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Seismic Behavior of Beam Column Joints in Reinforced Concrete Moment Resisting Frames

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SEISMIC BEHAVIOUR OF BEAM COLUMN JOINTS IN REINFORCED CONCRETE MOMENT RESISTING FRAMES - A REVIEW

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Abstract

The beam column joint is the crucial zone in a reinforced concrete moment resisting frame. It is subjected to large forces during severe ground shaking and its behaviour has a significant influence on the response of the structure. The assumption of joint being rigid fails to consider the effects of high shear forces developed within the joint. The shear failure is always brittle in nature which is not an acceptable structural performance especially in seismic conditions. This paper presents a review of the postulated theories associated with the behaviour of joints. Understanding the joint behaviour is essential in exercising proper judgments in the design of joints. The paper discusses about the seismic actions on various types of joints and highlights the critical parameters that affect joint performance with special reference to bond and shear transfer.

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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.

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 overstrength 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.

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.

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[1]. In a moment resisting frame, three types of joints can be identified viz.interior joint, exterior joint and corner joint (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. The objective of the paper is to review and discuss the well postulated theories for seismic behaviour of joints in reinforced concrete moment resisting frames.

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 discussed with reference to stresses and the associated crack patterns developed in them [2]. The forces on an interior joint subjected to gravity loading can be depicted as shown in Fig.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. 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.

The forces acting on an exterior joint can be idealized as shown in Fig. 3. The shear 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. 3(b) and Fig. 3(c). The bars bent away from the joint core (Fig.3(b)) 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.

The forces in a corner joint with a continuous column above the joint (Fig. 1 c) 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.

Opening corner joints tend to develop nascent cracks at the reentrant corner and failure is marked by the formation of a diagonal tensile crack.[3].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 [4]. The design and detailing schemes of these joints is beyond the scope of this paper and relevant information can be obtained elsewhere[5,6]. 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. Large deformations of joints result in significant increase in the storey displacement [7].

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.

JOINT MECHANISMS

In the strong column-weak beam design, beams are expected to form plastic hinges at their ends and develop flexural overstrength 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 [8]. The bond performance of the bars anchored in a joint affects the shear resisting mechanism to a significant extent.

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.

Interior Joint

In an interior joint, the force in a bar passing continuously through the joint changes from compression to tension. This causes a push-pull effect which imposes severe demand on bond strength and necessitates adequate development length within the joint. The development length has to satisfy the requirements for compression and for tension forces in the same bar. The distribution of bond along the longitudinal bars is shown in Fig 5. Insufficient development length and the spread of splitting cracks into the joint core may result in slippage of bars in the joint.

Slippage of bar occurs when the limiting bond stress is exceeded within the available development length. In the case of interior joints, the column depth is the available development length for the straight longitudinal bars passing through the joint. Hence, for a given limiting bond stress, the ratio of development length to the bar diameter becomes a constant value. Research has shown that when the development length is greater than 28 bar diameters little or no bond degradation was observed with respect to various shear stress levels in the joint [7]. In other words, to avoid bond deterioration, the column depth should be around 28 times the diameter of the bar. This observation suggests the adoption of relatively smaller bar diameters so as to obtain with smaller depth of columns. For example, if 20 mm nominal bar size is to be used, the member depth to be provided is 560 mm.

Exterior Joint

In exterior joints the beam longitudinal reinforcement that frames into the column terminates within the joint core. After a few cycles of inelastic loading, the bond deterioration initiated at the column face due to yield penetration and splitting cracks, progresses towards the joint core. Repeated loading will aggravate the situation and a complete loss of bond up to the beginning of the bent portion of the bar may take place. The longitudinal reinforcement bar, if terminating straight, will get pulled out due to progressive loss of bond. The pull out failure of the longitudinal bars of the beam results in complete loss of flexural strength. This kind of failure is unacceptable at any stage. Hence, proper anchorage of the beam longitudinal reinforcement bars in the joint core is of utmost importance.

The pull out failure of bars in exterior joints can be prevented by the provision of hooks or by some positive anchorage [9]. Hooks, as shown in Fig. 6 are helpful in providing adequate anchorage when furnished with sufficient horizontal development length and a tail extension. Because of the likelihood of yield penetration into the joint core, the development length is to be considered effective from the critical section beyond the zone of yield penetration. Thus, the size of the member should accommodate the development length considering the possibility of yield penetration.

When the reinforcement is subjected to compression, the tail end of hooks is not generally helpful to cater to the requirements of development length in compression[10]. However, the horizontal ties in the form of transverse reinforcement in the joint provide effective restraints against the hook when the beam bar is in compression [11].

Corner Joint

In a corner joint with column continuing above and in knee type joints, the bond requirements of longitudinal bars of beams will be similar to that in an exterior joint though there are no specific code requirements related to bond for knee joints. However, the performance of these joints is significantly influenced by shear diagonal cracks.

The bond deterioration along the beam reinforcement results in the following undesirable consequences:

1. Beam deformation is increased prior to beam flexural yielding.
2. Large beam end rotation associated with large crack opening accelerates concrete crushing at the face of the joint.
3. Repair of bond deterioration is difficult.

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 [12]. 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 [13]. 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.

Shear requirements of joint

The external forces acting on the face of the joint develop high shear stresses within the joint. The shear stresses give rise to diagonal stresses causing diagonal cracks when tensile stresses exceed the tensile strength of concrete. Extensive cracking occur within the joint under load reversals, affecting its strength and stiffness and hence the joint becomes flexible enough to undergo substantial shear deformation (distortion). Before discussing the shear beahviour in detail, it is imperative to arrive at the shear force demand on joints. The determination of shear force in the vertical and horizontal direction is usually essential. However, since well established code procedures aim at the beam hinging mechanism, it is generally sufficient to discuss the shear force demand in the horizontal direction only.

Shear force in an interior joint

Consider the interior beam-column joint subassemblage extending between the points of contraflexure, as shown in Fig. 7(a). The shear force acting on the joint can be computed using equilibrium criteria. The center-to -center height of the columns is l_c and the center-to-center span of the beams is l_b. Figure 7(b) shows the forces from the beam acting on the face of the joint. The bending moment and shear force distribution for the column is shown in Fig. 7(c) and Fig.7(d) respectively. For a perusal of Fig.7(c) it is clear that the nature of the moment above and below the joint changes and shows a steep gradient within the joint region thus causing large shear forces in the joint compared to that in the column. The horizontal shear force across the joint can be obtained based on equilibrium criteria.

Let a sagging moment, M_s and a hogging moment M_h act on opposite faces of the joint from the framing beams. Assuming the beams to be symmetrically reinforced, tensile force T_b and a compressive force C_b is developed in the beam reinforcement. The vertical beam shear on the face of the joint is V_b . Assuming $C_b = T_b$, the column shear, V_{col}, from the above forces is calculated from equilibrium criteria as

$$V_{col} = \frac{2T_b\, z_b + V_b\, h_c}{l_c} \tag{1}$$

where l_c is the storey height as illustrated in the Fig. 7(a). In the above equation, h_c is column depth and z_b is the lever arm. Considering the moment gradient within the joint core, the horizontal shear force, V_{jh} can be written as

$$V_{jh} = V_{col}\left(\frac{l_c}{z_b} - 1\right) - V_b\left(\frac{h_c}{z_b}\right) \tag{2}$$

Shear force in an Exterior Joint

Figure 8 shows the features of an exterior beam column joint where one beam frames into the column. Based on equilibrium principles, the column shear and the horizontal shear force in the joint can be calculated as follows.

The column shear force is

$$V_{col} = \frac{T_b\, z_b + V_b\, \frac{h_c}{2}}{l_c} \tag{3}$$

and the horizontal shear across the joint can be expressed as

$$V_{jh} = V_{col}\left(\frac{l_c}{z_b} - 1\right) - V_b\left(\frac{h_c}{2z_b}\right) \tag{4}$$

Shear force in a corner Joint

In the case of a corner joint, where the column is discontinuous, the shear force in the joint can be arrived at on the basis of the same principles as described above. (Fig. 9)

The column shear V_{col} is given as

$$V_{col} = \frac{T_b\, z_b + V_b \left(\frac{h_c}{2}\right)}{\frac{l_c}{2}} \tag{5}$$

and the horizontal shear force in the joint is

$$V_{jh} = \frac{V_{col}}{2}\left(\frac{l_c}{z_b} - 1\right) - V_b \left(\frac{h_c}{2z_b}\right) \tag{6}$$

It is to be noted that, if the hinging of the beams on both sides is considered, the column shear is to be calculated taking into account the enhanced flexural strength due to the presence of the slab. When the beam and slab are monolithic, the participation of the slab reinforcement is significant towards the negative flexural strength of the beam. The beam flexural overstrength has to be obtained by considering it as a T-beam or L-beam with appropriate flange width.

ENGINEERING DESIGN APPROACH FOR CALCULATION OF SHEAR

The above equations (1-6) are rigorous and involve the vertical shear force developed by the beam end moments. It can be seen from these equations that a larger column width, h_c, and higher vertical beam shear V_b, reduce the shear force in the joint. However, for engineering designs, a simpler approach is usually followed to arrive at a good estimate of the joint shear force assumed to act on a horizontal plane passing through the joint. Fig.10 is a schematic representation of joint shear equilibrium in interior, exterior and corner joints.

In an interior joint, the column shear, V_{col} can be expressed as

$$V_{col} = \frac{M_s + M_h}{l_c} \tag{7}$$

The corresponding equation is given as

$$V_{jh} = C + T - V_{col} \tag{8}$$

In an exterior Joint, the column shear, V_{col}

$$V_{col} = \frac{M_h}{l_c} \tag{9}$$

and the corresponding joint shear is

$$V_{jh} = T - V_{col} \tag{10}$$

On the same principles, the shear force in corner joint is equal to the tensile force in the top beam bar as

$$V_{jh} = T \tag{11}$$

Equations 7 through 11 give higher values of joint shear forces than those given by equations 1 through 6.

Joint shear area

The relative severity of joint shear forces may be conveniently expressed in terms of shear stresses. The cross sectional area over which the shear forces can be transferred can not be defined uniquely. Since the joint is the zone of intersection of beams and columns, the shear area of the joint is to be specified based on the dimensions of the beams and columns. The effective shear area A_j is defined by the width of the joint, b_j, and the depth of the joint h_j. The area effective in resisting joint shear may not be as large as the column's entire cross section area since the width of the beam, b_w and the column, b_c may differ from each other. The codes [1, 10] recommend effective joint shear area based largely on engineering approximations. Typical effective joint widths are illustrated in Fig. 11. The depth of the joint h_j is taken as the depth of the column, h_c.

SHEAR RESISTING MECHANISM

In general, the joint region is idealized as a two dimensional plane subjected to internal forces from the beam and the column acting on the joint face, as shown in Fig.12. The forces primarily consist of compressive, tensile and shear forces. The shear forces in the joint region develop diagonal compressive and tensile forces within the joint core, resulting in the formation of a diagonal failure plane. The essential components of the shear resisting mechanism are discussed with respect to an interior joint.

The shear resisting mechanism consists of a diagonal concrete strut action and a truss action as shown in Fig.13. The diagonal concrete strut mechanism is formed by the major diagonal concrete compression force in the joint. This force is produced by the vertical and horizontal compression stresses and the shear stresses on concrete at the beam and column critical sections. The truss mechanism is formed by a combination of the bond stress transfer along the beam and column longitudinal reinforcement, the tensile resistance of lateral reinforcement and compressive resistance of uniform diagonal concrete struts in the joint panel. The strength of the strut mechanism depends on the compressive strength of concrete and that of the truss mechanism on the tensile yield strength of the lateral reinforcement crossing the failure plane.

In resisting the joint shear, the diagonal strut mechanism can exist without any bond stress transfer along the beam and column reinforcement within the joint, while the truss mechanism can develop only when a good bond transfer is maintained along the beam and column reinforcement. Under seismic loading conditions, the bond along the beam reinforcement inevitably deteriorates especially after beam flexural yielding takes place unless the strength and size of the reinforcement is strictly restricted. With the outset of bond deterioration, the truss mechanism starts to diminish and the diagonal strut mechanism must resist the most dominant part of the joint shear. Under these conditions, the tension force in the beam reinforcement not transferred to the joint concrete by bond must be resisted by the concrete at the compression face of the joint, thus increasing the compression stress in the main strut. The concrete strut is progressively weakened by the reversed cyclic loading. At the same time, the compressive strength of the concrete is reduced by the increasing tensile strain perpendicular to the direction of main strut. The combination of these two phenomenon results in the failure of the concrete strut in shear compression. The principal role of the lateral reinforcement in this case is to confine the cracked core concrete.

JOINT SHEAR STRENGTH

The joint shear strength is affected by the parameters influencing the two principal shear resisting mechanisms. The total strength contributed by each mechanism can be considered as the shear strength of the joint in the horizontal direction and is given as

$$V_{jh} = V_{ch} + V_{sh} \tag{12}$$

in which V_{ch} is the contribution from the concrete strut and V_{sh} is the contribution from the truss mechanism.

The contribution of each mechanism is affected significantly by the prevailing bond conditions as discussed in the previous sections and also by the contributions from the slab [16].

Effect of slab contribution to joint strength

The slab contribution to flexural resistance of the longitudinal beam results in increased joint shear. The increased joint shear is applied directly along the compression zone of the longitudinal beams and is resisted within the joint by the inclined compression strut. Hence, additional joint shear reinforcement may not be necessary. However, the increased force along the strut may cause compression failure in the strut. Therefore, it is necessary to account for the enhancement of beam strength due to contribution from the slab when considering joint design.

In exterior joints, the increased tensile force due to the slab is introduced into the joint through shear, weak axis bending and twisting of transverse beams[14]. So, it is necessary to provide for additional shear reinforcement.

Contribution from strut and truss mechanism

The shear force in the joint is considered to be resisted by two principal mechanisms viz. the strut and the truss mechanisms. In the previous section, the role of the strut and the truss mechanism in resisting joint shear with respect to prevailing bond conditions has been discussed. To recapitulate a few points, the truss mechanism is supported by good bond transfer and well distributed vertical and horizontal reinforcement in the joint core. This mechanism tends to diminish in case of bond deterioration and the lateral reinforcements can no longer be utilised for taking up joint shear. The compressive strength of the diagonal concrete strut is the reliable source for resisting joint shear. The strength of the diagonal concrete strut in turn is affected by the tensile strain (or tensile stresses) in the core concrete. At this stage, the lateral reinforcement provides confinement to improve the efficiency of the concrete in the strut mechanism.

Based on the above observations, formulations have been suggested for the design of joints for shear. The recommendations focus on the following two major aspects:

1. Determination of the nominal shear stress in terms of a function of the compressive stress of core concrete f_c', or in terms of the tensile stress of core concrete expressed as function of $\sqrt{f_c'}$.
2. Provision of lateral reinforcement with specifications for the spacing and the area of the ties for confinement effect and to support the truss mechanism.

Even though codes seem to differ as far as their explicit recommendations are concerned, they broadly follow the above principles. The improved approaches towards the assignment of the total shear force to the two resisting mechanisms reported in literature [10,11] are described here. The purpose of discussing the mathematical formulation is to essentially appreciate various factors and their participation in the shear resisting mechanism.

The internal forces developed in the strut and truss mechanisms are illustrated in Fig13. It is assumed that plastic hinges are formed at both ends of the beams across the joint and both the top and bottom bars yield developing overstrength at strain hardening. As discussed earlier, the contribution from the slab towards the flexural strength of beam is accounted by considering the area of the top bars, A_{s1} as the total area of reinforcements from the effective slab width, A_{sf} and that within the joint width, A_s^*. Accordingly the tensile force T is the total force from the reinforcement within the effective joint width, T_b, and that from the slab reinforcement T_f. The tensile force from the slab is effectively transmitted to the strut in the form of diagonal compressive force, C_f. Apart from this, a fraction of the combined tension and compression forces from the top reinforcement anchored in the joint core (T_b and C_s') is transmitted by means of bond to concrete over the compression zone of the column and is referred to as B_s'. From the variables illustrated in Fig. 12 the horizontal shear can be written as

$$V_{jh} = (T - T_f) + C_f + C_c' + C_s' - V_{col} \tag{13}$$

The shear strength provided by the truss mechanism, V_{sh} can be written as

$$V_{sh} = V_{jh} - V_{ch} \tag{14}$$

$$\begin{aligned} &= (T - T_f) + C_f + C_c' + C_s' - V_{col} - (C_f + C_c' + B_s' - V_{col}) \\ &= T_b + C_s' - B_s' \end{aligned} \tag{15}$$

$$T_b = T - T_f = 1.25\, f_y\, (A_{s1} - A_{sf}) = 1.25 f_y A_s^* \tag{16}$$

$$C_s' = \gamma\, f_y\, A_s^* \tag{17}$$

where C_s' is the compression force developed in the top beam bars in which γ is the factor used to express the stress level in the bars in terms of yield stress.

After some bond deterioration, the compressive stress in the top beam reinforcement is not likely to exceed the stress level of $0.7f_y$ [15]. At the same time, this stress can not exceed $1.25\beta\, f_y$, where β is the ratio of bottom reinforcement to top reinforcement in the rectangular beam and is expressed as A_{s2} / A_s^* with $1.25\beta \geq \gamma \leq 0.7$. The value of γ may be less than 0.7 when the bottom reinforcement is about 50% of the top reinforcement or when the bottom beam reinforcement can not yield at column face. Then C_s' can be obtained from the actual stress, f_{s2} in the bottom reinforcement.

The total bond force that is transmitted to the joint core is

$$T_b + C_s' = \left(1 + \frac{\gamma}{1.25}\right) T_b \tag{18}$$

and $$B_s' = \frac{c}{h_c}\left(T_b + C_s'\right) = 1.56 \frac{c}{h_c} T_b \tag{19}$$

where c is the depth of the compression stress block in the column or is the neutral axis depth of the column.

Substituting the above values along with the approximate expressions for c in

$$V_{sh} = T_b + C_s' - B_s' \tag{20}$$

and for the maximum tension force in the top beam reinforcement, $T_b = 1.25\, f_y\, A_s^*$ we get,

$$V_{sh} = \left(1.4 - 1.6 \frac{N^*}{f_c' A_g}\right) f_y A_s^* \qquad (21)$$

where N^* is the minimum axial load at the ultimate limit state consistent with capacity design principles.

When the bottom reinforcement, A_{s2}, is developing overstrength at 1.25 f_y and is larger than the top beam reinforcement anchored in the joint core A_s^*, the force T' will control the design rather than T_b. Then in the above equation A_s^* should be replaced by A_{s2}.

The above illustration has highlighted the importance of various factors such as slab contribution on the enhancement of beam flexural strength, ratio of compression to tension reinforcement in beams, bond transfer and axial load on the column in contributing towards strut and truss mechanism.

At an exterior joint only one beam frames into a column and hence the joint shear will be generally less than that encountered in an interior joint. The shear transfer mechanism within the joint core will be similar to that postulated for interior joints and will comprise of a concrete strut and a truss sustaining the diagonal compression field. The diagonal strut will be developed between the bend of the hooked top tension bar and the diagonally opposite corner of the joint where compression forces in both the vertical and horizontal directions are introduced. If adequate anchorage of the beam flexural tension reinforcement in the form of a standard hook is provided, the contribution from strut mechanism will be taken care of. The truss mechanism shall be sustained by the longitudinal bars and the confining stirrups. The amount of stirrups needed for this may be obtained by considering the total tensile force contributed by the steel reinforcement, A_{s1}, including the effective flange width[11].

DESIGN OF SHEAR REINFORCEMENT

Presence of horizontal and vertical shear reinforcement within joint can develop truss mechanism in resisting shear. The design of shear reinforcement is governed by the minimum reinforcement area needed to support the truss mechanism and the maximum permissible area based on the limit stress corresponding to diagonal compression failure. As a minimum requirement, horizontal hoop reinforcement has to be designed for 40% of the total horizontal shear force [10].

At this point, even though the authors consider discussion of various code provisions is not in the scope of the paper, it is relevant and worth mentioning that certain design aspects do exhibit conflicts. For example, Eq.(14) as per NZS 3101:1995 gives the amount of horizontal shear reinforcement for interior joint for supporting the truss mechanism. However, other codes like ACI 352R-02 and IS 13920:1993 [16] suggest expressions for horizontal reinforcement based on confinement of core concrete requirement to maintain the axial load carrying capacity of the column.

IS 13920:1993 has been revised and draft recommendations with supporting design examples are available in open publications [17]. Nevertheless, the essence of detailing specifications has been discussed in this section.

After arriving at design horizontal shear, the vertical shear can be approximated when the columns do not form plastic hinges as:

$$V_{jv} = V_{jh}\left(h_b / h_c\right) \tag{22}$$

In general, intermediate column longitudinal bars are expected to contribute to vertical shear and if they amount to 1/3 of the total longitudinal column reinforcement, no additional vertical shear reinforcement is found to be necessary [10]. The bond force in the column bars extending into the joint core forms a part of the truss mechanism. Vertical transverse reinforcements are usually provided by the intermediate column bars. This necessitates every column to have at least one intermediate bar on each face of the column.

The required horizontal shear reinforcement to resist V_{sh} is to be provided in the form of closed stirrups, cross ties or overlapping hoops. The stirrups and ties are preferred to be bent with 135^o degree hooks having an extension of 6d, where d is the diameter of the stirrup. The arrangement of stirrups with regard to the orientation of the 90^o and 135^o hooks should be such that effective core confinement is available in the joint. The spacing requirement of horizontal stirrups is also governed by the buckling criteria of column bars passing through the joint. The lateral spacing of the stirrups is to be restricted so as to effectively transfer the bond force in the column bar into the joint core such that it forms a part of the truss mechanism.

On the research front, various detailing schemes have been tried so as to study the seismic performance of exterior joints [18]. The use of continuous beam bars bent in the form of a U placed horizontally and distributed through the depth of the beam provided a simple detail that worked effectively. However, the flexural strength of the beam was reported to have decreased in this case.

CONCLUSIONS

In Indian design practice, beam column joint has been given less attention than it actually deserves. Indian Code revisions are underway accounting for the recent research findings and suggestions by various international codes. In this scenario of fast developments, the paper contributes to the inexorable need for the design engineers to be aware of the fundamental theory of joint seismic behaviour.

In this paper, the general behaviour of common types of joints in reinforced concrete moment resisting frames has been discussed. The mechanisms involved in joint performance with respect to bond and shear transfer are critically reviewed and discussed in detail. The factors impacting the bond transfer within the joint appears to be well related to the level of axial load and the amount of transverse reinforcements in the joints. The parameters that affect the shear demand and shear strength of the joint are explained. The design of shear reinforcement within the joint and its detailing aspects are also discussed. A significant amount of ductility can be developed in a structure with well designed beam-column joints wherein the structural members could perform satisfactorily as per the capacity design principles.

Acknowledgement

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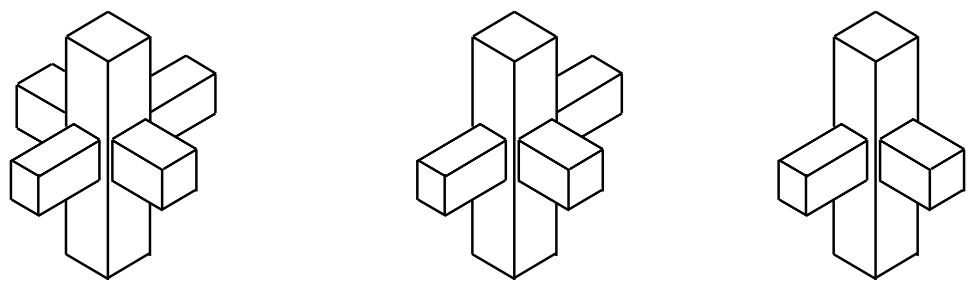
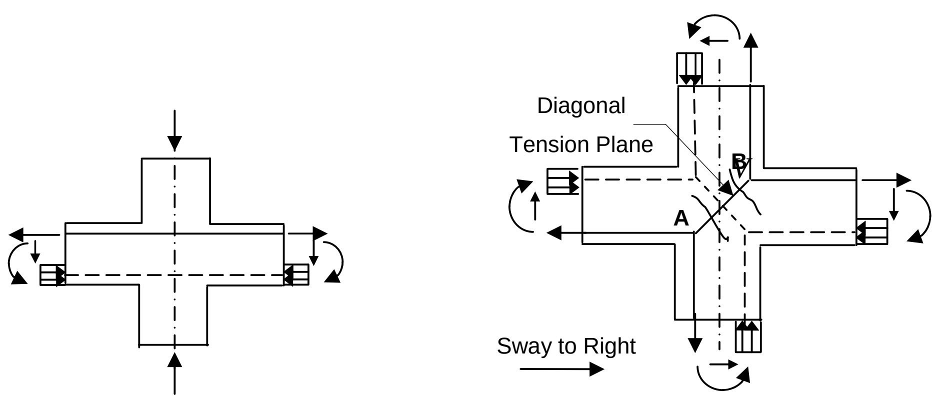
FIGURES



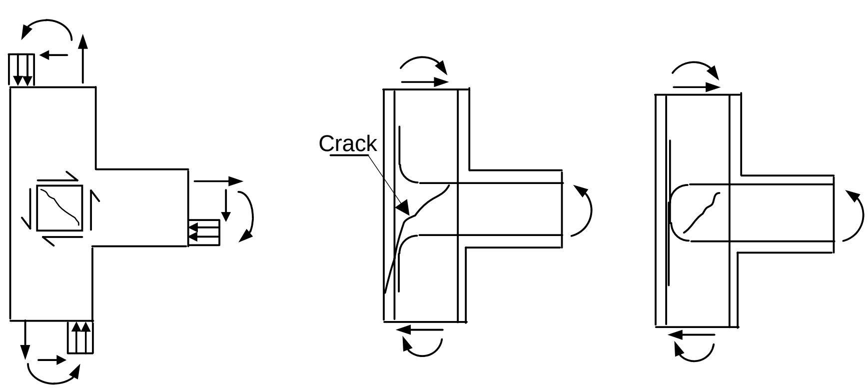
(a) Interior (b) Exterior (c) Corner

Fig.1 Types of Joints in a frame



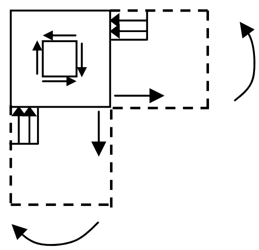
a. Gravity loading b. Seismic loading

Fig.2. Interior joint [2]

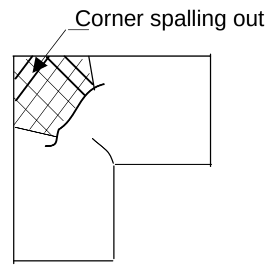


(a) Forces (b) Poor detail (c) Satisfactory detail

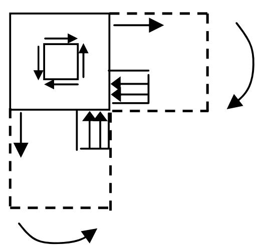
Fig. 3. Exterior Joint [2]



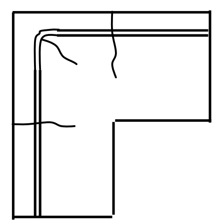
(a) Opening Joint (Top View)



(b) Cracks in an Opening Joint



(c) Closing Joint (Top View)



(d) Cracks in a Closing Joint

Fig. 4. Corner joints [2]

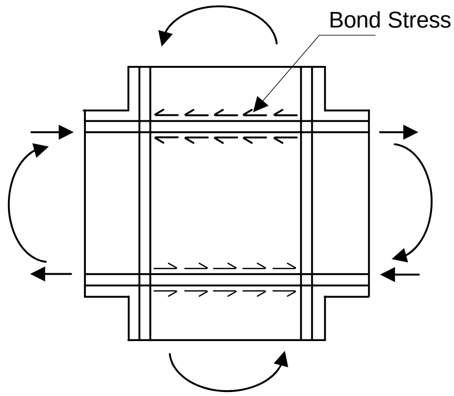


Fig.5 Bond stress in interior joint

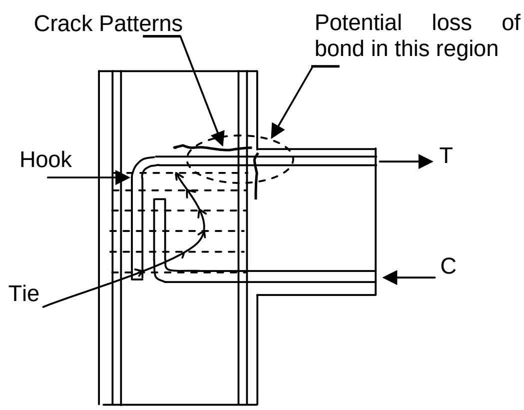
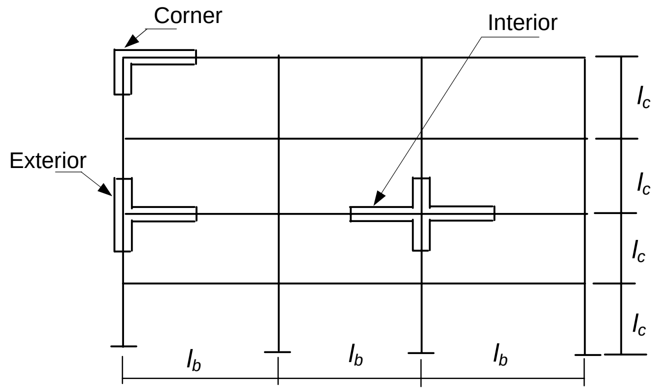
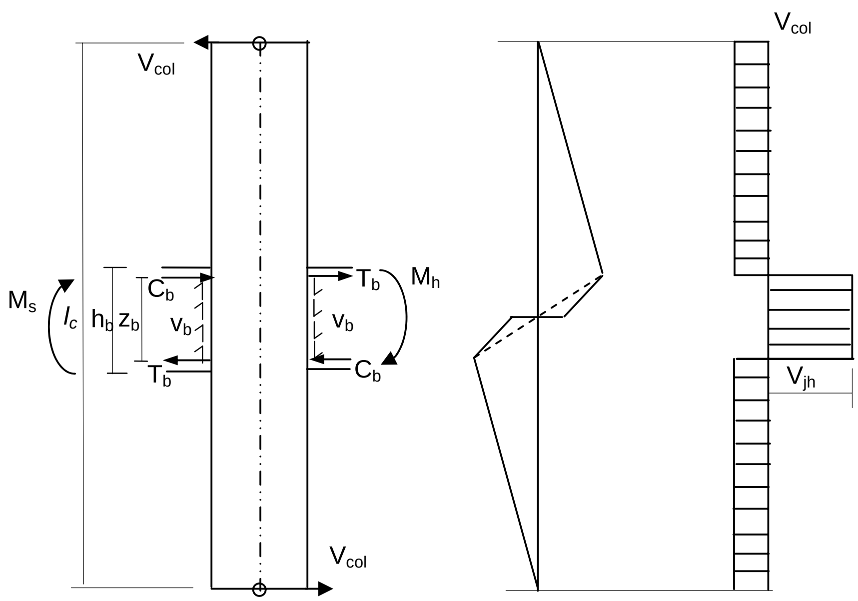


Fig. 6. Hook in an Exterior Joint

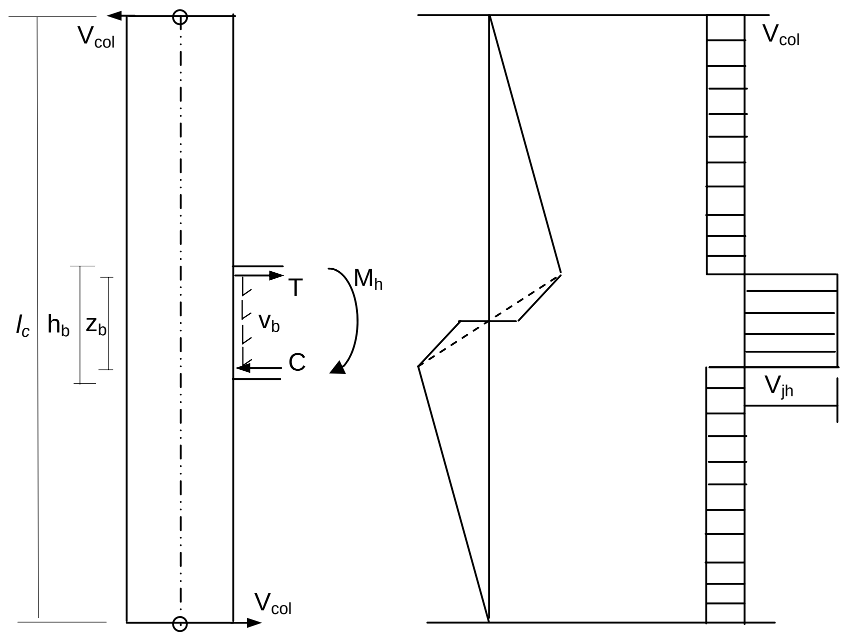


(a) Typical frame with beam column joint



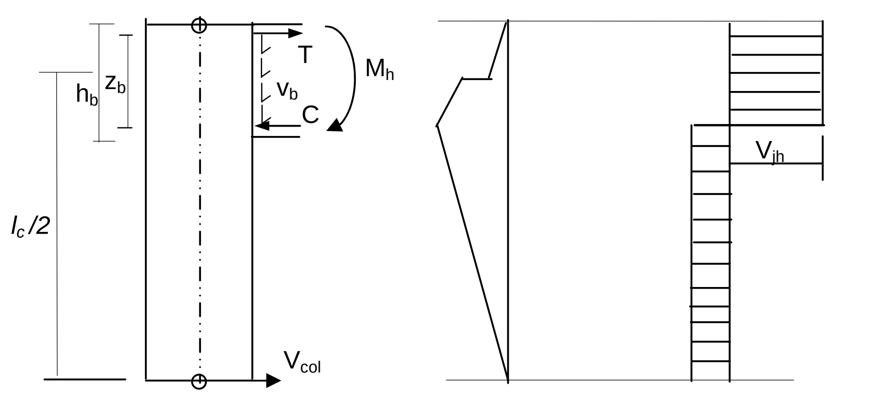
(b) Forces on the column (c) Bending moment (d) Shear force

Fig. 7. Horizontal Shear Force in an Interior Joint[11]



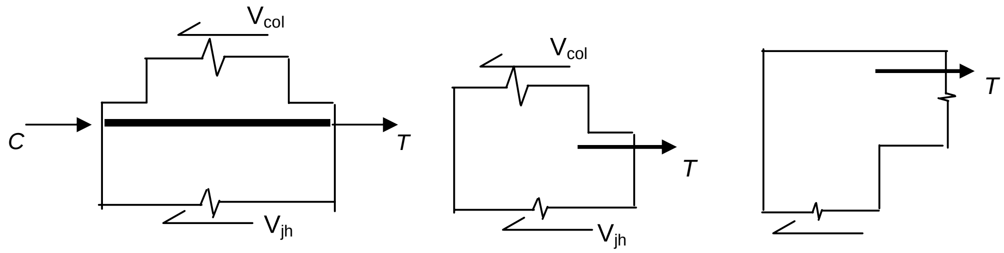
(a) Forces on the column (b) Bending moment (c) Shear force

Fig.8. Horizontal Shear in an Exterior Joint



(a) Forces on the column (b) Bending moment (c) Shear force

Fig.9. Horizontal Shear in Corner Joint



(a) Interior Joint (b) Exterior Joint (c) Corner Joint

Fig. 10. Joint Shear Equilibrium

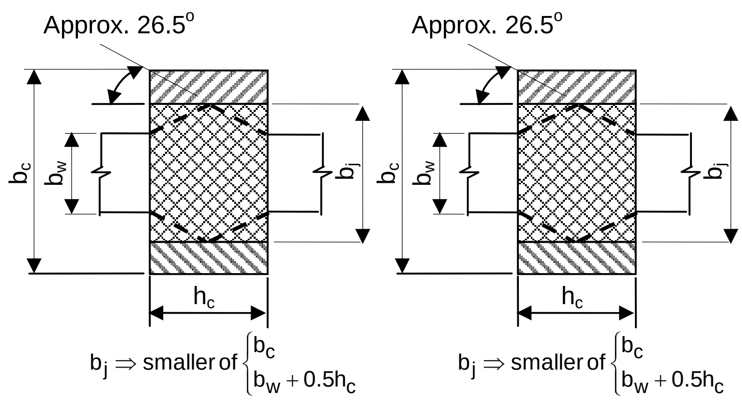
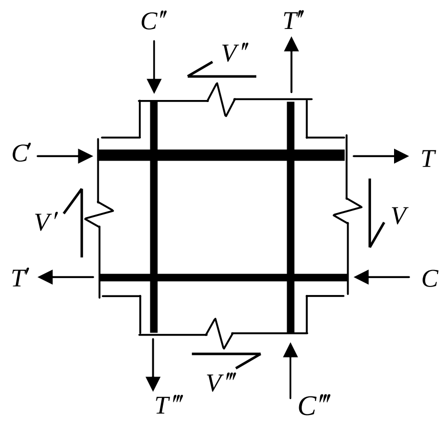
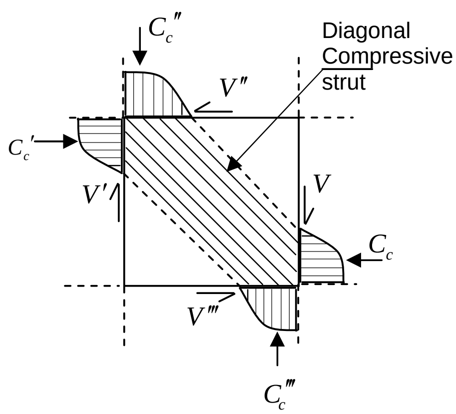


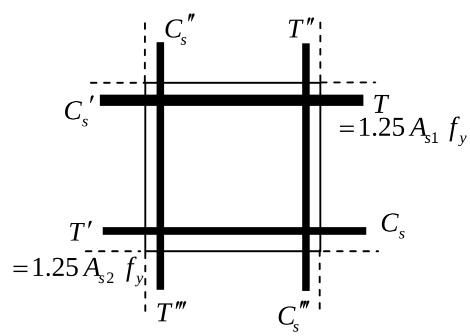
Fig. 11. Effective joint width, b_j [11]



(a) External actions on the joint

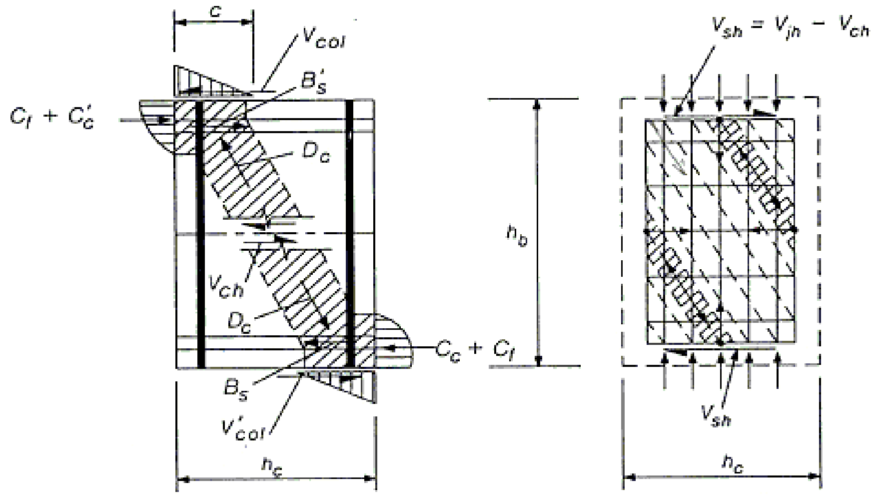


(b) Compression mechanism



(c) Forces in the reinforcements only

Fig.12. Idealised behaviour of an Interior Beam Column Joint



(a) Strut Mechanism

(b) Truss Mechanism

Fig.13. Shear resisting mechanisms [10]