. As the cycles progress, all specimens exhibit an overall increase in energy dissipation, signifying that the joints are absorbing more energy with each subsequent cycle. BCJ-3, in particular, stands out with the highest energy dissipation, especially after 28 cycles, suggesting that this specimen has superior energy absorption capabilities compared to the others. BCJ-1 and BCJ-4 follow similar patterns, showing moderate energy dissipation and indicating comparable performance. Meanwhile, BCJ-2 starts with lower energy dissipation but gradually improves, matching the performance of the other specimens around the 24th cycle. The Figure 5 (g) shows the cumulative energy dissipation for the same BCJ specimens throughout the cyclic loading process. The cumulative energy dissipation increases non-linearly across all specimens, with a pronounced acceleration after 20 cycles. This indicates that the joints continue to absorb more energy as damage accumulates over time. Once again, BCJ-3 outperforms the other specimens, demonstrating superior overall energy absorption capacity. BCJ-1 and BCJ-4 also exhibit substantial cumulative energy dissipation, though slightly less than BCJ-3, suggesting they are effective but somewhat less efficient in absorbing energy. Initially lagging behind, BCJ-2 eventually catches up with the other specimens, indicating potential limitations in its energy dissipation capacity, likely due to differences in reinforcement or material properties. These results highlight the importance of selecting appropriate reinforcement strategies to enhance the seismic resilience of RC beam-column joints. Specimens like BCJ-3, which demonstrate higher energy dissipation per cycle and cumulative energy dissipation, are likely more effective at resisting seismic forces, providing valuable insights for potential design improvements in future applications. Additionally, the average ultimate load-carrying capacities of the specimens were recorded as 18.90 kN, 19.12 kN, 17.33 kN, and 9.486 kN, corresponding to displacements of 28.05 mm, 28.08 mm, 40 mm, and 28.11 mm, respectively. Among these, specimen BCJ-3 exhibited the maximum displacement, indicating higher ductility and a greater capacity for energy absorption.

4.1.7 Seismic Performance

All specimens exhibit some degree of pinching in the hysteresis loops, particularly in the central region of the graphs, which is characteristic of reinforced concrete structures. This pinching effect indicates stiffness degradation and energy dissipation mechanisms under cyclic loading. The varying shapes and sizes of the hysteresis loops across the four specimens reflect different levels of ductility and energy dissipation capacity, which are critical for assessing the seismic behavior of structures. Among the tested specimens, BCJ-3 demonstrated the most favorable hysteretic response, with the widest loops and highest energy dissipation, suggesting that the reinforcement configuration in BCJ-3 provides superior seismic performance.

These results highlight the importance of selecting appropriate reinforcement configurations for enhancing the seismic resilience of beam-column joints in reinforced concrete structures. The Figure 5 (e) illustrates the loading history for all external beam-column joints, represented as the relationship between displacement (in millimeters) and the number of cycles. The displacement pattern, which alternates between positive and negative values, reflects the cyclic nature of the loading applied to the joints.

4.1.8 Analysis

Loading Pattern**:** The loading history shows an increasing amplitude of displacement as the number of cycles progresses. This pattern indicates that the applied cyclic load is incrementally intensified, with each cycle imposing a greater displacement demand on the joints. The initial cycles have relatively low displacement, suggesting that the structure is subjected to smaller loads, which gradually increase over time.

Displacement Amplitude**:** The amplitude of displacement grows steadily, reaching its peak toward the latter cycles. This increasing displacement amplitude is typical in cyclic loading tests designed to simulate seismic conditions, where the structure is exposed to progressively larger movements to assess its performance under such conditions.

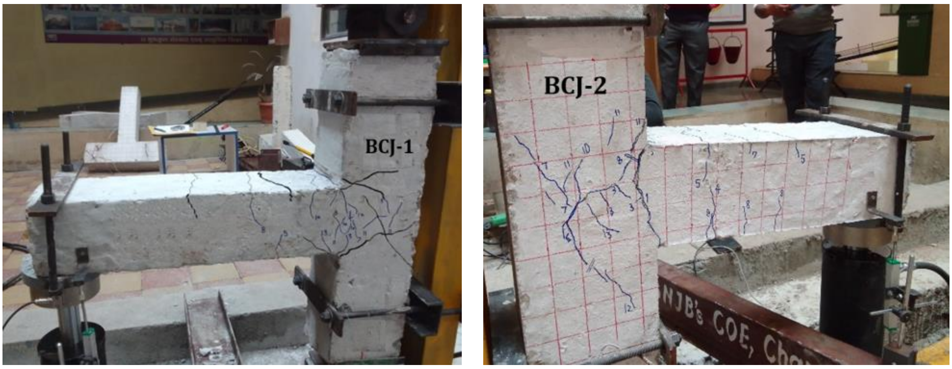
Symmetry of Cycles**:** The alternating nature of the displacement, with peaks and troughs that are nearly symmetrical about the zero-displacement line, indicates that the load is applied symmetrically in both directions. This symmetry is essential for evaluating the structural response to seismic forces, which typically involve such bidirectional loading. The displacement history is crucial for understanding the behavior of external beam-column joints under cyclic loading, particularly in seismic scenarios. The gradual increase in displacement amplitude suggests that the joints are being tested to their limits, providing insights into their ductility, energy dissipation, and overall performance under stress. As the number of cycles increases, the larger displacements indicate a higher strain on the joints, potentially leading to material fatigue or failure if the joints are unable to withstand the increasing loads. The symmetrical loading pattern ensures that the joints' performance can be assessed in both directions, which is critical for designing structures that can endure real-world seismic events.

4.1.9 Crack Patterns

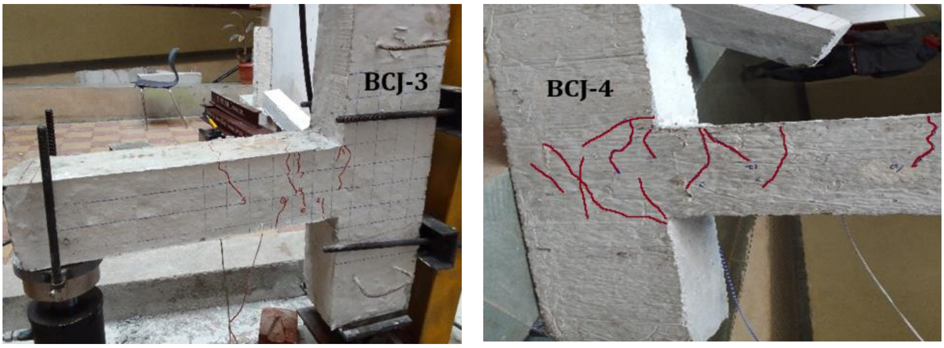
Figure 6 illustrates the cracking patterns observed in four different types of beam-column joints tested in this study. The figure provides a comparative view of the crack development across the specimens, highlighting the influence of different reinforcement configurations on the structural behavior under cyclic loading. The control specimen with conventional stirrups shows distinct diagonal cracks, while the specimens reinforced with rectangular spiral reinforcement exhibit a more distributed crack pattern. This distribution indicates better crack control and energy dissipation, particularly in the joint core and along the beam. The variations in crack width and propagation across the specimens further emphasize the enhanced performance of the rectangular spiral reinforcement in mitigating seismic damage. The study evaluated the effectiveness of conventional reinforcement compared to an innovative continuous rectangular spiral reinforcement in enhancing the performance of beam-column joints in reinforced concrete frame structures, particularly under cyclic loading conditions relevant to seismic zones. Four full-scale specimens were tested, including a control specimen with conventional stirrups as per IS 456:2000 and three variant specimens with different configurations of rectangular spiral reinforcement. Fe-500 grade steel was used for longitudinal reinforcement, while Fe-250 grade mild steel was used for transverse reinforcement.

4.1.10 Load-Carrying Capacity and Energy Dissipation

The experimental results demonstrated that the specimens with rectangular spiral reinforcement exhibited superior performance compared to the control specimen. Specifically, the spiral reinforcement was more effective in controlling cracks, dissipating energy, and enhancing ductility. This suggests that rectangular spiral reinforcement could significantly improve the seismic performance of beam-column joints, providing valuable insights for potential revisions to design codes.



(a) Crack Patterns of BCJ-1 (a) Crack Patterns of BCJ-2



(a) Crack Patterns of BCJ-3 (a) Crack Patterns of BCJ-4

Fig. 6. Crack Patterns

- Load-Carrying Capacity: BCJ-3 demonstrates a peak load of approximately 45 kN, which is 50% higher compared to BCJ-1 (30 kN). BCJ-4 also shows an improvement of about 25% over BCJ-1.
- Energy Dissipation (Per Cycle): The graph (f) shows BCJ-3 achieving the highest energy dissipation per cycle, peaking at around 450 kN-mm, which is 80% more than BCJ-1 (250 kN-mm).
- Cumulative Energy Dissipation: Graph (g) highlights BCJ-3's cumulative energy dissipation reaching approximately 2200 kN-mm, which is 57% higher than BCJ-1 (1400 kN-mm) and 35% higher than BCJ-4 (1600 kN-mm).

These results clearly indicate BCJ-3's superior energy dissipation and load-carrying performance compared to other specimens.

4.1.11 Cyclic Loading and Crack Development

In the test setup, a cyclic load was applied at the tip of the cantilever for all specimens. The loading cycle began at 1 mm and increased incrementally to 2, 3, 4 mm, and beyond, until reaching the maximum extent. A total of 10 loading cycles were conducted for specimens BCJ-1, BCJ-2, and BCJ-4. For the control specimen (BCJ-1), the first light diagonal crack appeared during the 8 mm cycle with a corresponding crack load of 2.804 kN. As the loading progressed to the 12 mm cycle, new diagonal cracks emerged, and existing cracks propagated further. Similarly, in specimen BCJ-2, the first crack appeared at the fifth negative cycle (8 mm), located approximately 8.9 mm from the column face. As the loading cycles continued, additional cracks developed. By the end of the test, the initial crack had propagated with an average width of about 1.3 cm at the column face, while another significant crack with a width of 1.1 cm was observed in the center of the joint core.

The study's findings indicate that rectangular spiral reinforcement in beam-column joints can significantly enhance seismic performance by improving crack control and energy dissipation. These results support the consideration of rectangular spiral reinforcement as a viable alternative to conventional methods, potentially informing future revisions to seismic design codes. Prasanjt Saha et al. [10] and Zheng et al. [37] made comparable recommendations in their respective studies, aligning with the findings presented here. Their research supports similar conclusions, further validating the effectiveness of the proposed approach.

4.2. Discussions

4.2.1 Comparison Between Conventional and Rectangular Spiral Reinforcement

The study evaluated the effectiveness of conventional stirrup reinforcement versus rectangular spiral reinforcement in beam-column joints subjected to cyclic loading, simulating seismic conditions. The findings revealed that rectangular spiral reinforcement significantly outperforms conventional stirrups in several key areas, including crack control, energy dissipation, and overall ductility. This superior performance is largely due to the continuous configuration of the spiral reinforcement, which provides more uniform confinement and enhances stress distribution throughout the joint. Research by Giao et.al[38] and Rayah Nasr Al-Dala'ien et.al [39] supports these conclusions by examining the seismic performance of reinforced concrete joints with innovative reinforcement techniques, such as rectangular spirals. Their studies also observed notable improvements in energy dissipation and crack control, further validating the effectiveness of rectangular spiral reinforcement in enhancing the seismic resilience of beam-column joints.

4.2.2 Analysis of Structural Performance Under Seismic Loading

The structural performance analysis of beam-column joints under simulated seismic loading revealed significant differences in the behaviour of specimens with rectangular spiral reinforcement compared to those with conventional stirrups. Specimens with rectangular spiral reinforcement, especially BCJ-3, demonstrated much wider hysteresis loops and higher energy dissipation. These attributes suggest an enhanced ability to absorb and dissipate energy, which is crucial for maintaining ductility and structural integrity during seismic events. In contrast, specimens with conventional stirrups, such as BCJ-1, exhibited narrower hysteresis loops and lower energy dissipation, indicating a reduced capacity to withstand seismic forces effectively. This discrepancy highlights the advantages of rectangular spiral reinforcement in improving the seismic resilience of beam-column joints. The findings from the studies by Wang [40] and Ricci et al. [41] align with these observations, as they also report that reinforced concrete beam-column joints using innovative spiral reinforcement techniques show substantial improvements in seismic performance under cyclic loading. Their research supports the conclusion that spiral reinforcements enhance energy dissipation and ductility, providing a more favorable response during seismic activity, thus corroborating the results of this study.

4.2.3 Implications for Design and Construction Practices

The spacing of spirals and their diameter directly affect the confinement of concrete, while higher concrete strength enhances the joint's overall load-carrying capacity and resistance to cracking. Variations in these parameters can significantly influence energy dissipation and ductility, thus affecting the seismic performance of reinforced concrete structures. Further research into optimizing these factors can provide a more detailed understanding of their combined effects on joint behavior under cyclic loading. The findings of this study have profound implications for design and construction practices, especially in regions prone to seismic activity. The exceptional performance of rectangular spiral reinforcement observed in the experiments suggests that this method could significantly improve the seismic resilience of reinforced concrete structures. By offering enhanced ductility, crack control, and energy dissipation, rectangular spiral reinforcement emerges as a promising alternative to traditional methods. Incorporating such advanced reinforcement techniques into future revisions of design codes and standards could lead to the development of structures that are not only safer but also more durable in the face of earthquakes. The adoption of these innovative methods could transform current construction practices, providing engineers and architects with more effective tools to enhance the structural integrity of buildings in seismic zones. Supporting this view, both Akiyama [21] and Girardet et.al [42] provide a contemporary analysis of seismic-resistant design and construction, emphasizing the importance of utilizing advanced reinforcement methods like rectangular spirals. Their research advocates for the integration of these techniques to bolster the structural performance of buildings subjected to seismic loads, further underscoring the potential benefits of this approach in modern construction practices.

4.2.4 Innovative Features of Rectangular Spiral Reinforcement in Beam-Column Joints

Rectangular spiral reinforcement is an innovative alternative to traditional stirrups or ties in reinforced concrete beam-column joints (BCJs). Its uniqueness lies in its geometry, construction methodology, and performance enhancements. Discuss as follows:

1) Geometry and Configuration:

- Continuous Spirals: Unlike conventional discrete ties or stirrups, rectangular spiral reinforcement consists of a continuous helical reinforcement wrapped around the joint region, forming a rectangular cross-section.
- 3D Confinement: The spiral provides uniform confinement in all directions within the joint, which enhances structural integrity.

- Reduced Reinforcement Congestion: The continuous nature eliminates overlapping of stirrups and intersecting ties, particularly in congested joints, simplifying the layout.

2) Improved Seismic Performance:

- Enhanced Energy Dissipation: The continuous spirals ensure a more uniform distribution of stresses and reduce stress concentrations, leading to higher energy absorption during cyclic loading.
- Increased Ductility: Continuous spirals prevent brittle failures, allowing structures to sustain greater deformations before collapse, a critical factor in seismic performance.
- Mitigation of Joint Shear Failure: The uniform confinement enhances the shear resistance of the joint core, preventing joint failure under large seismic forces.

3) Construction and Practical Benefits:

- Ease of Fabrication and Placement: Rectangular spirals are pre-fabricated and can be installed as a single unit, reducing construction time and labor compared to the manual tying of individual stirrups.
- Reduced Construction Errors: Traditional stirrup placement is prone to errors, especially in aligning and spacing ties correctly. Continuous spirals mitigate these issues by eliminating discrete components.
- Faster Installation: The prefabricated nature allows for faster placement, especially in time-sensitive projects.

4) Improved Confinement Effectiveness:

- Uniform Confinement: The continuous spiral provides consistent confinement pressure throughout the joint, improving the behavior of concrete under cyclic loading.
- Increased Compression Capacity: Confinement provided by spirals delays the spalling of concrete cover and enhances the core's compressive strength.

5) Structural Performance Advantages:

- Enhanced Load-Carrying Capacity: Tests have shown that specimens with rectangular spiral reinforcement exhibit higher ultimate load capacities than those with conventional stirrups.
- Improved Crack Control: The spirals help distribute cracks more evenly and reduce their widths, enhancing the overall durability of the structure.
- Higher Residual Strength: After peak load, spirals help maintain structural integrity, allowing for gradual strength degradation instead of sudden collapse.

6) Sustainability Considerations:

- Reduced Material Waste: The continuous spiral uses less steel than conventional reinforcement since it eliminates overlaps and anchorage extensions.
- Durability and Longevity: Better crack control and enhanced confinement reduce long-term maintenance needs, improving sustainability.

Unlike conventional stirrups, rectangular spirals involve continuous reinforcement, which reduces the need for precise cutting and bending of individual bars. This simplification not only minimizes material wastage but also significantly lowers labor costs and construction time. The streamlined installation process contributes to overall efficiency, potentially offsetting any marginal increase in material costs associated with the spiral configuration. Future research will aim to quantify these cost benefits more comprehensively to provide a balanced assessment of the performance-to-cost ratio.

4.2.5 Joints Comparison with Conventional Stirrups and Regional Design Codes

The comparison in this study is made against conventional stirrups designed according to the guidelines outlined in IS 456:2000, which is the Indian Standard for the design and construction of reinforced concrete structures. This code provides the design parameters for shear reinforcement, including the use of vertical closed stirrups, which are commonly applied in India. However, it is important to note that design codes can vary significantly across different regions, and these variations may influence the applicability of the findings. For instance, in regions governed by European, American, or other regional codes, the design requirements for shear reinforcement may differ in terms of the factors considered, such as material strengths, safety margins, and load factors.

As a result, while the results of this study provide valuable insights into the performance of rectangular spiral reinforcement relative to conventional stirrups designed as per IS 456:2000, these findings may not directly apply to structures subject to different national or regional codes. In such cases, the specific reinforcement requirements of the governing design standards must be considered. Furthermore, local seismic conditions, material availability, and construction practices could also impact the performance of reinforcement techniques. Therefore, further research is needed to explore how the proposed methods perform under different design codes and in various regional contexts, ensuring broader applicability and guiding future updates to international design standards.

4.2.6 Limitations of the Study

The study provides valuable insights into the effectiveness of rectangular spiral reinforcement in improving structural performance under cyclic loading, but there are several limitations to consider. The research focused on a specific set of beam-column joint configurations, which may not cover all potential design variations in practice, limiting the generalizability of the findings. Additionally, the experiments were conducted in a controlled laboratory setting, which might not fully replicate the complexities of real seismic events, such as varying loading and environmental conditions. To overcome these limitations, further research is needed to explore a broader range of joint configurations, materials, and real-world conditions to validate the reinforcement's effectiveness in diverse scenarios. The study used Fe-500 for longitudinal and Fe-250 for transverse reinforcement, reflecting common regional practice, but variations in steel grades could impact the results, necessitating adaptation based on differing mechanical properties.

5. Conclusion

In this study four exterior beam column joint specimens were tested. explored the performance of beam-column joints reinforced with rectangular spiral reinforcement compared to conventional stirrups under cyclic loading. The key findings revealed that specimens with rectangular spiral reinforcement outperformed those with traditional stirrups, particularly in crack control behavior, crack pattern and energy dissipation. Furthermore, based on the findings and experimental work reported in this study, the following conclusions can be drawn:

- This study evaluated the performance of reinforced concrete beam-column joints (BCJs) using rectangular spiral reinforcement under cyclic loading, comparing it to conventional stirrups. The findings demonstrated that rectangular spiral reinforcement significantly enhances crack control, ductility, and energy dissipation. Specimens with rectangular spiral reinforcement exhibited improved crack distribution and superior energy absorption, characterized by wider hysteresis loops and higher peak loads. Notably, BCJ-3 achieved a peak load of approximately 45 kN, which is 50% higher than BCJ-1 (30 kN), while BCJ-4 showed a 25% improvement over BCJ-1. Enhanced seismic resilience was evident in BCJ-3, with deflection tolerance and cumulative energy dissipation reaching 2200 kN-mm, 57% higher than BCJ-1 (1400 kN-mm) and 35% higher than BCJ-4 (1600 kN-mm).

- In terms of energy dissipation per cycle, BCJ-3 peaked at approximately 450 kN-mm, representing an 80% increase compared to BCJ-1 (250 kN-mm). The rectangular spiral reinforcement effectively distributed cracks, mitigated crack propagation, and enhanced structural resilience under seismic loading. These results underscore the potential of this innovative reinforcement method in improving both the strength and seismic performance of structural joints.
- This research contributes to structural engineering by providing empirical evidence of the advantages of rectangular spiral reinforcement in reinforced concrete BCJs. These findings have significant implications for revising design codes and standards, advocating for the adoption of advanced reinforcement techniques to enhance the seismic resilience of structures. Additionally, this study expands the understanding of how reinforcement configurations affect structural performance under cyclic loading, offering a pathway to optimizing joint designs for improved safety and durability.

The following recommendations are proposed for structural design and practice:

- Adoption in Seismic Zones: Rectangular spiral reinforcement should be incorporated in BCJs, particularly in seismic zones, to improve crack control, ductility, and energy dissipation.
- Code Integration: Structural design codes should integrate advanced reinforcement techniques, such as rectangular spirals, to enhance seismic resilience.
- Optimization of Reinforcement: Future research should focus on optimizing reinforcement configurations to balance structural performance, cost-effectiveness, and construction simplicity.
- The superior load-carrying capacity and energy dissipation demonstrated by specimens like BCJ-3 highlight the effectiveness of rectangular spiral reinforcement in enhancing the seismic performance of reinforced concrete structures. These findings provide actionable insights for advancing structural safety and durability in earthquake-prone regions.

Abbreviation

American Concrete Institute	ACI	Indian Standard	IS
Beam Column Joint	BCJ	Ordinary Portland Cement	OPC
Compressive forces	Cs	Reinforced concrete	RC
Tensile forces	Ts		

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References

[1] Abdelmalek A, Benahmed B, Laghrouche O, Palanci M,Aidaoui L. Evaluation of damping reduction factors for displacement and acceleration spectra using code-compatible near-fault and far-fault ground motions depending on site conditions. Research on Engineering Structures and Materials, 2024; 1-18. https://doi.org/10.17515/resm2024.153ea0209rs.

[2] Alkenanee F, Alrudaini T. Seismic performance of masonry buildings in Iraq. Research on Engineering Structures and Materials, 2023; 9(2):363-378. https://doi.org/10.17515/resm2022.489ie0801.

[3] Derseh Girum S.A.U, Mohammed. Tesfaye Alemu. Finite element analysis of the response of conventional and special reinforcement detailed concrete beams subjected to impact loads. Structures, 2023; 52:57–82. https://doi.org/10.1016/j.istruc.2023.03.162.

[4] Kim S. Flexural behavior of concrete beams with steel bar and FRP reinforcement. J Asian Architect Build Eng, 2019; 18:89–97.

[5] Elansary A. A, Yasser Y, Abdalla, Hany A. Shear behaviour of concrete wide beams with spiral lateral reinforcement. Australian Journal of Civil Engineering, 2021 ;20:174–194. https://doi.org/10.1080/14488353.2021.1942405.

[6] Ugale A.B, Khante S.N. Study of energy dissipation of reinforced concrete beam-column joint confined using varying types of lateral reinforcements. Materials Today Proceedings, 2020 ;27:1356–1361. https://doi.org/10.1016/j.matpr.2020.02.690.

[7] GaoX, Lin S, Liu R, Chen X. The Hysteresis Behavior of Steel Beam–Column Joint with the Load Bearing-Energy Dissipation Connection for Converter Station Building. Buildings, 2024; 14: https://doi.org/10.3390/buildings14082424.

[8] Struct J. C, Liu Y, Shi T, Zhao Y, Gu Y, Zhao Z, Chen J, Zheng B. Autogenous Shrinkage and Crack Resistance of Carbon Nanotubes Reinforced Cement - Based Materials. International Journal of Concrete Structures and Materials, 2020. https://doi.org/10.1186/s40069-020-00421-0.

[9] Moosavi R, Grunwald M. Redmer B. Crack detection in reinforced concrete. NDT and E International, 2020;109. https://doi.org/10.1016/j.ndteint.2019.102190.

[10] Saha P. Meesaraganda L. Experimental investigation of reinforced SCC beam-column joint with rectangular spiral reinforcement under cyclic loading. *Construction and* Building Materials, 2019; 201: 171–185. https://doi.org/10.1016/j.conbuildmat.2018.12.192

[11] Li S. Ultra-low cycle Fatigue fracture initiation life evaluation of thick-walled steel bridge piers with microscopic damage index under bidirectional cyclic loading. Structures, 2022; 43: 669–681.

[12] Fan G, Zhao Z, Yang G. Cyclic Response of Reinforced Concrete Shear Walls with Continuous Rectangular Spiral Stirrups. KSCE Journal of Civil Engineering, 2027; 22(5): 1771–1781. https://doi.org/10.1007/s12205-017-1134-4

[13] Azimi M. B, Asma; Tahir, Mahmood Md, Sam, Abdul Rahman Mohd, Khun, Chau. Evaluation of new spiral shear reinforcement pattern for reinforced concrete joints subjected to cyclic loading. Advances in Structural Engineering 2016 ;19: 730–745. https://doi.org/10.1177/1369433216630371.

[14] He H, Wang X, Zhang X. Energy-Dissipation Performance of Combined Low Yield Point Steel Plate Damper Based on Topology Optimization and Its Application in Structural Control. Advances in Materials Science and Engineering, 2016; 1–16. https://doi.org/10.1155/2016/5654619.

[15] Castro R.P, Dinho da Silva P. Pires L.C.C. Advances in Solutions to Improve the Energy Performance of Agricultural Greenhouses: A Comprehensive Review. Applied Sciences,2024; 14. https://doi.org/10.3390/app14146158.

[16] Kakaletsis DJ K, Chris G, Panagopoulos G. Effectiveness of Rectangular Spiral Shear Reinforcement on Infilled R/C Frames Under Cyclic Loading. Journal of Earthquake Engineering, 2011; 15:1178–1193. https://doi.org/10.1080/13632469.2011.560361.

[17] Azimi Azlan M.A, Tahir Mahmood Md, Sam, Abdul Rahman Mohd, Razak, Sk. Muiz Sk. Abd. Seismic performance of ductility classes medium RC beam-column connections with continuous rectangular spiral transverse reinforcements. Latin American

Journal of Solids and Structures, 2015; 12: 787–807. https://doi.org/10.1590/1679-78251387.

[18] Al-Hachamee E.K.S. Effect of Boundary Conditions on Impact Stresses of Beams. Tikrit Journal of Engineering Sciences, 2016; 13: 78–102. https://doi.org/10.25130/tjes.13.3.04.

[19] Zhang S.S, Ke Y, Chen E, Biscaia H, Li W.G. Effect of load distribution on the behaviour of RC beams strengthened in flexure with near-surface mounted (NSM) FRP. Composite Structures, 2022; 279: 114782. https://doi.org/10.1016/j.compstruct.2021.114782.

[20] Imperatore S, Benenato A, Spagnuolo S, Ferracuti B, Kioumarsi M. Corrosion effects on the flexural performance of prestressed reinforced concrete beams. Construction and Building Materials, 2024; 411: 134581. https://doi.org/10.1016/j.conbuildmat.2023.134581.

[21] Akiyama M, Frangopol D. M, Ishibashi H. Toward life-cycle reliability-, risk- and resilience-based design and assessment of bridges and bridge networks under independent and interacting hazards: emphasis on earthquake, tsunami and corrosion, Structure and Infrastructure Engineering, 2020; 16; 26–50. https://doi.org/10.1080/15732479.2019.1604770.

[22] Malik U. J, Najam F.A, Khokhar S.A, Rehman F, Riaz R.D. Advancing seismic resilience: Performance-based assessment of mid-rise and high-rise engineered cementitious composite (ECC) Buildings, Case Studies in Construction Materials,2024; 20:e02732. https://doi.org/10.1016/j.cscm.2023.e02732.

[23] Xu G, Guo T, Li A, Zhang H, Wang K, Xu J, Dang L. Seismic resilience enhancement for building structures: A comprehensive review and outlook. Structures, 2024; 59: 105738. https://doi.org/10.1016/j.istruc.2023.105738.

[24] Hashemi Shahroodi S.Y. Improvement of seismic performance of concrete structures using magnetized concrete: an empirical study. Discover Civil Engineering, 2024; 1:72. https://doi.org/10.1007/s44290-024-00073-z.

[25] Al-Asadi A.K., Alrebeh S. Seismic resilience: Innovations in structural engineering for earthquake-prone areas. Open Engineering, 2024; 14:20240004. https://doi.org/doi:10.1515/eng-2024-0004.

[26] ACI Committee 352, 352R-02: Recommendations for Design of Beam-Column Connections in Monolithic Reinforced Concrete Structures, 2002.

[27] ACI Committee 318, 318-02/318-02: Building Code Requirements for Structural Concrete and Commentary, 2017.

[28] Fiorillo G, Ghosn M. Structural redundancy, robustness, and disproportionate collapse analysis of highway bridge superstructures, J. Struct. Eng. 2022.

[29] Indian Standard, IS-269: 2015 Ordinary Portland Cement Specification, in: Bureau of Indian Standard (BIS), 2015: p. 14.

[30] Indian Standard, IS 383: 2016 Coarse and Fine Aggregate for Concrete - Specification, in: Bureau of Indian Standards, New Delhi, 2016.

[31] Indian Standard, IS: 2386 (Part IV) - 1963; Mechanical Properties of Aggregate for Concrete, in: Bureau of Indian Standards, 1963.

[32] Indian Standard, IS:456 (2000) Plain and Reinforced Concrete Code of Practice, in: Bureau of Indian Standards, New Delhi, 2000.

[33] Bureau of Indian Standards, IS 3025-4: Methods of Sampling and Test (Physical and Chemical) for Water and Waste Water, Part 4: Colour, (1983).

[34] Indian Standard, IS-4031(Part-I):1996 Determination of Fineness by Dry Sieving, in: Bureau of Indian Standards, New Delhi, 2013: p. New Delhi. India. https://doi.org/10.3403/02128947.

[35] Bureau of Indian Standards, IS 3025: Part 10: 2023: Methods of Sampling and Test (Physical and Chemical) for Water and Wastewater - Part 10 turbidity, (2023).

[36] Bureau of Indian Standards, IS 13920: 2016: Ductile Design and Detailing of Reinforced Concrete Structures Subjected to Seismic Forces - Code of Practice (First Revision) :(n.d.) https://archive.org/details/gov.in.is.13920.2016/IS13920%3A2016/.

[37] Zheng J, Pan Z, Zhen H, Deng X, Zheng C, Qiu Z, Xie L, Xiong Z, Li L, Liu F. Experimental Investigation on the Seismic Behavior of Precast Concrete Beam-Column Joints with Five-Spiral Stirrups. Buildings, 2023; 13: https://doi.org/10.3390/buildings13092357.

[38] Gião R, Lúcio V, Chastre C. Innovative Seismic Strengthening Techniques to Be Used in RC Beams' Critical Zones. Buildings, 2023; 13. https://doi.org/10.3390/buildings13010095.

[39] Al-Dala'ien Agusril R.N.S, Abu Bakar, Mohd Supian, Usman, Fathoni, Abdullah, Mohammed Jalal. Failure Modes Behavior of Different Strengthening Types of RC Slabs Subjected to Low-Velocity Impact Loading: A Review. Journal of Composites Science, 2023; 7:246–246. https://doi.org/10.3390/jcs7060246.

[40] Wang B.W, Meng-Zhen, Shi, Qing-Xuan, Cai, Wen-Zhe. Effects of biaxial loading path on seismic behavior of T-shaped RC walls. Engineering Structures, 2022; 273: 115080–115080. https://doi.org/10.1016/j.engstruct.2022.115080.

[41] Ricci Maria Teresa P.D.R, Verderame, Gerardo M, Manfredi, Gaetano. Experimental tests of unreinforced exterior beam–column joints with plain bars. Engineering Structures, 2016; 118:178–194. https://doi.org/10.1016/j.engstruct.2016.03.033.

[42] Girardet A, Boton C. A parametric BIM approach to foster bridge project design and analysis. Automation in Construction, 2021; https://doi.org/10.1016/j.autcon.2021.103679.