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PERFORMANCE EVALUATION AND STRENGTH PREDICTION OF BEAM - COLUMN JOINTS UNDER CYCLIC LOADING

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ABSTRACT

Joints between beams and columns can be considered the weakest sections in multi-storey reinforced concrete (RC) frame structures subjected to earthquake loads, as these joints significantly influence load moment transmission. To examine earthquake-resistant performance, four joint samples consisting of RC material were created to simulate cyclic lateral loading under controlled laboratory conditions. In the investigated study, two joint specimens were designed according to IS: 456-2000 specifications, symbolizing non-ductile design, while another two were designed according to IS: 13920-1993 specifications for ductile design. Additionally, the two ductile joint specimens were designed to simulate the effect of 10% and 20%, specifically referring to their axial load capacity, column loads. All joint specimens were designed using C30-concrete strength grade. In the testing procedure, constant column loads were applied to the columns, but the beams were loaded using a hydraulic actuator under displacement-controlled loading conditions. Increasing displacement was applied under a constant load rising to a maximal value. Hysteresis loop data were collected to examine performance under seismic loads. The key performance parameters, such as load carrying capacity, stiffness deterioration, energy dissipation, and ductility, were investigated in detail. The ductile joints performed better under cyclic loading and exhibited better strength characteristics, higher energy dissipation capacity, and post-yield behaviour. In addition to this, the effect of axial load on the columns also assisted in improving the bounding effect that helps to resist the deterioration of joints. The results highlight the significance of ductile detailing to improve the seismic resistance of RC framed structures. The need for earthquake-resistant design parameters has been emphasized to avoid any catastrophic damage to structures during earthquake occurrences.

KEYWORDS: Beam-column joints, Ductility, Cyclic loading, Hysteretic curves, Energy dissipation.

1. INTRODUCTION

1.1 General

Beam-column joints in reinforced concrete are essential components in seismic-resistant designs of reinforced concrete moment-resisting frames. In order to contribute towards the stability of the structure, the joint should be able to provide sufficient stiffness and strength to resist the forces coming from the other beams and columns. Because the strength of concrete is low in the case of reversals, the joint is often reinforced. In a majority of the RC structure collapses, the joint is the point where the failure of the structure is initiated. This happens mostly because of the combined effects of flexural and shear stresses. When the joint is subjected to cyclic loading arising from earthquakes, the internal forces within the joint become very high. Joint performance during such a phenomenon requires analysis that is concerned with the strength and capacity of the joint to undertake plastic deformation. The RC structure is highly dependent on the overall reinforcement details provided in the joint region.

1.1 Requirements of Beam-Column Joints

The methods of connectivity that have been used are either conventional bolting methods by themselves or a hybrid approach that uses combined mechanical fastening and adhesive bonding methods. The variables that have been considered in the experimental study are bond agents and materials, the possibility of being able to deform columns, materials for cleats, and joint designs altogether. Joints that have combine bolts and adhesive materials have shown an improved bending strength and stiffness as well. The adoption of steel cleats in place of existing fiber-reinforced polymer cleats has shown an observed augmentation in moment strength by as much as 50%.[1] The inclusion of end-anchored steel plates in PC-S PC specimens to and from the ends of layers of carbon fiber-reinforced polymer layers in CFRC layers in outer joints has changed the failure mode to IC debonding in PC-S PC units; it further led to an increased capability in terms of maximal loads by about 10% by deflecting CFRC failure along joint edges.[2] The experimental program included parameters such as hysteretic response, energy dissipation, and loss of stiffness, which showed that precast concrete (PC) connections with embedded steel tendons in the joint core satisfy seismic performance levels. In addition to this, a computational analysis was performed by adopting a finite element method analysis, which offered reliable results corresponding to actual behavior. It has been observed that increasing the compressive strength of concrete and increasing the diameter of supplementary reinforcing steel in the joint core has a positive influence on the stiffness of the connection.[3] A total of thirty different joint configurations were analyzed in detail, to study the influence of parameters like the compressive strength of concrete, axial force in columns, joint core stirrups, and the geometry of the top reinforcement in beams on the load-carrying capacity and beam tip deformation. For each model, the concrete size and the reinforcement layout have been selected to ensure the occurrence of joint failure. Among the geometrical shapes taken into consideration, straight anchorages of the top reinforcement in beams provided reduced peak load capacities with respect to L- and U-shaped anchorages. Rather surprisingly, L and U-shaped reinforcement anchorages provided similar structural responses.[4] To this effect, a three-dimensional finite element numerical model was developed utilizing the software ABAQUS/CAE version 6.14. Concrete Damage Plasticity (CDP) modeling was also employed to describe non-linear concrete behavior to evaluate structural performance. It was observed that with concrete containing 1.5% steel fibers and ductile reinforcement details, there was a marked improvement in performance. Numerical predictions were in good agreement with experimental data, with a variation of less than 10%.[5] As is commonly practiced in seismic designs to provide resistance to transverse forces induced in RC beams due to seismic activities, transverse reinforcement in RC beam-column joints is normally provided to resist shearing forces. In the case of moment-resisting frames subjected to high lateral seismic loads, a closely spaced stirrup is required in the joint region.

However, such a high level of reinforcement may lead to overcrowding, complex construction procedures, and might result in ineffective concrete casting and compaction, which will adversely impact the seismic vulnerability of the structure.[6] This paper proposes a simplified approach to model the nonlinear behavior of beam-column joint regions of RC moment-resisted frames. The proposed model will utilize a zero-length component at the beam-column connection that will capture the nonlinear shear behavior of the joint core through a rotational spring component. The damages estimated by this approach were found to be consistent with experiments conducted on a laboratory model.[7] The behavior of beam–column joints has a great influence on seismic performance of RC frame structures.

In structures designed before the enforcement of modern seismic provisions, the commonly inadequate ductile detailing leads to increased joint degradation when subjected to cyclic deformations. Techniques for retrofitting provide feasible solutions to enhance the structural capacity of deficient joints. However, the effectiveness of these interventions relies heavily on the level of damage already present and on the characteristics of the retrofit material. To this end, an experimental program was executed using ultra-high-performance hybrid fiber-reinforced concrete (UHP-HFRC) as a retrofitting medium for externally damaged beam-column joints. The severity of damage was classified by using the Park and Ang damage index to define four levels: slight, moderate, severe, and complete damage. The retrofitted Specimen then underwent cyclic loading tests. The results showed that for joints reinforced with UHP-HFRC, an important increase in load-carrying capacity, energy absorption capacity, and ductility has been observed compared to that of the control specimens.[8] The absence of joint encasements in existing pre-1970s RC buildings is considered an important problem in terms of creating vulnerable points in the joint area and even catastrophic collapse failure of structures under an earthquake.[10] The study has four main targets: first, it aims to suggest novel methods for joint repair in structures using advanced FP composites and pre-cured connectors; second, it validates these methods via extensive experimental tests; third, it investigates and analyzes data related to original and repaired joint structures; and finally, it provides future directions for further study.[11] Many RC beam–column assemblies in older structures were built without adherence to current seismic standards, making them prone to brittle failure modes such as joint shear or plastic hinging in columns under earthquake loads. To address these deficiencies, this experimental study investigated the performance of novel FRP-based retrofit systems. Five half-scale exterior beam–column joints were fabricated and tested under combined constant axial loading and reversed cyclic lateral displacement to assess the retrofit efficacy.[10]

As many aging structures were not originally engineered to resist seismic forces, reinforcing their most vulnerable components has become increasingly important. Targeted strengthening efforts can enhance both the structural reliability and longevity of these buildings. Previous studies have demonstrated that various retrofitting methods can substantially improve the strength of beam–column joints. However, these enhancements may inadvertently shift the failure mode to the joint core if not properly detailed. Although vertical reinforcement has proven effective in reducing flexural damage at the column-joint boundary, failures have still been observed within the joint region itself. The use of diagonal reinforcement, on the other hand, has shown promise in limiting joint failure.[11]

To gain further insight into the effect of construction defects during earthquakes, there have been experiments performed by some researchers on scaled RC models using shake tables.[12-14] Though there are risks associated with earthquakes, aging due to environmental effects also causes risks to the performance of the structure. Carbonation and chloride ion penetration affect the durability of the structure in the context of reinforced concrete.[15] A major aspect of RC structure construction is that most of these buildings were designed prior to the development of seismic design standards. Therefore, most of these buildings are susceptible to brittle failure modes of failure, such as joint shear fracture or flexural fracture of columns, when there is an earthquake.[16] The basic stability of the structure of reinforced concrete frames relies on beam-column connections. Since joints are the origin of failure of structures when there are earthquakes, it is important to gain more information about joint performance. A variety of techniques have been adopted to improve the performance of these joints.[17] Analysis and design of GFRP reinforced beam-column joints are done using the strut and tie model. Strut and Tie Models are concepts based on steel reinforced models for beam-column joints. The strut and tie model developed for GFRP reinforced beam-column joints estimates the shear strength of joints. The joint shear strength calculated experimentally has been compared with the theoretical estimation of the shear strength of steel reinforced beam-column joints as well as GFRP reinforced beam-column joints.[18] Conducted experiments on full-scale precast joint specimens of precast beam-column joints of recycled powder concrete (RPC). They performed well under cyclic loading conditions with good hysteresis, energy absorption, and performance, thereby implying the sustainability of recycled powder concrete.[19] Open Sees analysis has been done with experimental validation; the outcomes have shown improvement in seismic performance because of fiber reinforcement with respect to strength, stiffness, and energy dissipation capacity, while maintaining the shear span length of between 2.0 and 2.5 ratios.[20] Physical experiments were coupled with FE analyses using software (ANSYS) to investigate non-ductile RC joints with inclined columns. The outcomes revealed a strong correlation between the hysteresis and stiffness curves obtained from the analysis and experimental models, and ferrocement retrofitting improved the values of ductility and energy dissipation capacity.[21]

An experimental and numerical evaluation was done for half-scale RECC columns, five RECC specimens, and one conventional RC specimen subjected to cyclic lateral loading conditions. Varying shear span ratios and transverse ratios in the experiment demonstrated the improvement of shear capacity in RECC columns with larger shear span ratios and transverse ratios, including improvement in ductility (with a value larger than 5), energy dissipation capacity (with an increased capacity of 1.2-4.1 times compared with the RC specimen), ultimate strength deterioration (with an ultimate drift of more than 3.4%), and failure mechanisms.[22, 23]

1.2 Classification of joints

A joint is identified as the zone of a column enclosed by the depth of the deepest beam spanning it. The joints in moment-resistant frames can be classified based on their position and design within the frame. The joints include: Interior joints, where the beams intersect on opposite sides of a column, Exterior joints, where one beam intersects one side of a column, and Corner joints, which are common at the outer extremities of buildings.

1.2.1 Interior joint

When all four sides of a column are joined to the beams, it is called an interior joint. The effect of the gravitational load on the joint is shown in Figure 1a. The axial load on the columns and the tension/compression load on the beam are transferred across the joint. When the lateral load, shown in Figure 1b, acts on the structure during an earthquake, the combination of the beam and column loads causes diagonal tensions and compressions to occur within the joint. The resulting cracks on the joints are shown by the lines perpendicular to the direction of the tensile diagonal (A-B in Figure 1b). The dashed lines in the figure represent the compression members, while the solid lines represent the tie members.

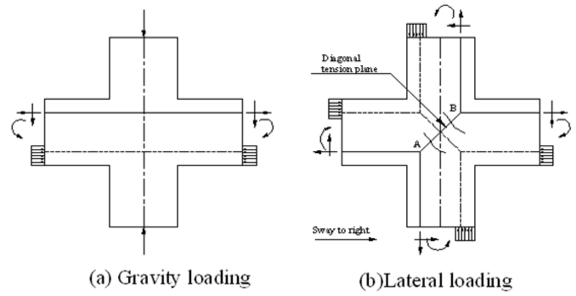
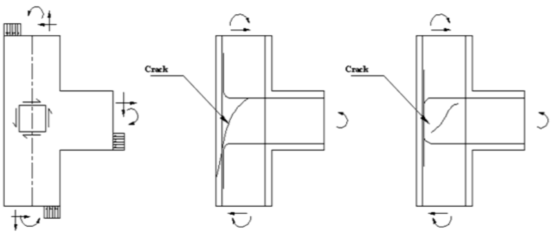


Figure 1a, b. Interior joint.

1.2.2 Corner joint

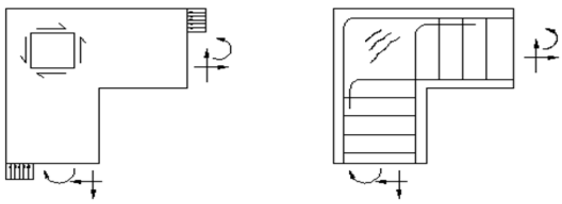
In case of a beam, if every frame is split into two sides of the vertical face of a column, then the joint is referred to as the corner joint. Wall corners belong to the other form of joints wherein the applied moments result in closing or opening the corners. These joints can also be referred to by the name knee joints or L-joints. Stresses and cracks that form in such joints are shown in the Fig. 2 a, b, c.



(a) Forces (b) Bars bent away from the joint (c) Bars anchored in the joint

Figure 2a, b, c. Exterior joint.

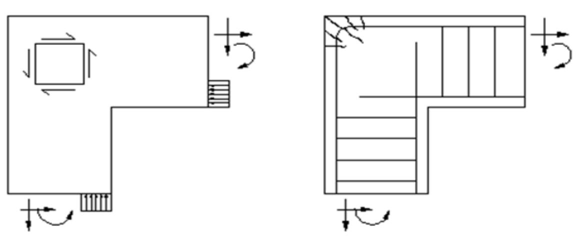
A normal knee joint undergoing an opening type of bending moment shows typical behavior, as depicted in Fig. 3a & b. Mostly, such joints are subjected to the effect of bending moments, axial forces, as well as shear forces. The cracking zone of such joints normally starts from the re-entrant corner, while ultimate failure occurs mainly due to the formation of a diagonal tensile crack.



(a) Forces (b) Cracks in an opening joint

Figure 3 a, b. Knee joint subjected to 'Opening' moment.

In Figures 4a and 4b, the closing bending moment on the knee joint is depicted. The internal forces experienced in a closing joint react oppositely to the forces that exist in the opening joint. The dominant crack is usually diagonally placed at the joint corner. Compared to the opening joint, the closing joint is expected to have relatively better performance.



(a) Forces (b) Cracks in a closing joint

Figure 4 a, b. Knee joint subjected to 'Closing' moment.

Type 1 joints are designed with priority to basic strength demands without the necessity to provide for substantial ductility. Moreover, joints with designs capable of sustaining basic loads without loss of capacity due to repeated inelastic deformation fall in the category of Type 2 joints. Joints for structures subjected to normal gravity loads and normal wind forces are classified as Type 1 joints.

Furthermore, joints designed for resisting extreme lateral loads such as those produced by earthquakes, explosion loads, or cyclonic winds are classified as Type 2 joints.

1.3 Aim and Objectives of the Present Investigation

1.3.1 General

Beam-column joints represent one of the most important elements that control the seismic behavior of RC moment-resisting frames. The areas around beam-column joints are particularly vulnerable to damage during strong earthquakes due to the very high bending moments and shear forces that develop in these regions.

This paper addresses the investigation into beam-column joint sub-assemblies that have developed joint shear failure. The joint shear demand is quantified in terms of strain measurements acquired from the reinforcement within the test specimens. Forces such as external loading, beam shear, and column axial loads contribute to stress conditions that may trigger failure in both concrete and steel.

Diagonal cracking and localized concrete crushing have been shown to dramatically reduce the stiffness of the joint, and since the connections are designed to be strong and rigid components of the structural system, joint failure cannot be tolerated.

1.3.2 Aim of Investigation

The salient aim of this investigation is to evaluate the maximum shear resistances and corresponding ductility of such important structural components as beam-column joints. Ideally, for maximum structural performance, a joint should perform well compared to that of the surrounding beams and columns when working under service load conditions. The current investigation aims to examine the effect of shear resistance on beam-column joints, including an assessment of these joints as well as their reinforcement details.

1.3.3 Objectives of Investigation
The important objectives for carrying out this research are as follows:
- To examine the ductility properties of the reinforced concrete beam-column joint.
- To investigate the behavior of exterior RC beam-column joints under cyclic lateral loading.
- To conduct a detailed analysis of structural behavior patterns such as column flexure, column shear, beam shear, beam flexure, and joint shear.
- To examine partially fixed boundary conditions at the end of the column.
- To determine the impact of the stirrup spacing in the beams and columns, which are the only variables in this study.
- To investigate how a 10% axial load ratio for a column can affect the strength and ductility of the critical components of a joint.

2. Experimental Investigation
2.1 General
Beam-column joints are very important for the seismic-resistant performance of RC moment-resisting frames. Beam-column joints should have sufficient stiffness and strength to resist forces that are transferred from the connected beams and columns.

In the study, two specimens were designed, among designed by IS 456 and the other by IS 13920. The specimens were characterized by equal cross-sectional sizes of the columns as well as the beams. The next subsections describe the materials as well as the experiment setup.

2.2 Properties of Materials
The materials employed in this investigation adhered to applicable Indian standards, and their properties were confirmed through standard testing procedures. The specific details are outlined below.

2.2.1 Ordinary Portland cement
To prepare the beam-column joint specimens, 43-grade Ordinary Portland Cement (OPC), a standard choice in construction, was utilized. The essential characteristics of the cement were evaluated through testing and are summarized in Table 1.

Table 1: Properties of Cement.

Sl.No	Tests performed	Results
1	Standard Consistency	31%
2	Initial Setting Time	95 minutes
3	Final setting Time	230 minutes
4	Specific Gravity	3.10

2.2.2 Aggregates
Fine aggregate consisted of river sand meeting the specifications of IS 650:1996, while coarse aggregate comprised crushed granite with a maximum particle size of 20 mm. The relevant properties of both types of aggregates are provided in Tables 2 and 3.

Table 2: Properties of Fine Aggregate.

Sl.No.	Property	Fine Aggregate
1	Specific Gravity	2.70
2	Water absorption	1.0%

Table 3: Properties of Coarse Aggregate.

Sl.No.	Property	Coarse Aggregate
1	Specific Gravity	2.74
2	Water absorption	0.5%

2.2.4 Steel
The size and diameter of the reinforcement were selected in accordance with the relevant Bureau of Indian Standards specifications. The 12 mm and 8 mm reinforcing bars (rebar) were tested for tensile stress using a computerized universal testing machine.

2.2.5 Mix Design Details
The concrete used for fabrication was designed by IS: 10262-2009. The mix design details are presented in Tables 4 and 5.

Table 4: Mix Design Details.

Sl. No	Properties	Values
1	Characteristic compressive strength read field at 28 days	30 MPa
2	Maximum size aggregate	20mm
3	Workability	75mm (Slump)
4	Degree of quality control	Good
5	Type of exposure	Mild
6	Specific gravity of cement	3.10
7	Specific gravity of coarse aggregates	2.74
8	Specific gravity of fine aggregates	2.67

9	Target strength of concrete 30+(1.65x5) = 38.25	38.25MPa

Table 5: Mix Proportions.

	Water (liter/m^3)	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)
Quantity	192	427	609.133	1213.43
Ratio	0.45	1	1.42	2.8

2.2.6 Tests on Concrete Specimens

Concrete cubes designed for M30 grade were cast and cured for 28 days. After the curing period, the cubes were tested for compressive strength. The results are presented in Table 6.

Table 6: Compressive strength of concrete for M30 grade.

Sl. No	Specimen Code	Curing period	Compression load (Tons)	Average compressive strength (N/mm^2)
1	C-1	28 days	105	46.67
2	C-2	28 days	98	43.56
3	C-3	28 days	94	41.78
			Average	44.03

2.2.7 Specimen Details

The details of the beam column joint used in the experimental investigation were designed with beam and column members with cross-sectional measurements of 230 mm × 230 mm. Four specimens were prepared for the experimental investigation. Of these, two were prepared as per IS 456: 2000 (non-seismic) criteria, while the other two were made as per IS 13920: 1993 criteria, which deals with the details for earthquake-resistant designs.

In each code, one specimen was considered non-ductile and other ductile; this has been tabulated in Table 7. The reinforcement details for IS 456:2000 and IS 13920:1993 have been shown in Figure 5 and Figure 6 respectively.

Table 7: Details of specimen.

Sl. No.	According to IS codes	Type	Beam Details
1.	IS456-2000	A	Non-Ductility specimen
2.	IS13920-1993	B	Ductility specimen

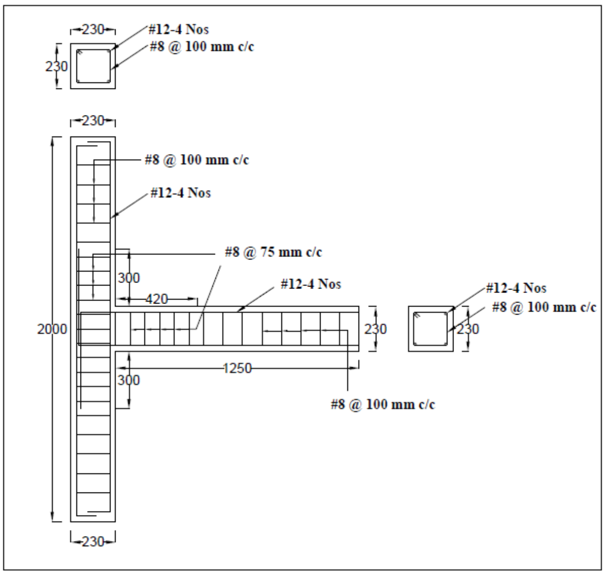


Figure 5: Reinforcement details for non-ductile joint (Type A).

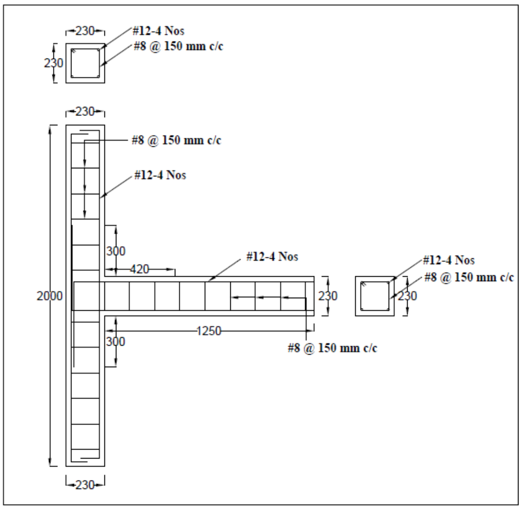


Figure 6. Reinforcement details for ductile joint (Type B).

3. RESULTS AND DISCUSSIONS

3.1 Test Arrangement

Figure 7: Experimental setup for the proposal testing of a beam-column joint. The column is held in position but not restrained in direction at both ends (partially fixed end condition). To simulate the axial load acting on the column, the column is pre-stressed approximately.

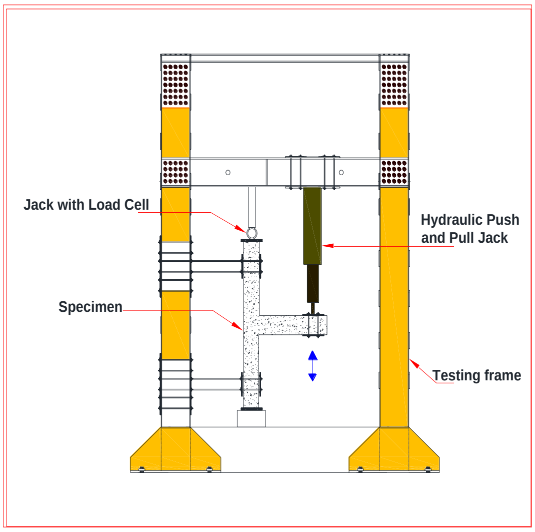


Figure 7: Schematic view of the setup for cyclic loading.

3.2 Experimental Test Results on Non-Ductile Specimen

Figure 8 portrays the hysteretic diagram of the non-ductile specimen, and the results are shown in Table 8. In the process, the specimen showed a small capability of energy dissipation and deformation during the cycle of loads applied, as should be for the specimen that is not ductile. It attained a maximum of 20 kN during the push process and 18 kN in the pull process. Moreover, it failed at 30 mm displacement, showing low deformation capability as opposed to the ductile specimen.

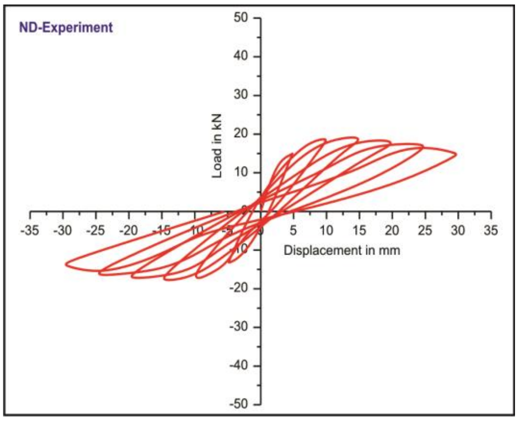


Figure 8: Hysteresis behavior of non-ductile specimen.

Table 8" Energy dissipation and stiffness for non-ductile specimens.

Displacement Mm	Energy dissipation (kN mm)	Stiffness (kN/mm)
	ND	ND
5	54.25	2.96
10	174.40	1.90
15	378.51	1.30
20	622.81	0.92
25	931.09	0.70
30	1254.59	0.50

Hysteresis curve analysis was performed to assess the energy dissipation capacity and stiffness changes occurring in the specimen during a series of loading cycles. Cumulative energy dissipated by the specimen was estimated to be 1254.59 kNmm, which largely depicts the capacity to effectively dissipate seismic loads. However, with respect to stiffness changes, it was largely noted that a substantial decrease took place with an increase in the number of loading cycles. The corresponding stiffness for the specimen was estimated to be 2.96 kN/mm for the first loading cycle, thereafter reducing to 0.50 kN/mm for the final loading cycle. This depicts a realistic effect on the stiffness of a structure due to material nonlinearity caused due to the loading cycles.

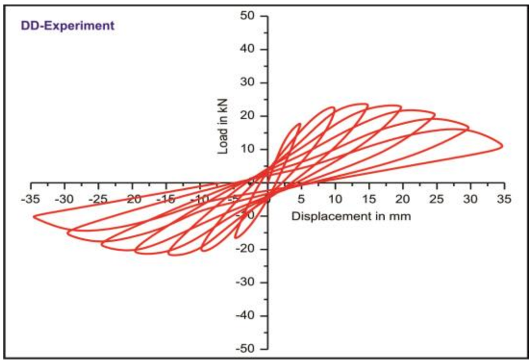


Figure 9: Hysteresis behavior of a ductile specimen.

3.3 Experimental Test Results on Ductile Specimen

The hysteretic response of the ductile specimen is illustrated in Figure 9 and summarized in Table 9. The specimen exhibited stable cyclic behavior up to failure, indicating effective energy dissipation characteristics under reversed loading.

Table 9: Energy dissipation and stiffness for a ductile specimen.

Displacement mm	Energy dissipation (kN mm)	Stiffness (kN/mm)
	ND	ND
5	65.44	3.70
10	219.43	2.35
15	484.06	1.60
20	827.79	1.17
25	1239.71	0.84
30	1684.29	0.56
35	2134.24	0.32

3.4 Comparison between Non-Ductile and Ductile

3.4.1 Cumulative Energy Dissipation and Stiffness for Non-Ductility and Ductility

Figures on the cumulative energy dissipation and stiffness curves for both non-ductile and ductile specimens are shown in Figure 10 and discussed in more details in Table 10. It is important to note that for the ductile beam, there is a total positive change of 41% in energy dissipation compared to that of the non-ductile beam, accentuating the excellent performance of a ductile beam in withstanding cyclic loading. At cycle one of displacement loading, the non-ductile beam dissipates a total of 54.25 kNmm in energy compared to a ductile beam that dissipates a total of 65.44 kNmm. This shows that even in the early stages of loading, a ductile beam has a significant ability to mitigate seismic loads compared to a non-ductile beam. As for data on stiffness degradation over all loading cycles for both non-ductile and ductile beams, a steady degradation is seen in consistency with rational cyclic loading principles. At cycle one of displacement loading, the initial values for both non-ductile and ductile beams were measured at 2.96kN/mm and 3.70kN/mm respectively. This shows that in terms of initial loading displacement capacity, a ductile beam outperforms a non-ductile beam with increased initial loading displacement ability of about 25%.

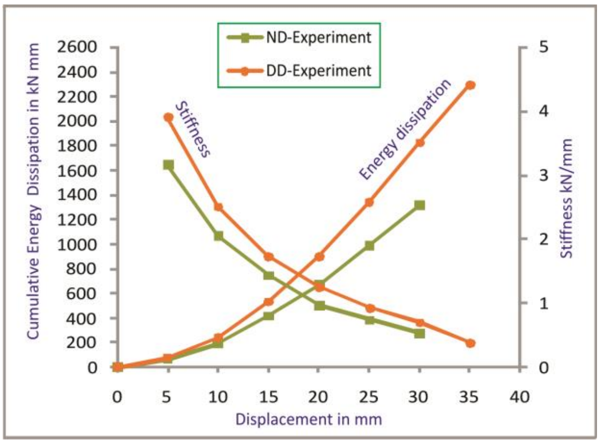


Figure 10: Cumulative energy dissipation and stiffness Vs. displacements.

Table 10: **Energy dissipation and stiffness at various displacements.**

Displacement (mm)	Energy dissipation (kN mm)		Stiffness (kN/mm)	
	ND	DD	ND	DD
5	54.25	65.44	2.96	3.70
10	174.40	219.43	1.90	2.35
15	378.51	484.06	1.30	1.60
20	622.81	827.79	0.92	1.17
25	931.09	1239.71	0.70	0.84
30	1254.59	1684.29	0.50	0.56
35	-	2134.24	-	0.32

4. CONCLUSION

Based on the findings of an extensive experimental investigation, the following conclusions have been drawn:

- By studying the simulation of beam-column joints through the load versus deflection curve of the free end of the beam, the simulation can represent the behavior of the joint under loading conditions. It shows that the setup is reliable and realistic.
- It is noted that the total shear strength in the critical joint section for structures designed as per IS 13920:1993 is higher compared to that for structures designed as per IS 456:2000 provisions. This confirms that seismic details in IS 13920 provide improved strength to beam-column joints against shear.
- The use of conventional anchoring systems with 90° bent hooks in the joint core during intense earthquakes requires a large cross-section of the column. This is required due to the congestion caused by the heavy rebar present in the beams. However, the use of mechanical anchoring systems avoids rebar congestion and facilitates optimal utilization of the joint core. This is achieved with the use of mechanical anchored bars of the type that resembles the shape of the letter ‘T.’ Such systems provide a viable alternative for conventional hooked anchoring systems.
- Ductile detailing in beams improves the dissipation of seismic energy by up to 41%, compared to non-ductile reinforcement configurations. This justifies the need to adhere to ductile design to improve the general structural resiliency against seismic forces.
- Among the other alternative reinforcement strategies tested, T-type mechanical anchorage was found to show the most promise as a replacement for conventional hook anchorage, with both structural and constructability benefits in seismic environments.

5. Conflict of Interest

No conflicts of interest are disclosed by the writers.

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