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Seismic Behaviour of Exterior Beam - Column Joints

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Abstract— Seismic failures are vulnerable and beam-column joints are critical in transferring the forces and moments in multistoried RC framed structures. Reinforced concrete beam-column joints are fabricated and cyclic loads are applied. Two numbers of specimen were cast out of which one is based on strong column weak beam and the remaining based on strong beam weak column. In work mix design for the concrete specimen and strength of concrete cubes and beam column joints specimen casting were completed. The column subjected to an axial force while the beams are subjected to cyclic load with controlled displacement. The displacement is increased monotonically using a hydraulic push and pull jack. The hysteretic curves of the specimen have been plotted. The results show that the strengthened beam column joint exhibit increased strength, stiffness, energy dissipation and composite action until failure.

Keywords: Seismic Failures, Interior Joint, RC Framed Structures

I. INTRODUCTION

In the analysis of reinforced concrete moment resisting frames the joints are generally assumed as rigid. In Indian practice, the joint is usually neglected for specific design with attention being restricted to provision of sufficient anchorage for beam longitudinal reinforcement. This may be acceptable when the frame is not subjected to earthquake loads. There have been many catastrophic failures reported in the past earthquakes, in particular with Turkey and Taiwan earthquakes occurred in 1999, which have been attributed to beam-column joints. The poor design practice of beam column joints is compounded by the high demand imposed by the adjoining flexural members (beams and columns) in the event of mobilizing their inelastic capacities to dissipate seismic energy. Unsafe design and detailing within the joint region jeopardizes the entire structure, even if other structural members conform to the design requirements.

Since past three decades extensive research has been carried out on studying the behaviour of joints under seismic conditions through experimental and analytical studies. Various international codes of practices have been undergoing periodic revisions to incorporate the research findings into practice. The paper is aimed at making designers aware of the theoretical background on the design of beam column joints highlighting important parameters affecting seismic behaviour of joints.

II. STRUCTURAL BEHAVIOUR UNDER SEISMIC ACTIONS

The seismic design philosophy relies on providing sufficient ductility to the structure by which the structure can dissipate seismic energy. The structural ductility essentially comes from the member ductility wherein the latter is achieved in the form of inelastic rotations. In reinforced concrete members, the inelastic rotations spread over definite regions called as plastic hinges. During inelastic deformations, the actual material properties are beyond elastic range and hence damages in these regions are obvious. The plastic hinges are “expected” locations where the structural damage can be allowed to occur due to inelastic actions involving large deformations. Hence, in seismic design, the damages in the form of plastic hinges are accepted to be formed in beams rather than in columns. Mechanism with beam yielding is characteristic of strong-column-weak beam behaviour in which the imposed inelastic rotational demands can be achieved reasonably well through proper detailing practice in beams. Therefore, in this mode of behavior, it is possible for the structure to attain the desired inelastic response and ductility. On the other hand, if plastic hinges are allowed to form in columns, the inelastic rotational demands imposed are very high that it is very difficult to be catered with any possible detailing. The mechanism with such a feature is called column yielding or storey mechanism.

One of the basic requirements of design is that the columns above and below the joint should have sufficient flexural strength when the adjoining beams develop flexural over strength at their plastic hinges. This column to beam flexural strength ratio is an important parameter to ensure that possible hinging occurs in beams rather than in columns.

A. Beam Column Joints

The functional requirement of a joint, which is the zone of intersection of beams and columns, is to enable the adjoining members to develop and sustain their ultimate capacity. The demand on this finite size element is always severe especially under seismic loading. The joints should have adequate strength and stiffness to resist the internal forces induced by the framing members.

1) Types of Joints in Frames

The joint is defined as the portion of the column within the depth of the deepest beam that frames into the column. In a moment resisting frame, three types of joints can be identified viz. interior joint, exterior joint and corner joint (Fig.1.).

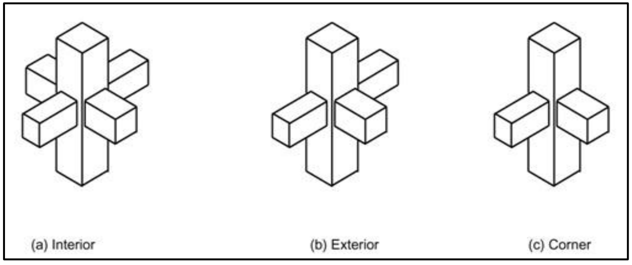


Fig. 1:

When four beams frame into the vertical faces of a column, the joint is called as an interior joint. When one beam frames into a vertical face of the column and two other beams frame from perpendicular directions into the joint, then the joint is called as an exterior joint. When a beam each frames into two adjacent vertical faces of a column, then the joint is called as a corner joint.

The severity of forces and demands on the performance of these joints calls for greater understanding of their seismic behaviour. These forces develop complex mechanisms involving bond and shear within the joint.

2) Forces Acting on a Beam Column Joint

The pattern of forces acting on a joint depends upon the configuration of the joint and the type of loads acting on it. The effects of loads on the three types of joints are with reference to stresses and the associated crack patterns developed in them. The forces on an interior joint subjected to gravity loading can be depicted as shown in Fig.1.2 (a). The tension and compression from the beam ends and axial loads from the columns can be transmitted directly through the joint. In the case of lateral (or seismic) loading, the equilibrating forces from beams and columns, as shown in Fig. 1.2(b) develop diagonal tensile and compressive stresses within the joint. Cracks develop perpendicular to the tension diagonal A-B, in the joint and at the faces of the joint where the beams frame into the joint. The compression struts are shown by dashed lines and tension ties are shown by solid lines. Concrete being weak in tension, transverse reinforcements are provided in such a way that they cross the plane of failure to resist the diagonal tensile forces.

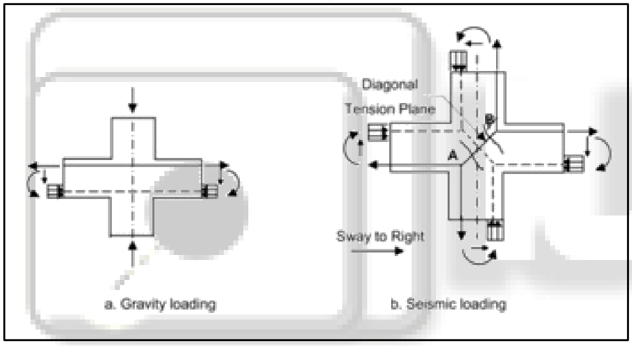


Fig. 2: Interior joint

The forces acting on an exterior joint can be idealized as shown in Fig. 1.3. The sheer force in the joint gives rise to diagonal cracks thus requiring reinforcement of the joint. The detailing patterns of longitudinal reinforcements significantly affect joint efficiency. Some of the detailing patterns for exterior joints are shown in Fig. 1 and Fig. 2. The bars bent away from the joint core (Fig.2) result in efficiencies of 25-40 % while those passing through and anchored in the joint core show 85-100% efficiency. However, the stirrups have to be provided to confine the concrete core within the joint.

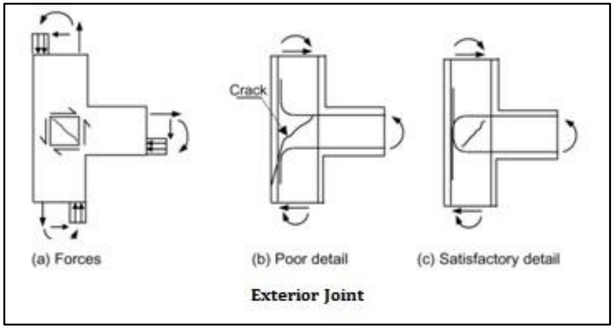


Fig. 3:

The forces in a corner joint with a continuous column above the joint (Fig. 3) can be understood in the same way as that in an exterior joint with respect to the considered direction of loading. Wall type corners form another category of joints wherein the applied moments tend to either close or open the corners. Such joints may also be referred as knee joints or L-joints. The stresses and cracks developed in such a joints are shown in Fig. 4.

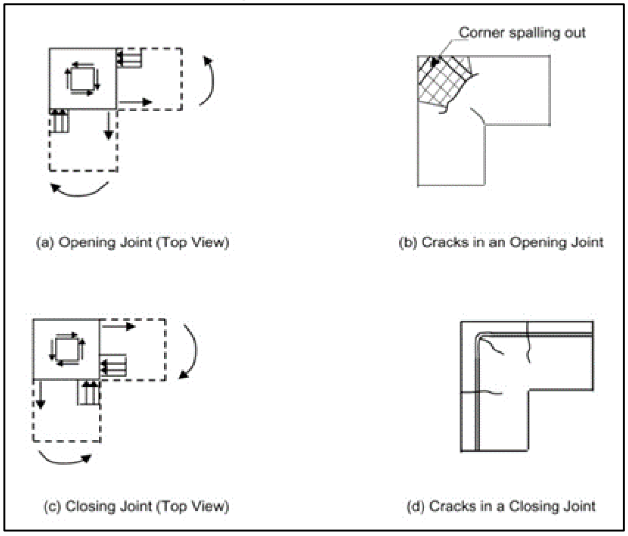


Fig. 4: Corner joints

Opening corner joints tend to develop nascent cracks at the reentrant corner and failure is marked by the formation of a diagonal tensile crack. The detailing of the longitudinal reinforcement significantly influences the behavior of such joints. The forces developed in a closing joint are exactly opposite to those in an opening corner joint. The major crack is oriented along the corner diagonal. These joints show better efficiency than the opening joints. During seismic actions, the reversal of forces is likely and hence the corner joints have to be conservatively designed as opening joints with appropriate detailing. Failure of opening corner or knee joint is primarily due to the formation of diagonal tension crack across the joint with the outer part of the corner concrete separating from the rest of the specimen. Special and careful detailing is required to avoid failure of such joints so that the strength of adjacent members could be developed. The stress resultants from the framing members are transferred into the joint through bond forces along the longitudinal reinforcement bars passing through the joint and through flexural compression forces acting on the joint face. The joints should have enough strength to resist the induced stresses and sufficient stiffness to control undue deformations.

B. Performance Criteria

The moment resisting frame is expected to obtain ductility and energy dissipating capacity from flexural yield mechanism at the plastic hinges. Beam-column joint behaviour is controlled by bond and shear failure mechanisms, which are weak sources for energy dissipation. The performance criteria for joints under seismic actions may be summarized as follows:

1) The joint should have sufficient strength to enable the maximum capacities to be mobilized in the adjoining flexural members.

2) The degradation of joints should be so limited such that the capacity of the column is not affected in carrying its design loads.
3) The joint deformation should not result in increased storey drift.

1) *Joint Mechanisms*

In the strong column-weak beam design, beams are expected to form plastic hinges at their ends and develop flexural over strength beyond the design strength. The high internal forces developed at plastic hinges cause critical bond conditions in the longitudinal reinforcing bars passing through the joint and also impose high shear demand in the joint core. The joint behavior exhibits a complex interaction between bond and shear. The bond performance of the bars anchored in a joint affects the shear resisting mechanism to a significant extent.

2) *Bond Requirements*

The flexural forces from the beams and columns cause tension or compression forces in the longitudinal reinforcements passing through the joint. During plastic hinge formation, relatively large tensile forces are transferred through bond. When the longitudinal bars at the joint face are stressed beyond yield splitting cracks are initiated along the bar at the joint face which is referred to as ‘yield penetration’. Adequate development length for the longitudinal bar is to be ensured within the joint taking yield penetration into consideration. Therefore, the bond requirement has a direct implication on the sizes of the beams and columns framing into the joint.

C. *Factors Affecting Bond Strength*

The significant parameters that influence the bond performance of the reinforcing bar are confinement, clear distance between the bars and nature of the surface of the bar. Confinement of the embedded bar is very essential to improving the bond performance in order to transfer the tensile forces. The relevant confinement is obtained from axial compression due to the column and with reinforcement that helps in arresting the splitting cracks. Joint horizontal shear reinforcement improves anchorage of beam bars. But, there is an upper bound to the beneficial effects of confinement. At this limit, maximum bond strength is attained beyond which the crushing of concrete in front of the rib portion of the deformed bar occurs. Research indicates better bond performance when the clear distance between the longitudinal bars is less than 5 times the diameter of the bar. As expected, the deformed bars give better performance in bond. The behavior of the reinforcing bar in bond also depends on the quality of concrete around the bar.

D. *Cyclic Loading*

The structures subjected to repeated loading their services lives. They can fail at relatively low values of the applied stress, if this stress is repeated a sufficient number of times are called fatigue. In the fatigue mode of failure a crack will form and propagate and eventually rapture will occur under the repeated action of stresses that are considerably lower than those required to cause failure under static load.

1) *Types of Cyclic Loading*

There are two types of cyclic loading they are listed below

1) Low-cyclic loading
2) High- cyclic loading

2) *Low Cyclic Loading*

In which load history contains a few cycles, but having large stress rangers. Low cycle loading commonly arise in seismic and high-wind stress loadings.

3) *High Cyclic Loading or Fatigue Loading*

In which load history containing many cycles, but at a low stress range. Bridge members, offshore structures and members supporting vibrating machinery are often subjected to this type of loading.

4) *Design Aspects*

- The flexural strength ratio of beam and column, degree of confinement, development of length of bars and joint shear stress should be considered in the design.
- Stirrups in the beam and tiers in the column near the joint should be provided as per recommendations of code.
- The detailing of reinforcement at the joint affects the strength of joints to a large extent.
- For best structural performance of beam-column joint, the beam reinforcement should be bent downwards into the column.

In the beam-column joints, with 20% of axial load capacity column.

5) *Aggregates*

The river sand confirming to IS-650-1996 was used as the fine aggregate and crushed granite stones aggregates of maximum size 20mm was used as the coarse aggregate. The desired properties of both aggregates determined.

6) *Steel*

The size and diameter of reinforcement were selected with references to the relevant specifications of Bureau of Indian Standards. The 12mm and 8mm rebar used have been tested for their tensile stress in a computerized universal testing machine.

	Water	Cement	Fine aggregate	Coarse aggregate
Quantity	192	427	609.133	1213.43
Ratio	0.45	1	1.42	2.8

Table 1: The actual mix proportions:

E. *Compressive Strength of Concrete*

The concrete cubes designed for M30 grade were cast and curried for 28 days, after the casting period the cubes were tested for this Compressive strength. The observations are presented below table.

1) *Specimen Details*

The Beam column joint consisted of both column and beam 230x230 mm size. Two specimens were cast out of which one is based on IS: 456-2000 and remaining is based on IS : 13920-1993. In each case one specimen is considered as Non-ductility specimen and other one is Ductility specimen as given in table 2. The details of reinforcements in the two cases are shown in figures 5 and 6 respectively. The size, grade of concrete, amount of main steel are same and the difference is only in the spacing of the stirrups.

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

Table 2: Ductility of specimen

Fig. 5: Typical testing for Non-Ductile joint (IS:456-2000)

III. EXPERIMENTAL TEST RESULT FOR NON DUCTILE SPECIMEN

The hysteresis behaviour of Non-Ductility specimen is shown in figure 6 For Non-Ductility specimen, the maximum load is 20 kN in push and 18 kN in pull respectively and the specimen failed in 30 mm displacement.

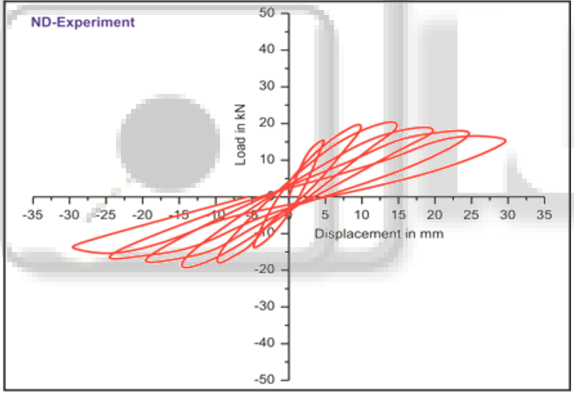


Fig. 6: Hysteresis behavior of Non-Ductile specimen

Displacement Mm	Energy dissipation (KN mm)	Stiffness (KN/mm)
	ND	ND
5	62.60	3.16
10	196.49	2.05
15	414.39	1.43
20	669.19	0.97
25	986.91	0.74
30	1316.34	0.53

Table 3: Energy dissipation and stiffness for Non-Ductile specimen

Based on the hysteresis behavior energy dissipation and stiffness degradation per cycle are worked out. The total cumulative energy dissipation observed is 1316.34kN mm (Table 3). The stiffness degraded from 3.16 kN/mm to 0.53 kN/mm.

Fig. 7: Crack Pattern for Non- ductile joint (Type A)

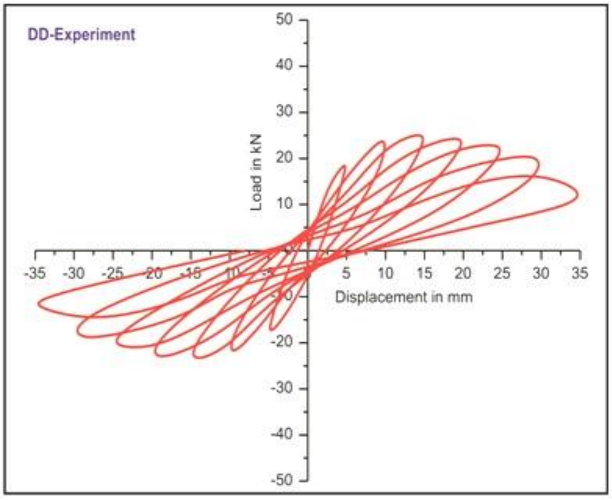
Fig. 8: Typical testing for Ductile joint (Type B) (IS:13920-1993)

IV. EXPERIMENTAL TEST RESULT FOR DUCTILE SPECIMEN

The hysteresis behaviour of Ductility specimen is shown in figure 9. For Ductility specimen, the maximum load is 25 kN in push and 22 kN in pull respectively and the specimen failed in 35 mm displacement.

A. Hysteresis Behavior of Ductile Specimen

Energy dissipation and stiffness for ductile specimen



B. Comparison between Non-Ductile and Ductile Specimen

1) Cumulative Energy Dissipation and Stiffness for Non-Ductile and Ductile Specimen

The cumulative energy dissipation and stiffness for Non-Ductility and Ductility specimen are given in figure.4. The increase in energy dissipation of ductile detailed beam is 42.5 percent when compared with the non-ductile detailed beam. The energy dissipation at first cycle of displacement for ND specimen is 62.60 kN mm and DD specimen is 73.33 kN mm. The stiffness at various cycle of loading, it can be seen that the stiffness degrades continuously in all the cycles. The stiffness at first cycle of displacement for ND specimen is 3.16 kN/mm and the DD specimen is 3.90 kN/mm.

Displacement (mm)	Energy dissipation (KN mm)		Stiffness (KN/mm)	
	ND	DD	ND	DD
5	62.60	73.33	3.16	3.90
10	196.49	240.24	2.05	2.50
15	414.39	528.46	1.43	1.73
20	669.19	894.75	0.97	1.25
25	986.91	1336.40	0.74	0.93
30	1316.34	1816.40	0.53	0.70
35		2288.39		0.38

Table 4: Energy dissipation and stiffness at various displacements

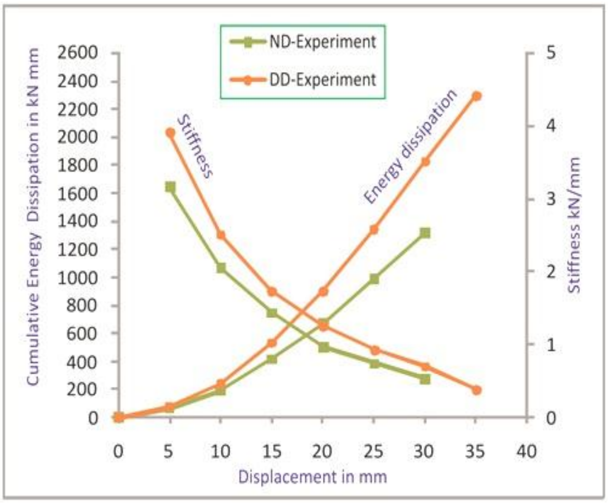


Fig. 10: Cumulative energy dissipation and stiffness Vs. displacements

V. CONCLUSION

- The simulation of beam-column joint through experimental work represented by the load-deflection plots at free end of beam shows good.
- The total shear resistance at the critical section of the IS 13920-1993 specimen is higher than IS 456-2000.
- The use of conventional 90◦ bent hook anchorage arrangements in the beam-column connection region for severe earthquake leads to increase in size of column to accommodate the required amount of beam reinforcement in the joint core, whereas the use of mechanical anchorage results in the reduction of reinforcement and rebar congestion in the joint core area. The T-type mechanical anchored bar is a variable alternative to the use of conventional 90◦ bent hook anchorages.
- The increase in energy dissipation of ductile detailed beam is 42.5 percent when compared with the non-ductile detailed beam.

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