# RCC Interior Beam Column Joints Under Reversed Cyclic Loading

## State of the Art

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*Abstract*— **Design of Reinforced Cement Concrete Moment Resisting Frames is of great importance in Earthquake prone areas. Beam column sub assemblage is a crucial part in any reinforced concrete moment resisting frame. The joints should be strong enough to resist and sustain the lateral load in the event of an earthquake. Beam column joints are designed based on the 'strong column weak beam' behaviour so as to result in a ductile failure. Since 1967, a great deal of experimental investigations and a reasonable number of analytical investigations were carried out with the aim to describe and predict the joint responses under seismic forces. An attempt has been made in this paper to describe the interior joint behavior under seismic lateral loading and also to discuss about the current scenario.**

***Keywords—Interior beam column joints; reversed cyclic loading; ductile failure; shear behaviour; failure modes***



## I. INTRODUCTION

Design of reinforced concrete moment resisting frames has attained great importance since the focus was shifted to earthquake resistant design of structures. Beam column joint sub assemblage has become the centre of attraction since 1967, when Hansen and Conner [1] conducted the first seismic loading test on it. Since then, a great deal of experimental investigations and a reasonable number of analytical investigations were carried out with the aim to describe and predict the joint responses in the event of an earthquake. Drawing input from these works, building codes all over the world have undergone a substantial change, revising the existing and including the new provisions so as to result in a safe design. The RC moment resisting frames are designed based on the so called 'strong column weak beam' behavior with the intention of having a ductile failure, if the situation calls for it. Despite these provisions, discrepancies have been reported in many cases of joint failures. This can be attributed to the failure in identifying the significance of the role of various design parameters that control the joint behavior.

During earthquakes, moment resisting RC frames are subjected to lateral loading. These will result in the development of a variable shear which reaches a maximum at the base and, a bending moment which tends to cause tension at the loaded edge and compression at the far edge. Hence these frames are designed for strength and ductility. The strength will influence the maximum capacity of the structural element to resist the lateral load. The maximum deformation beyond the yield point without the loss of strength is governed by the ductility of the structural member [2].

## II. BEHAVIOUR OF JOINTS

Joints or beam column sub assemblages are the weakest links in any structure under lateral loading. In all the relevant earthquake resistant design codes, design of joints is based on the 'strong column weak beam behaviour. This is aimed to provide the maximum energy dissipation during an earthquake. This ensures the development of plastic hinges in the beams at the beam column interface while all the vertical members including walls and columns remain elastic. The energy dissipation takes place in the plastic hinges which requires the provision of special confining reinforcement in the concerned structural member [3, 4].

### *A. Failure Mechanisms*

A joint may fail under the seismic lateral loading in three ways. In the first category, shear failure occurs in joints without affecting the strength of beams framing into the columns. Here the beam will remain elastic and is considered to be a brittle failure. This type of failure is sudden and imminent and is to be avoided at any cost. In the second category of failures, beam yields and fails without affecting the safety of the columns or joints. Here all the vertical members remain elastic except for the beams and it supports the strong column weak beam behavior. This is considered to be the perfect ductile failure preferred in moment resisting fames under seismic loading. In the third category, the failure of joint occurs as a combination of beam yielding followed by joint shear failure. All these types of failure are frequently observed in joint failures reported previously even with proper confining reinforcements [5-9]. The reason for this can be attributed to the failure in identifying the significant parameters and their role in determining the joint shear strength and ductility of associated structural elements.

## III. SHEAR TRANSFER MECHANISMS

The horizontal shear acting on the free body cut at the horizontal line at the mid height of the joint core is considered to be the definition of joint shear [1]. It is suggested that the joint shear failure may be precluded by limiting the shear stress to the level at which joint shear failure occurs. The study conducted by Paulay et al. (1978) [10] regarding the shear transfer mechanism is universally accepted and is considered as a milestone in the research area of joints. The resistance of shear forces in a joint core can be based on two postulated mechanisms such as the strut mechanism and the truss mechanism.

### *A. Strut Mechanism*

Here the joint shear is transferred via a diagonal concrete strut which sustains only compression. The diagonal concrete strut is assumed to be inclined at an angle close to that of the potential corner to corner failure plane. The concrete compressive forces at the two corners of the joint core and the bond forces transmitted from the longitudinal reinforcement contributed largely to the diagonal compressive force. As shown in Fig. 1., the area enclosed within the dark line is referred to as the shear carried by concrete [10-12].

### *B. Truss Mechanism*

Unlike the strut mechanism, this considers the contribution of the shear resistance of the vertical and horizontal reinforcement inside the joint core. The vertical and horizontal forces transferred by bond from the beam and column longitudinal bars are transmitted via the area, lying outside the 'shaded area' of Fig. 1., to the concrete core. These forces are idealized to be considered as a shear flow as shown in Fig. 2. With proper joint transverse reinforcement, a diagonal compressive field can be sustained to transmit the bond forces even with the presence of extensive cracking. This compressive field is generated by the truss mechanism and it involves the contribution of joint transverse reinforcement, column reinforcement and the diagonal concrete struts [12].

The two mechanisms may then be superimposed to resist the total joint shear force in the horizontal and vertical directions.

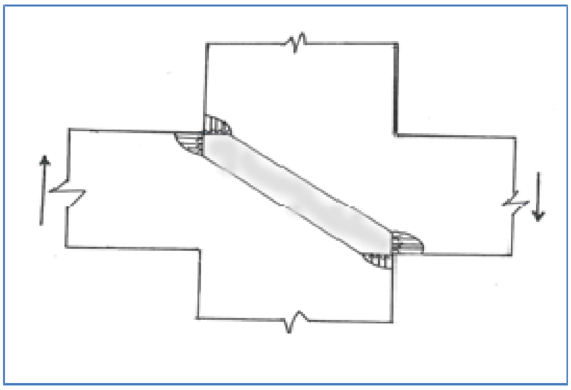

Fig. 1. Strut Mechanism

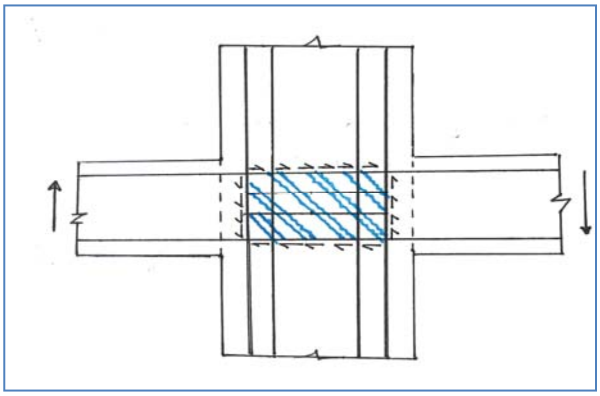

Fig. 2. Truss Mechanism

## IV. COMPUTATION OF JOINT SHEAR FORCE

With reference to the diagram shown as Fig. 3., the joint horizontal shear force can be computed in the following manner. The joint shear forces are arrived from the internal forces associated with the adjoining members. The horizontal joint shear force demand ($V_{jh}$) is the net force acting on a horizontal plane across the joint including the forces from the beam and the shear force from the column [13-15].

$$V_{jh} = T_1 + T_2 - V_c \quad (1)$$

Where $T_1$ and $T_2$ are the tensile forces in the top and bottom beam longitudinal bars and $V_c$ is the column shear. The forces $T_1$ and $T_2$ can be calculated as:

$$T_1 = \alpha_o A_{s1} f_{y1} \quad (2)$$

$$T_2 = \alpha_o A_{s2} f_{y2} \quad (3)$$

Here $\alpha_o$ represents the over strength factor for yield strength of steel at strain hardening and is taken equal to 1.25. $A_{s1}$ and $A_{s2}$ are the areas of longitudinal beam bars at the top and bottom. $f_{y1}$ and $f_{y2}$ are the yield strength of beam longitudinal bars at the top and bottom respectively.

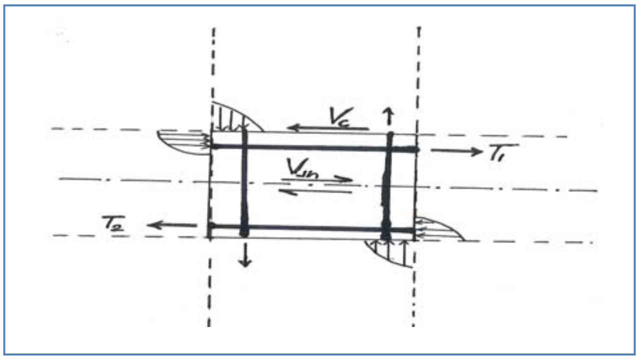


Fig. 3. Horizontal Joint Shear

The column shear $V_c$ can be computed as [16]:

$$V_c = \frac{M_{1o} + M_{2o}}{\left(l_c + l_{c'}\right)/2} \quad (4)$$

Where $M_{1o}$ and $M_{2o}$ are the flexural over strength capacities of beams including the contribution of floor slab on either side of the joint, and, $l_c$ and $l_{c'}$ are the heights of the column above and below the joint.

The joint shear force demand in the vertical direction ($V_{jv}$) may be obtained by considering the equilibrium of forces in the vertical direction. Another approximation which is in use worldwide is based on the assumption of uniform distribution of stresses along each face of the joint. The vertical joint shear force can be expressed in proportion to the horizontal joint shear force as [16] :

$$\frac{V_{jh}}{b_j h_c} = \frac{V_{jv}}{b_j h_b} \quad (5)$$

From this, $V_{jv}$ can be obtained as

$$V_{jv} = \frac{h_b}{h_c} V_{jh} \quad (6)$$

Where $b_j$ denotes the effective width of the joint, $h_c$, the depth of the column and $h_b$, the depth of the beam.

Since the column is assumed to be strong and the design of the frame is aimed at beam hinging mechanism, it is generally sufficient to estimate only the horizontal joint shear.

## V. EFFECT OF DESIGN VARIABLES

Researchers all over the world have investigated the joint behavior by considering numerous factors like geometry, material properties, area of reinforcement, reinforcement detailing, effect of transverse beams and slabs, effects of eccentric beams etc. The seismic performance of the joints is evaluated in terms of the strength and stiffness by conducting experimental investigations in which RC interior beam column joints were tested to failure under quasi static cyclic lateral loading. The investigators have identified certain design variables as the significant ones in influencing the general joint behaviour. The following sections discuss the various significant factors that are to be considered with importance before designing the beam column sub assemblages.

### *A. Aspect Ratio*

Aspect ratio is defined as the ratio of the depth of the beam to the depth of the column. This is related to the shear strength of the joint. This plays a relatively important role in differentiating the joint shear failure from beam failure. Higher value of aspect ratio does not support the strong column weak beam behavior. As the value of aspect ratio increases, the likelihood of joint shear failure increases compared to beam failure. Beam column joints with larger aspect ratio have lower joint shear strength. The aspect ratio seems to have critical impact on the joint shear strength [15, 17, 18].

### *B. Joint Transverse Reinforcement*

The amount of transverse reinforcement in the joint plays a crucial role towards the core confinement. The transverse reinforcement shall be provided by either single, or over lapping spirals, circular hoops or rectangular hoops with or without crossties. Transverse reinforcement shall be provided over a length $l_o$ from each joint face and on both sides of any section where flexural yielding is likely to occur as a result of inelastic lateral displacements of the frame. The length $l_o$ shall not be less than the largest of the following such as (i) depth of the member at the joint face or the section where flexural yielding is likely to occur, (ii) one-sixth of the clear span of the member and (iii) 18 in [19].

The spacing of the transverse reinforcement along the length $l_o$ of the member shall not exceed one-quarter of the minimum member dimension. This requirement is necessary for the adequate concrete confinement [19]. The ACI 318-11 [19] specifies equations for calculating the amount of transverse reinforcement to be provided in joints whether it is circular or rectangular hoops. Previous research have underlined the importance of joint transverse reinforcement in resisting shear effectively [12, 15, 20-22].

### *C. Anchorage Length of Beam Bars*

Studies on the effect of anchorage length of beam bars have shown that the energy dissipation capacity of joints is affected by this factor [23, 24]. As per the guide lines provided in the ACI codes [19, 25], where the longitudinal beam reinforcement extends through a beam column joint, the column dimension parallel to the beam reinforcement shall not be less than 20 times the diameter of the largest longitudinal beam bar for normal weight concrete. It has been reported that the straight beam bars may slip within the beam column joint during a series of large moment reversals. To reduce the slip substantially during plastic hinge formation, the limit of 1/20 of the column depth in the direction of loading for the maximum size of beam bars were chosen. For light weight concrete the limit was chosen to be 1/26 [19, 23, 26-28].

### *D. Bond Deterioration of beam bars*

During moment reversals, the beam bars may be subjected to high bond stresses. The force in the bars changes continuously from tension to compression during seismic loading. This puts great demand on the bond strength of the beam bars. Kitayama (1987) [29] has proposed the 'bond index' to indicate the bond deterioration along the beam bars. The feasibility of bond degradation may be expressed by the bond index as :

$$B_i = \frac{f_y d_b}{2h_c\sqrt{f_c^{'}}} \quad (7)$$

Where $f_y$ is the yield strength of the beam bars, $d_b$ is the diameter of the beam bars, $h_c$ is the column depth and $f_c^{'}$ is the concrete compressive strength. The value of bond index increases with higher strength and larger diameter of beam bars, smaller column width and reduction in concrete compressive strength. The bond deterioration is more likely to occur for higher values of bond index [22, 28-34].

*E. Column Axial Strength*

Research studies on the effect of column axial load in the general behavior of joints have produced contradictory results. Some studies have shown that, while increase of axial load is favourable to energy dissipation capacity of joints with small shear, this results unfavourable effect such as crushing of concrete in the joints with high shear [35, 36]. In some other studies, column axial load was reported to be one of the most influential factors on bond performance of joints [20, 32]. The column axial load was reported to influence the internal force flow in joint panel significantly [15, 20].

*F. Concrete Compressive Strength*

Usually the moment resisting frames are constructed with high strength concrete so as to withstand the large cyclic deformations without any significant loss of strength or stiffness. According to the recommendations in the current ACI codes [19, 25] the shear strength of the joint is evaluated as the sum of concrete shear strength and the contribution of steel obtained using the truss analogy. The nominal joint shear force is estimated to be $1.7\sqrt{f_c^{'}}A_j$ if the joint is confined by beams on all four sides, $1.25\sqrt{f_c^{'}}A_j$ if the joint is confined by beams on three faces or on two opposite faces, and $1.0\sqrt{f_c^{'}}A_j$ for other cases. $A_j$ is the effective cross sectional area within a joint computed from joint depth times effective joint width and $f_c^{'}$ represents the cylinder compressive strength of concrete in MPa.

A number of studies have underlined the importance of concrete compressive strength in promoting the strength and stiffness of joints [31]. Durrani (1982) [28] reported that higher strength of concrete helps to reduce the stiffness degradation of joints under lateral loading. The compressive stress strain behavior of concrete can be related to the strength of the beam column sub assemblage through principal stresses and strains [37]. As per the studies conducted by Kim (2008) [38] and Murakami (2000) [39], the concrete compressive strength was the most important parameter in determining the reinforced concrete joint shear strength [15, 34, 40, 41].

*G. Flexural Strength Ratio*

If the columns are not stronger than the beams framing into the joint, there is likelihood of inelastic action. Ultimately, flexural yielding can occur at both ends of all columns in a given storey, resulting in a column failure mechanism that can lead to collapse. The limit for flexural strength ratio of columns to beams is specified in ACI code [19] as

$$\frac{\sum M_{nc}}{\sum M_{nb}} \geq 6/5 \quad (8)$$

Where $\sum M_{nc}$ is the sum of the nominal flexural strengths of columns framing into the joint, evaluated at the faces of the joint and $\sum M_{nb}$ is the sum of nominal flexural strengths of beams framing into the joint, evaluated at the faces of the joint. The flexural strengths should be summed such that the column moments oppose the beam moments. Column flexural strengths should be calculated for the factored axial force, consistent with the direction of the lateral forces considered, resulting in the lowest flexural strength [19]. If this condition is not satisfied at a joint, lateral strength and stiffness of columns framing into that joint should be ignored when determining the calculated strength and stiffness of the structure.

The research undertaken by Durrani (1982) [28] have stressed the need to maintain this ratio as 1.5 in order to promote the beam hinging mechanism and thus aiding the strong column weak beam design approach. The research works of Shiohara (2009, 2010)) [7, 8] proved that the extent of insufficiency in the story shear is larger if the flexural strength of the column is equal to or nearer to the flexural strength of beam, and if the depth of the column is larger than that of the beam.

*H. Presence of Transverse beams or slabs*

Cyclic loading tests of joints with transverse beams or slabs have indicated that transverse beams and slabs provide effective confinement to the joint faces and thus delaying joint strength deterioration at large deformations. The ACI code [19] stipulates that where members frame into all four sides of the joint and where each member width is at least three-fourths the column width, the amount of reinforcement specified in the joint shall be permitted to be reduced by half and the spacing required shall be permitted to be increased to 6 in. Previous research reported that the joint shear stress level is found to be more critical for specimens without transverse beams. The increase in the amount of joint reinforcement was observed to be more effective in improving the behavior of specimens with transverse beams and slab [28]. From the results of previous studies, the one conclusion that has the greatest impact from a designer's point of view is that, the transverse beams are effective in preventing joint shear failure in the case of interior joints [12, 15, 21, 31, 41].

*I. Presence of Eccentric beams*

Eccentricity of beams framing into the joint has detrimental effect on joint strength and stiffness. It is a fact that the heavy eccentricity between columns and beams cause torsional moments in columns and joint and hence leads to severe damage. It has been generally observed that joints with one sided eccentric beams suffer larger torsional moment and it reduce the effective joint width. Joh et al. (1991) [22] reported in his study on joints with eccentric beams that one of the main causes of destruction of buildings was the effect of torsional moment on the column due to the eccentricity between beams and columns. This study pointed out that the eccentric joint frames with slabs are acted by the same torsional moment diagram as those with no slab.

Previous research has shown that the eccentricity in beams led to decrease in story shear by considerable amount. Eccentricity of beams was cited as the main reason for causing severe concrete damage in the joint on the side to which the centre line of the beam shifted to. It has been observed that eccentric beams cause large strain in the joint hoops on the side perpendicular to the direction of applied load [42]. Joints with eccentric beams but without slabs may cause larger deflection to out of plane direction which causes severe concrete damage in joint than that with slabs [9, 43-46].

### J. *Area of Longitudinal reinforcement*

The gross sectional area of reinforcement is observed to have an effect on joint shear capacity during seismic loading. A few studies have reported that as the amount of tensile reinforcement increases, the observed joint shear capacity also increases to some extent [7, 31].

## VI. NON CONVENTIONAL REINFORCEMENT DETAILING

In order to promote the strong column weak beam behavior and thus to have a preferable ductile failure under earthquake, most of the internationally accepted building codes have provided guidelines regarding the detailing of reinforcement in the structural components. ACI codes [19, 25] have provisions for the diameter, spacing and amount of the longitudinal as well as the transverse reinforcements. Special confining reinforcement are provided in columns and beams or wherever applicable with the purpose of developing beam hinging mechanism under seismic loading. Despite these provisions, non ductile failures have been observed in many cases of joint failure. Hence investigators all over the world have been trying to revise the detailing pattern suggested in the codes with modifications considering different aspects of the joint behaviour.

In the study conducted by Zaid et al. (1999) [47], the beam column joints were designed such that they would fail in joint shear failure mode by increasing the amount of beam bars passing through the joint. This resulted in improved lateral story shear resistance than that of the joints with conventional detailing pattern. A number of researches were conducted to assess the validity of current anchorage provisions in the ACI codes. The results indicated that current design recommendations are adequate for moderate earthquakes, but would probably lead to significant strength and stiffness losses under a major earthquake. A value of 24 times the bar diameter has been suggested as the ideal anchorage value for interior beam column joints with respect to bar slippage and anchorage [23, 24, 48].

Research studies on joints with parameters like amount of longitudinal reinforcement, column to beam flexural strength ratio and column to beam depth ratio unlike those with conventional pattern have reported improved shear behaviour and better energy absorption capacity for joints [8, 49, 50]. The experimental research has proved that providing additional diagonal bars in the beam or column through the joint resulted in promoting the joint stiffness [52-58].

The strength of conventionally detailed joints with prestressed concrete was compared with that of nonprestressed concrete joints in some studies. Most of the studies revealed no significant difference in the maximum story shear force between the prestressed and nonprestressed concrete units. It is generally assumed that the prestressing force does not play a major role on the ultimate shear strength of joints. [59-62].

The common factor in almost all the research studies is the aim to improve the joint shear strength of concrete so as to avoid a brittle failure. With this in mind, several behavioral models have been proposed to represent the joint shear behaviour [18, 63-75]. One of the notable concepts among these studies is the 'quadruple flexural resistance', proposed by Shiohara (2004) [17]. Joint shear failure of beam column joints is redefined as the failure of quadruple flexural resistance. The resistance of the joints to the moments coming from the members framing into the joint is portrayed with four pairs of resultants on diagonal sections. Failure criteria of concrete, steel, bond and anchorages are combined with the equilibrium conditions to predict the strength and failure type of beam column joints.

## VII. SUMMARY

A brief outline of the behaviour of RCC interior beam column joints under seismic lateral loading has been presented. The design approach commonly employed for designing multi storied building frames generally focuses on beam hinging mechanism and the concept was discussed in detail. Since the focus of most of the research studies was concentrated on changing the failure mode from brittle failure mode to ductile failure mode, various failure mechanisms and their characteristics were explained. Joint shear demand is considered to be the most critical parameter which controls the strength and stiffness of the joint. Various shear transfer mechanisms like strut and truss mechanisms and the equations to arrive at the joint shear forces were discussed with importance being given to the computation of joint horizontal shear force. Even though numerous research works have been conducted so far, a consensus on the effect of certain design parameters on deciding the failure mechanisms, energy absorption capacity, strength etc has not been reached. A very little effort has been placed on quantifying the effect of the design parameters on joint behaviour. The design variables and their effects on joint strength and stiffness were discussed by citing prominent studies in the field with emphasis on variables like aspect ratio, anchorage length, bond deterioration of beam bars, flexural strength ratio, transverse reinforcement, column axial load, concrete compressive strength, eccentricity of beams etc. Several research works were conducted to identify the flaws in the conventional design and detailing of reinforcement specified in the building codes. Some of the important studies with non conventional detailing pattern and their outcomes, promoting joint strength and stiffness, have been explained. A new concept of quadruple flexural resistance for defining the moment resistance of joints was discussed to provide insights into the happenings in the area of research.

## VIII.CONCLUDING REMARKS

Prominent studies by the investigators in the research area of behaviour of RCC interior joints under seismic lateral loading have been thoroughly surveyed. Based on these, several important conclusions have been drawn so as to provide clear insights into the joint strength and stiffness behaviour. This has been resulted in providing an effective foundation for further research.

- The preferable ductile mode of failure is the outcome of the collective role played by significant design variables like joint shear stress demand, bond deterioration, amount of transverse reinforcement and the relatively less significant aspect ratio.
- Joints failed in shear exhibited larger values of bond index and shear stress and smaller amount of transverse reinforcement.
- In joints failed in beam yielding, there is a favourable combination of low bond index, a great reduction in joint shear stress demand and higher amount of joint transverse reinforcement.
- Joint shear strength and stiffness are greatly influenced by the significant factors like concrete compressive strength, presence of transverse beams and slabs, transverse reinforcement, beam reinforcement and presence of eccentric beams.
- In many of the investigations, the observations are drawn from a limited number of test specimens. This considerably affected the judgments.
- Research studies with similar and comparable results involved greater number of test specimens than with those conducted on a few number of test specimens.
- The present study finds it appropriate and relevant to suggest a new methodology like statistical modelling to represent the joint strength and stiffness behaviour and the failure modes. By using probabilistic approach, a large test data base can be effectively utilized to capture the joint behaviour and to identify and quantify the significant design variables in deciding the shear strength and energy absorption capacity.

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