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# A Review on Behavior of Reinforced Concrete Beam-Column Joint

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**Abstract**: In reinforced concrete framed structure the beam-column joint are critical regions and the joint take part in a very significant role both during the design and construction stages. There are practical difficulties involved in the construction of reinforced beam-column joints. In this review to focus on the general behaviour with specific structural properties of common types of joints in reinforced concrete moment resisting frames to be aware of the fundamental theory of the joint for better efficiency.

**Keywords**: Strength, Ductility, Stiffness, Reinforced Concrete, Anchorage, Exterior joint.

## I. INTRODUCTION

A beam-column joint is a very critical zone in reinforced concrete framed structure where the elements intersect in all three directions. Joints ensure continuity of a structure and transfer forces that are present at the ends of the members (Pradip Sarkar et. Al. 2007). In reinforced concrete structures, failure in a beam often occurs at the beam-column joint making the joint one of the most critical sections of the structure (Mohammad Shamim and Kumar, V, 1999). Sudden change in geometry and complexity of stress distribution at joint are the reasons for their critical behaviour. In early days, the design of joints in reinforced concrete structures was generally limited to satisfying anchorage requirements. In succeeding years, the behaviour of joints was found to be dependent on a number of factors related with their geometry; amount and detailing of reinforcement, concrete strength and loading pattern. The requirements Criteria for the desirable performance of joints can be summed up as: (Park. R & Paulay.T, 1975).

(i)The strength of the joint should not be less than the maximum demand corresponding to development of the structural plastic hinge mechanism for the frame. This will eliminate the need for repair in a relatively inaccessible region and for energy dissipation by joint mechanisms, which, as will be seen subsequently, undergo serious stiffness and strength degradation when subjected to cyclic actions in the inelastic range.

(ii) The capacity of the column should not be jeopardized by possible strength degradation within the joint. The joint should also be considered as an integral part of the column.

(iii)The joint reinforcement necessary to ensure satisfactory performance should not cause undue construction difficulties.

## II. 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 joints should have adequate strength and stiffness to resist the internal forces induced by the framing members.

### A. *Indian Standard Classification*

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 as shown in Fig1&2.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.

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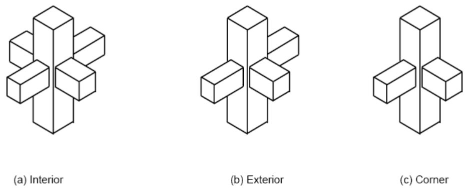


Fig 1: Types of joints in frame
*(Source: Joint ACI-ASCE Committee 352, 2002)*

B. *International classification*

ACI-ASCE Committee classifies the beam-column joint in two categories based on loading conditions and anticipated deformations:

(a) Type 1 joint – These are designed on the basis of strength without considering special ductility requirements.
(b) Type 2 joint – These joints are designed to have sustained strength under deformation reversals into inelastic range.

Any joint in structural frame designed to resist gravity and normal wind loads falls into Type 1 category. Joints in framed structures designed to resist lateral loads due to earthquake, blast and cyclonic winds fall into Type 2 category (ACI-ASCE Committee 352, 1985).

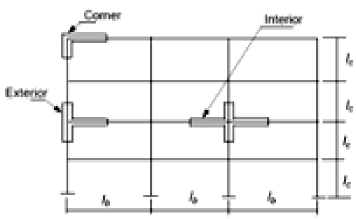


Fig 2: Typical frame with beam column joints

## III. EXTERIOR JOINT

In exterior joints, after a few cycles of inelastic loading, due to yield penetration and splitting cracks, the bond deterioration is initiated at the face of the column and progresses towards the joint core.

On repeated loading, the situation will aggravate and a complete loss of bond up to the beginning of the bent portion may take place. The longitudinal reinforcement bar will get pulled out if terminating straight, 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 on any condition. 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 beam column anchorage. Hooks 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 development length of the hook is not generally helpful to cater to compression. 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.

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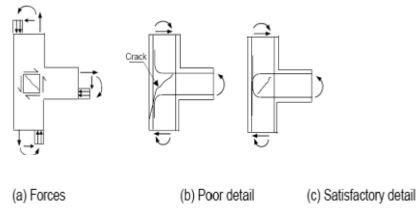


Fig 3: Exterior joint
*(Source: Uma & Mehar Prasad,2006 )*

A. *Failure mechanism of the joint*

In seismic design philosophy, the beam-column joint is designed based on strong column-weak beam criteria, the plastic hinges are expected to be formed on the beams near the face of the column 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 (Shiohara, H., 2001). The bond performance of the bars anchored in a joint affects the shear resisting mechanism to a significant extent.

B. *Bond strength requirements*

The moment from the adjoining members cause tension or compression forces in the longitudinal reinforcements passing through the joint. During plastic hinge formation, these forces produce large tensile forces that are transferred through bond. When longitudinal beam bars near the column face are stressed beyond yield stress, splitting cracks are initiated along the joint face which is referred to as 'yield penetration'. Longitudinal bar is to be provided with adequate development length at the joint, taking yield penetration into consideration. Therefore, the size of the beams and columns framing into the joint depends on the bond requirement of the bar (Uma. S. R and Sudhir K. Jain, 2006).

C. *Factors affecting bond strength*

The bond performance of the reinforcing bar is influenced by confinement, clear distance between the bars and nature of the surface of the bar. For effective bond performance confinement of the embedded bar is very essential to transfer the tensile forces. The additional confinement is obtained from column axial compression and with reinforcement that helps in arresting the splitting cracks. Joint horizontal shear reinforcement improves anchorage of beam bars (Ichinose, T., 1991). But, there is an upper bound to the beneficial effects of confinement. At this limit the crushing of concrete in front of the rib portion of the deformed bar occurs, as maximum bond strength is attained. Research indicates that the bars with spacing less than 5 times the diameter show better bond performance (Eligehausenet al. 1983). 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. *Forces on Joint*

A shear and flexural stresses acts simultaneously in a complex combination within the joint region. Design of a joint is often governed by shear forces which are transferred through the joint, along with the ability of the joint to remain intact under reversed cyclic loading (Somerville, G. and Taylor, H.P.J 1972). The moments and shear forces generated in the beams and columns of a building frame introduce internal stress resultants at the faces of joint core as in Fig 3. The stress resultants cause both horizontal and vertical shear forces in the joint cores. Finally, internal diagonal tensile and compressive stresses would occur due to the development of joint core shear. If the diagonal stress is large enough, it would lead to diagonal cracking (in tension) or crushing (in compression) of the core concrete. Unless adequate shear resistance is provided in the joint core failure of the joint core may eventually occur along the corner to corner diagonal plane (El-Metwally, S.E. and Chan, W.F. 1988).

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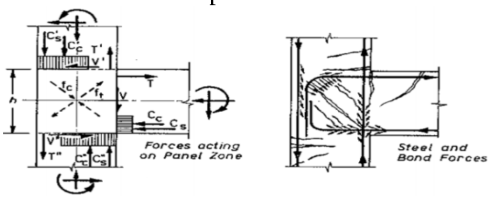
A particularly critical situation can arise in certain exterior beam-column joints of plane multistory frames when these are subjected to seismic loading. The external action and the corresponding internal forces generated around such a joint are indicated in Fig. 4 (Park.R & Paulay.T, 1975). The following notation refers to the stress resultants:

Cc = Compression in concrete
Cs = compression in reinforcement
T = tension force in reinforcement
V = sum of shearing stress

From the position of the stress resultants it is apparent that diagonal tension and compression stresses ($f_c$ and $f_t$) are induced in the panel zone of the joint. The diagonal tension may be high when the ultimate capacity of the adjoining members is developed, and this can lead to extensive cracking. The severity of diagonal tension is influenced by flexural steel content and the magnitude of the axial compression load on the column (Park.R & Paulay.T, 1975).

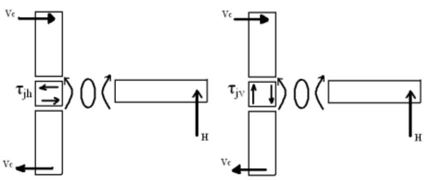



(a) Stress resultants (b) Crack pattern and bond forces
Fig 4: Actions at exterior beam-column joint of a multistory frame
*(Source: Siva chidambaram &Thirugnanam, 2012)*

The anchorage conditions for the top beam bars are extremely unfavorable where they enter the joint. The surrounding concrete is subject to sedimentation, and it is exposed to transverse tension. Usually a splitting crack forms along these bars at a relatively early stage of the loading. Relative loading will aggravate the situation, and a+ complete loss of bond up to the beginning of the bent portion of the bar may occur. Consequently, high bearing stresses may be generated in the bend which can be sustained only if the surrounding concrete is in sound condition. The straight vertical portion following the bend must be sufficiently long if the full strength of the top bar is to be developed (Park.R & Paulay.T, 1975).

E. *Shear forces on the joint core*

The large shear forces may be introduced into beam-column joints irrespective of whether plastic hinges develop at column faces or at some other section of beams. These shear forces may cause a failure in the joint core due to the breakdown of shear or bond mechanisms or both (El-Attar, A. G. White, R. N. et al 1997).The joint region is subjected to horizontal and vertical shear forces whose magnitude is typically many times higher than in the adjacent beams and columns (El-Attar, A. G., White, R. N. et al 1997). If not designed for, joint shear failure can result. The reversal in moment across the joint also means that the beam reinforcement is required to be in compression on one side of the joint and at tensile yield on the other side of the joint. The high bond stresses required to sustain this force gradient across the joint may cause bond failure and corresponding degradation of moment capacity accompanied by excessive drift (El-Attar, A. G., White, R. N. et al 1997). To gauge the relative severity of joint shear forces, it is convenient to express this in terms of shear stresses (El-Attar, A. G., White, R. N. et al 1997). As different mechanisms are involved in the shear transfer after the onset of diagonal cracking, no physical meaning should be attached to shear stress. It should be considered only as a useful index of the severity of joint shear forces.



(a) Horizontal shear (b) Vertical shear
Fig. 5. Forces acting on the Exterior Joint
*(Source: ACI 318-02, 2005)*

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The exterior beam–column joint is usually subjected to large shear forces due to lateral loading (Mohammad Shamim and Kumar, V., 1999). The bending moments and shear forces acting on the joint give rise to both horizontal and vertical shear forces at the joint core as shown in Fig. 5. The situation becomes critical under large cyclic reversals of ground shaking, possibly causing extensive damage to the joints. In the ductile design approach, the frame is expected to undergo inelastic lateral displacements, with the beams forming plastic hinges adjacent to the column while the column is normally designed to remain elastic with the possible exception of beam–column joints and ground storey columns.

It is essential that the beam–column joint is capable of transmitting the necessary shear forces across the joint core, which may have cracked (Mohammad Shamim and Kumar, V., 1999). The external forces acting on one face of the joint develop high shear stresses within the joint. The increase in shear stresses intensifies the diagonal stresses, causing diagonal cracks when tensile stresses exceed the tensile strength of concrete. Extensive cracking occurs within the joint under load reversals, affecting its strength and stiffness. In due course, the joint becomes flexible enough to undergo substantial shear deformation. (Mohammad Shamim and Kumar, V., 1999 &El-Attar, A. G., White, R. N. et al 1997).

## IV. BEHAVIOUR OF RC BEAM-COLUMN JOINTS

### A. *Significance of Geometry of the joint*

The absolute size of a joint has some influence on its performance. Ideal bond and anchorage conditions are very difficult to simulate in a small joint (Park.R&Paulay.T, 1975). For a small joint it is suggested that the percentage of reinforcement must be kept less. Besides the absolute size, the relative size of members and the magnitude of the forces also affect the behaviour of joint as well as the practical limits of detailing (Park.R &Paulay.T, 1975). For Type 2 cases ACI-ASCE Committee 352 apply only to joints designed on ‘strong column-weak beam’ philosophy where the column width is equal to or greater than the beam width (ACI Committee 352, 1985). For ductile structures, it is necessary that the column should be strong than beams to ensure a desirable hierarchy of yielding. It is generally desirable to provide stronger columns and to allow the yielding of beams in flexure prior to possible yielding in columns, because column failure generally leads to the collapse of entire structure. In case of shear as well as flexural yielding of columns, degradation is greater than yielding of beams due to axial compression on the columns (Lee. H, 1996).The width of the column framing into a beam-column joint is a vital factor that governs the bond condition of the longitudinal bars in the beam and also contributes to resistance to horizontal shear (Roufaiel, M.S.L. and Meyer, C 1987) as indicated in Fig6. In case of an exterior joint, where the beam bar terminates at joint core, the bond stresses are not so high. Nevertheless, it is desirable to provide wide columns in order to improve the bond condition. Accordingly many international codes (prEN 1998-1-3:2003 &Pradip Sarkar, Rajesh Agrawal and DevdasMenon, 2007) specify a minimum column width in (terms of beam bar diameter) for exterior joints. The anchorage for the longitudinal bars terminating into the joint core in exterior beam-column joint is usually provided in the form of standard 90-degree hooks, which include a horizontal development length and a vertical tail extension (prEN 1998-1-3:2003 & Kumar, V.,1995). The code requires a minimum horizontal development length and thereby a minimum column width, to ensure the proper anchorage condition.

### B. *Significance of concrete strength*

Strength of concrete affects the mechanism of failure, ductility and strength of joint. Effect of confinement of concrete under axial compression in column is more predominant in richer mixes, as compared to lean mixes (kumar.vet. Al. 1995). When the beam and column are made of same concrete or when the beam concrete is stronger than column concrete, the column fails in tension at low axial loads on column(kumar.v et. Al. 1995).When the column and beam are made of same grade of concrete or when the column concrete is stronger than the beam concrete, the moment carrying capacity of joint increases with increase in axial level (kumar.v, 1995). Joint with same grade of concrete in beam and column has more rotation capacity than any other combination (Kumar, V, 1995). When the beam concrete is richer than column concrete, the behaviour of beam column joint is not consistent at different axial load levels. High strength concrete exhibits less ductile behavior. This fact is important because increased ductility improves the performance of joint under large deformations. When high strength concrete is used, only those joints with low joint shear stresses and high joint confinement show a good performance, with respect to achieving of expected strength of

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the beam, and sustaining their load carrying capacities over the displacement cycles (Ehsani M.R & Alameddine.F, 1991).

C. *Significance of reinforcement bars*

Presence of reinforcement affects the performance of individual members as well as beam-column joints. Concrete members with longitudinal tension steel have considerably high ductility. Ductility of concrete in compression can be enhanced either by using spirals or confining stirrups (Shah S.P & Rangan.B.V, 1970). Due to the complex stress distribution at the joint, its ductility and strength may be expected to depend on the area of tensile and compression reinforcement, and amount and distribution of transverse reinforcement. The main reinforcement which is continued from adjacent members (beams and columns) into the joint core has prominent effect on behaviour of joint. The increase in the percentage of tensile reinforcement in beam increases the ultimate strength, but the efficiency of joint decreases (Kumar .V &Shamim .M, 1999). The severity of diagonal tension is influenced by flexural steel content as well as the magnitude of axial load on the column (Park.R&Pauley.T, 1975) upon the relative strengths of beams and columns. To produce plastic hinges in the beams rather in column, it is recommended that the sum of nominal moment strengths of the column section above and below the joint should not be less than 1.4 times the sum of the nominal moment strengths of the beam at the joint (ACI-ASCE Committee, 1985). Structural members having substantial main reinforcement, require provision of secondary reinforcement to preserve the integrity of the concrete in the joint (Park.R&Pauley.T, 1975). The provision of transverse reinforcement, sufficient to resist any internal shear in excess of that carried by core concrete is necessary (Al-Aamel.H.S& El-Ghazaly, 1991). The parameters, contributing towards shear strength of joint core concrete, are as follows (Bhattacharya .S &Sengupta.B, 1990):

(a) Shear transfer by concrete
(b) Interface shear transfer
(c) Dowel action of main reinforcing bar
(d) Shear transfer by shear reinforcement

When the axial compression on the column is small, the contribution of concrete shear resistance should be ignored (Park.R&Pauley.T, 1975). Unless the shear reinforcement is provided, the joint will not be able to transfer all the moment applied to it by beams (Bhattacharya .S &Sengupta.B, 1990). The increase in the percentage of shear reinforcement results in the increase of the ratio of actual ultimate moment to theoretical ultimate moment capacity of joint (Kumar.Vet. Al. 1991). Increase in vertical shear reinforcement does not affect the ultimate strength at low axial loads (upto 20 percent of ultimate strength of column). But at higher axial loads, the ultimate strength of exterior joint increased with increase in shear reinforcement (El-Metwally S.E &Chan.W.F, 1988). The increase in shear reinforcement decreases the ultimate deflection of exterior joint, particularly with high percentage of tensile reinforcement in beam (Kumar .V &Shamim .M, 1999). The effectiveness of the joint shear reinforcement depends on the ability of the flexural reinforcement and the surrounding concrete to inter-change high intensity bond stresses (Park.R&Pauley.T, 1975).

The satisfactory performance of a beam-column joint, particularly under seismic loads, depends strongly on the lateral confinement of the joint. Effective confinement benefits in two ways: (1) core concrete is strengthened and its strain capacity is increased, and (2) column longitudinal bars are prevented from buckling. Confinement of core concrete is achieved by a combination of longitudinal column reinforcement and either transverse members framing into the column or transverse reinforcement or both (ACI-ASCE Committee, 1985). The current ACI 318-89 philosophy for confining concrete in earthquake resistant design is that the increase in the strength of the core of a column due to confinement must offset the loss of strength due to spalling of the unconfined cover (Ehsani M.R &Alameddine.F, 1991). The decrease in the percentage of the reinforcement results into the decrease of efficiency of exterior joints. ACI-ASCE Committee 352 recommendsthat at least two layers of transverse reinforcement should be provided between the top and bottom levels of longitudinal reinforcement of the deepest beam framing into the joint (ACI-ASCE Committee, 1985).

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D. *Significance of beam reinforcement*

Kumar and Shamim found that ultimate strength of beam-column joint increases with increase in axial load level upto 80%. Also the ultimate deflection of joint reduces with increase in axial load level upto 80% irrespective of amount of tensile reinforcement. The axial load level, amount of tensile reinforcement and shear reinforcement in the beam affects the cracking moment of joint very little.

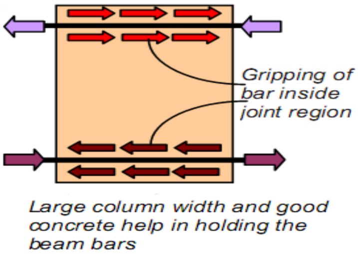


Fig: 6 Loss of grip on beam bars in joint region
*(Source: C.V.R.Murthy, 2003)*

Increase in shear reinforcement does not affect the ultimate strength at low axial load level (upto 20%) but at higher axial load levels (upto 80%) the ultimate strength of joint increases with increase in shear reinforcement. Increase in shear reinforcement decreases the ultimate deflection of beam-column joint and this reduction is significant at higher percentage of tensile reinforcement in beams (Veerendra Kumar and Mohammed Shamim, 1999).In construction of RC frames, it is very tedious to provide closed-tie transverse reinforcement in joints and to anchor the top and bottom beam bars into the column through the joint. This is particularly severe in frames with small volume joints typical of gravity-only (pre-seismic) frames.

E. *Influence of loading*

One of the factors affecting the beam-column joint behaviour is the loading on the joint. Typical forces acting on the joint during ground shaking in shown in fig 7. Type as well as amount of load is found to affect the strength, efficiency, rotation, capacity and mechanism of failure. Particularly the axial load on column is dominant in affecting the joints behaviour. Joints, where axial load on column is small, are the most critical joints (Kumar .V &Shamim .M, 1999). Shear forces are applied on the joint by bond forces in the beam reinforcement. An increase in the joint shear has a distinct effect on the load-carrying capacity of the joint (Seckin.M and Fu.H.C, 1990). The severity of diagonal tension in the joint region is influenced by the magnitude of axial compressive load on the column. At low axial load on column, the column fails in tension when the concrete in beam and column are of same grade or beam concrete is richer than the column concrete (Kumar.V,1995). Beam-column joints fail by development of a plastic hinge in beam at the face of column at high column load, while at low column loads, the joints fail by extensive cracking (Scott.R.H, 1996). However, the influence of column axial load on bond stress-slip is negligible and 90 degree hooks and 180 degree hooks show nearly same behavior (Marques.J.L.G&Jirsa.J.O, 1975). Also there is not much effect of change in column axial load on cracking moment and the ratio of actual cracking moment to theoretical cracking moment remains almost equal to unity for all cases of column axial load levels (Kumar.Vet. Al, 1991). The ultimate strength of joint increases with increase in axial load level upto 80%. The ratio of measured ultimate strength to theoretical ultimate moment carrying capacity increases with increase in axial load level. The efficiency of joint increases with increase in axial load level when beam and column are made of same concrete or column concrete is stronger than beam concrete, but the efficiency decreases above 20% axial load level when the beam concrete is stronger than column concrete (Kumar.V et. Al, 1991). High column load specimens closely approach their full theoretical moment of resistance at joint cracking, but low column load specimens reach only about 50% of their theoretical values when the joint first cracked (Scottt.R.H, 1996). Deflection behaviour of joint is also dependent on column axial load, when column concrete is richer than or of same grade as that of beam. The plastic rotation capacity of exterior joint decreases with increase in axial load (Kumar.V et. Al,1991). It is not necessary that joints always have high compressive force in column. Much reduced column compression and even tension may be experienced in columns of intermediate stories of high rise concrete structures.

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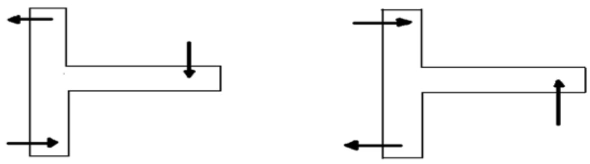
The concrete contribution to the shear resistance of the joint region is hampered by the reduction in axial column load or by presence of axial tension. Due to this loss of shear strength and consequent bond deterioration, the cracking is mainly concentrated in the joint. The column tension causes losses in ductility, joint-shear strength and energy dissipation capacity (El-Mustafa, M.H.Elnashai.A.S, 1996)



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(a) Ground Movement (Left to Right) (b) Ground Movement (Right to left)
Fig 7: Forces on exterior joint during ground shaking
*(Source: ACI 318-02,2002)*

F. *Beam-Column Joint Failure Mechanism*

Knowledge of stresses in joint and failure mechanism is necessary for the joint designs that can efficiently carry the forces. Beam column joints are usually designed following the generally accepted strong column weak beam philosophy for reinforced concrete structures in seismic areas (Somerville, G. and Taylor, H.P.J.,1972). This is desirable because the inelastic actions take place in beam plastic hinges; at the same time plastic hinges in the columns, which can result in a soft story mechanism, are avoided. However, in general the failure in a beam-column joint may occur in one of the following ways (Kumar and Sharad, 1988):

1) Formation of plastic hinge in beam portion near the beam-column interface.
2) Formation of plastic hinge in column portion near the joint core.
3) Formation of diagonal crack in the joint region.

Besides other factors, the strength of beam-column joint depends upon the compressive, shear and bond strength of concrete, and tensile strength of reinforcement at the joint. The main causes of failure of joint can be described as (Al-Zamel, H.S. and El-Ghazaly, H.A., 1991):

1) Anchorage failure
2) Failure due to yielding of reinforcement
3) Failure due to crushing of concrete
4) Diagonal tension cracking

In structural frames, load on slabs is transferred from beam to column through beam-column joints. The critical sections for transfer of member forces to the joint are at the joint member interface (ACI-ASCE Committee 352, 1985). The load transfer mechanism by bond is particularly influenced by detailing. Very heavy lateral loading, particularly form seismic forces, produces large horizontal shears within the joint. Shear in the joint causes diagonal cracks that form a grid of inclined cracks during load reversals. The diagonal tension may be very high when the ultimate capacity of the adjoining members is developed and this can lead to extensive diagonal cracking. The beam-bar anchorage is deteriorated as a result of this diagonal cracking. Besides diagonal cracking, some flexural cracking may also occur in the joint. In strong column-weak beam joints, most of the crack damage is concentrated in the beams near the column face (Raffaelle, G.S. and Wight, J.K., 1992). The largest flexural cracks occur at the interface of beam ends and the column face (Raffaelle, G.S. and Wight, J.K., 1992).

G. *Failure pattern of joint*

Flexural cracking in the beam portion during early load stages is followed by propagation of a diagonal crack in the connection zone. Further loading leads to the joint failure, either by plastic hinge formation in the beam at the face of the column or by extensive cracking in the connection zone, depending upon the relative influence of reinforcement percentage, detailing and column load (Scott .R.H, 1996). Thus behaviour of exterior joint upto failure can be divided in two stages

(a) upto diagonal cracking in connection zone
(b) after diagonal cracking upto the failure

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In exterior joints, the first crack usually occurs at the beam column junction, but the major structural crack is always the diagonal crack. The bending moment transferred from the beam to the column is carried by the column in equal amounts, above and below the joint until the diagonal crack forms (Somerville, G. and Taylor, H.P.J.,1972). At the point of joint cracking, main reinforcement of beam portion is in tension over its full length at high column loads as indicated in fig 8. At low column loads, a substantial zone of tension is observed along the beam reinforcement around both bends (and back into the beam in the case of U-bars details) and tensile strains are observed in the column bars (Scott .R.H, 1996).

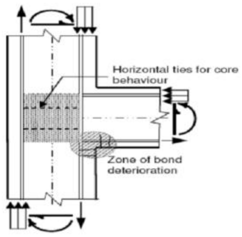


Fig 8: Bond deterioration
*(Source: Pradip Sarkar, Rajesh Agrawalet.al., 2007)*

After the diagonal has formed, the joint is able to take more load depending upon the steel percentage in the beam. Upto the joint cracking, load transfer is predominantly by bond developed at the bend of reinforcement as shown in fig 9. After the joint cracking, loss of bond at the bend is compensated by developing bond stresses over an increasing length of reinforcement, giving substantial load increment between joint cracking and joint failure. After the formation of diagonal crack, the closing corner side of joint shares more moment than the weak opening corner side and at the ultimate moment, around 70 percent of moment is shared by closing side (Somerville, G. and Taylor, H.P.J.,1972).

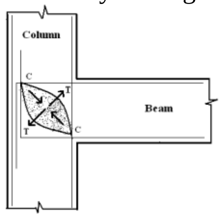


Fig 9: Diagonal compression and tension fields in RC exterior beam-column joints
(*Source: PradipSarkar, Rajesh Agrawal and DevdasMenon, 2007)*

After the joint cracking stage with further loading, there is a steady progression of tensile strain down the vertical leg of main beam reinforcement upto the failure, in case of joints with main beam reinforcement bent towards closing side and in joints with U-bar reinforcement. This gives a substantial increase in load between joint cracking and failure. In case of joints with main reinforcement bent towards opening side, there is hardly any progression of tensile strain along vertical legs of the bars between joint cracking and failure, so load increments between joint cracking and failure are small (Scott .R.H, 1996). Column bars in high column load joints remain in compression upto failure, although the distribution of the compression changes in response to beam loading. Tensile strains occur in columns bars of low column load specimens (Scott .R.H, 1996Flexural cracks are also observed above and below the joint in low column load cases.

## V. Structural Properties of Joint

The specific structural properties that need to be considered in conjunction with the three levels are as follows:

### A. *Stiffness*

If deformations under the action of lateral forces are to be reliably quantified and subsequently controlled, designers must make a realistic estimate of the relevant property called stiffness (ACI 318, 2005). This quantity relates loads or forces to the ensuing structural deformations. Familiar relationships are readily established from first principles of structural mechanics, using geometric properties of members and the modulus of elasticity for the material. In

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reinforced concrete and masonry structures these relationships are, however, not quite as simple as an introductory text on the subject may suggest. If serviceability criteria are to be satisfied with a reasonable degree of confidence, the extent and influence of cracking in members and the contribution of concrete or masonry in tension must be considered, in conjunction with the traditionally considered aspects of section and element geometry, and material properties (Hung-Jen Lee and Jen-wen ko (2007) &ACI 318, 2005).

### B. *Strength*

If a concrete structure is to be protected against damage during a selected or specified seismic event, inelastic excursions during its dynamic response should be prevented (ACI 318, 2005). This means that the structure must have adequate strength to resist internal actions generated during the elastic dynamic response of the structure. Therefore, the appropriate technique for the evaluation of earthquake-induced actions is an elastic analysis, based on stiffness properties. The seismic actions, combined with other loads on the structure, such as gravity, will lead, perhaps with minor modifications, to the proportioning of structural members (Hung-Jen Lee and Jen-wen ko 2007). Thereby the designer can provide the desired strength in terms of resistance to lateral forces envisaged.

### C. *Ductility*

To minimize major damage and to ensure the survival of buildings with moderate resistance with respect to lateral forces, structures must be capable of sustaining a high proportion of their initial strength when a major earthquake imposes large deformations (ACI 318, 2005). These deformations may be well beyond the elastic limit. This ability of the structure or its components, or of the materials used to offer resistance in the inelastic domain of response, is described by the general term ductility. It includes the ability to sustain large deformations, and a capacity to absorb energy by hysteretic behavior. For this reason it is the single most important property sought by the designer of buildings located in regions of significant seismicity. Ductility in structural members can be developed only if the constituent material itself is ductile. Thus it is relatively easy to achieve the desired ductility if resistance to be provided by steel in tension. However, precautions need to be taken when steel is subjected to compression, to ensure that premature buckling does not interfere with the development of the desired large inelastic strains in compression (ACI 318, 2005).

## VI. NEED FOR DUCTILE DETAILING

The designing and detailing of the joints play a crucial role in providing ductility and strength required to sustain large deformations and reserved stress during earthquakes. Despite the critical role of joints in sustaining large deformations and forces during earthquakes, specific guidelines are not explicitly included in current Indian codes of practice (IS 1893:2002, IS 13920:1993 and IS 456:2000) (Hakuto, S., Park, R. and Tanaka, H.(2000) &Uma. S. R and Sudhir K. Jain, 2006). On account of this, it is tacitly assumed in practice that adequate lapping of the main reinforcement and provision of transverse ties satisfies the integrity and strength of joints. The problems of detailing and construction of beam-column joints are often not appreciated by designers (Paulay. T and Priestley.M.J.N, 1992). Because of the restricted space available in the joint block, the detailing of reinforcement assumes more significance than anywhere else. Indeed, the conflict between the small size bar requirement for good performance, and large size bars required for ease of placement and concreting is more obvious at the joints than anywhere else(SP 123, 1991). This is particularly true at internal joints, where the beams intersect in both the horizontal directions where large moments are to be sustained by the connections. In the absence of specifications from the designers, site engineers often adopt expedient procedures for detailing, which are not always conducive for satisfactory structural performance.

### A. *Detailing of Reinforcement at Joint*

A specific characteristic of reinforced concrete is that, there are always different methods of detailing satisfying the requirements. Arrangement and sizing of reinforcement bars in individual members are carried out in accordance with the guidelines given in IS: 456 and IS: 13920 (Hakuto, S., Park, R. and Tanaka, H.2000). Situations, which are not simple and straight forward, e.g. case of beam-column joint, may exist where the application of these rules may not always reflect the actual forces distribution. The reinforcement proportioning and its arrangement in the beam-column

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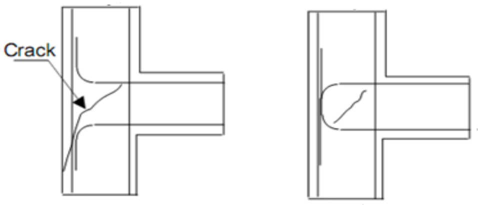
joint should be such that proper ductility under the most critical and severe loading conditions is ensured. The detailing as per IS 13920-1993 is shown in fig 11. The detailing of reinforcement affects the efficiency (the ratio of measured strength to the theoretical flexural strength of the members) of the joint and its cracking pattern to a considerable degree. Load transfer by bond is particularly influenced by detailing. Most efficient reinforcement arrangement can generally be determined from a simple consideration of the forces to be transmitted.




(a) Poor Detail (b) Satisfactory Detail

Fig 10: Detailing of Exterior joint

*(Source: Somerville, G. and Taylor, H.P.J, 1972)*

Exterior joint can be either closing or opening corners. Three detailing arrangements may be used – (i) bending tension bars towards closing corner, (ii) bending beam tension bars towards opening corner, and (iii) U-bars. It is reported that exterior beam-column joints with high steel percentage can have efficiencies less than 100%. It has been found that detail in fig. 10 (a) is weaker but that in fig. 10 (b) is equally effective. However, at very low column loads, detail shown in fig. 10 (b) is weaker.

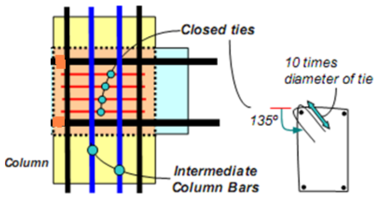



Fig 11: Closed loop steel ties in beam-column joints

*(source: C.V.R.Murthy, 2003)*

B. *Role of Beam bar Anchorage in Joints*

The high bond stresses within a joint can severely undermine the anchorage of a bar passing through it, and if this bond within the joint is broken, the loosened bar easily slips back and forth within the joint core under cyclic loading (Roufaiel, M.S.L. and Meyer,C,1987). This behavior is reflected as severe pinching in the hysteretic loops associated with the lateral load-deformation response because of large displacements occurring with a small increase in resistance as the bars slip through the joint. The factors affecting these bonds and anchorage conditions within the joint core are: amount of transverse reinforcement confining the concrete in the joint core; size of the longitudinal bar passing through the joint core fig-12; spacing of longitudinal bars; and level of compressive stress generated by axial load in the column (Al-Zamel, H.S. and El-Ghazaly, H.A, 1991 & Ganesan N, Indira P.V and Abraham R., 2007). To ensure adequate bond and anchorage, most design standards limit the size of the bar diameter in relation to the size of the joint core and specify details to be followed while bending bars and hooks.

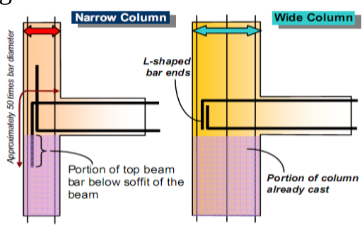



Fig 12: Anchorage of Beam Bars in Exterior Joints

*(Source: C.V.R.Murthy, 2003)*

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The requirements of anchorage of longitudinal beam bars into the joint assume greater importance when these bars are subjected to stresses in excess of the yield stress as in a hardened plastic moment hinge; this happens when the development length provided is insufficient as in gravity-only designed frames and when the surrounding concrete is cracked due to diagonal shear under large inelastic actions. It is possible to correlate the joint shear stress, anchorage length, and bar diameter by considering reduced bond for shear cracking at peak joint shear stress corresponding to the over strength capacity of adjoining members (IS 1893, 2002).

C. *Role of Transverse Reinforcement in Joints*

The design requirement for a beam-column joint in earthquake-resistant RC frames is rather simple, that is the joint must not yield before the adjoining members reach their capacities and must not deform excessively. The joint region is subjected to excessive shear stresses when any of the adjoining members reach its over strength moment capacity associated with the hardened plastic hinge (NZS 3101: Part 1:1995). The joint must have a sufficient shear strength capacity to resist these shear stresses. The joint shear strength comprises of three components: shear strength of plain concrete, shear strength due to longitudinal steel of framing members, and shear strength due to web steel provided in the joint in the form of transverse steel (PradipSarkar, Rajesh Agrawal and DevdasMenon, 2007). In design for gravity loads, the shear strength provided by the plain concrete and longitudinal steel is adequate in most cases. The shear strength demand imposed by hardened plastic hinges developed under seismic conditions, however, is too large, and additional steel in the form of transverse reinforcement is often required in the joint region to confine the concrete in the joint core, thereby enhancing its strength and delaying the onset of cracking (Kumar, V. and Shamim, M. 1999).
A system of diagonal compression strut and tension tie is developed in the concrete core to transmit the joint shear forces as indicated in fig 13. The strength of this diagonal strut controls the joint strength before cracking. The transverse reinforcement in the joint helps confine the concrete diagonal strut in the joint core, and thereby increase the strength of the joint. And, when joint shear forces become large, diagonal cracking occurs in the joint core followed by crushing of concrete in the joint core. At this stage, the joint reinforcement alone cannot prevent the undesirable pinching in the hysteresis loops. It is therefore necessary to limit the magnitude of horizontal joint shear stress to protect the joint against diagonal crushing. Therefore standards such as ACI 318 and NZS 3103 require (prEN 1998-1-3:2003 &Kunnath. K.S., Hoffmann. G, Reinhorn. A. M and Mander. J. B, 1995) that the shear stresses in the joint core are kept below a maximum permissible value. In addition, standards specify the design of transverse reinforcement for resisting the transverse shear and for confining the joint core concrete.

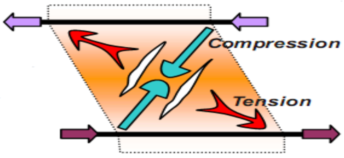


Fig 13: Forces acting on beam bars
*(Source: C.V.R.Murthy, 2003)*

When the frame has deep columns, the joint shear stresses become small, and, as a result, the problem of diagonal cracking in the joint core is considerably minimized, if not eliminated. Thus, the physical size or volume of the joint becomes the most important parameter because it not only directly controls the level of stresses in compressed diagonal concrete but also dictates how much transverse steel in each direction needs to be provided (El-Attar, A. G., White, R. N. and Gergely, P.(1997) & Hung-Jen Lee and Jen-wenko 2007). Further, the stiffness of the joint, which determines the contribution of the joint deformation to overall frame deformation, is also proportional to the volume of the joint. Non-seismic frames result in small volume joints and therefore deform excessively and contributing significantly towards the overall frame deformation in comparison to large volume joints in RC frames. To improve the performance of moment frames, if the size of the column cannot be increased, the options remaining are: 1) to provide a sufficient amount of transverse reinforcement in the joint in a suitable manner, not only to delay the onset of shear cracking but also to restrict its damaging effect on the core concrete and improve the ductility of such frames; and 2) to provide adequate anchorage of longitudinal beam bars such that slip is minimized (Hakuto, S., Park, R. and Tanaka, H.(2000) & Paulay. T and Priestley.M.J.N., 1992).

## VII. CONCLUDING REMARKS

In Indian design practice, beam column joint has been given less attention than it actually deserves. This proposal contributes to the inexorable need for the design engineers to be aware of the fundamental theory of joint behaviour. In this context, 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 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. Further amount of reinforcement, detailing of reinforcement, strength of concrete and type of loading have distinct effects on the performance of beam-column joints. All these parameters should be considered while designing the joint for better effectiveness.

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