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Conceptual Review on Seismic Analysis of Reinforced Concrete Beam-Column Joints

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Abstract: ***Beam column joints are critical elements in reinforced concrete moment resistant frames (RCMR). Due to inherent complexity of load transfer mechanism and constrained geometric conditions, seismic design codes expressed conflicting views on design of joints. This makes joints more vulnerable during critical action of seismic loads and unable to perform its desired functionality. During seismic excitation non ductile performance of joint system often leads to shear deformation and storey drift both are considered under brittle failures. Hence the seismic design procedure recommends ductile property of joint and its subassemblage. A good detailing practice of joint system and sub assemblage improves ductile performance of structure. But the constrained geometric conditions and uncertainties in design guidelines critically influence detailing and construction practice. In this context, specific attention need to focus on detailed analytical study of beam column joint. Application of seismic loads are in the form of quasi static, and dynamic conditions during which joints subjected to stress reversal, fatigue and impact forces. Hence this review focused on associated theories, hypothetical views on stress distribution, load transfer mechanism, and damage studies at impending failure of a joint. Accordingly specific recommendations are suggested to improve the design aids of R/C beam column joints***

Keywords: Beam-column joint, Seismic codes, Postulated theories, Critical observations

1. Introduction

The dynamic action of seismic vibrations induce large amount of horizontal and vertical shear force on RCMR joint system , whose magnitude is many times higher than the adjacent beam or column shear [29]. This is due to column experience opposite moments at above and below the joint and beams experience reversal moments adjacent to the rigid joint .This reversal bending stresses cause steep gradient of shear forces which transferred through the joint core. This action successively increase shear deformation and inter storey drift of structure , and ultimately demands high bond stress conditions within joint core against [38],[43]. An efficient joint system enables to transfer critical loads within the connecting members and develop ultimate moment capacity to sub assemblage of joint system [12]. Joints are often the weakest links in the structural system as it needs to accommodate high fixed end moments and lateral shear of sub-assemblage. The complex load transfer mechanism and failure conditions of R/C beam column joints identified as one of the potential area of research studies. Experimental studies conducted by Vladimir et al., [4] concluded that the external force transfer in joint system is in the form of shear, moment and bearing stresses. Under critical combination of service loads, the joint behavior significantly influenced the global performance of the structure.

The current state of seismic design practice considered R/C beam column joints as a rigid joint system, but in reality most of joints are constructed under semi rigid conditions. This partial fixity conditions seriously influence the structural performance of joints and its sub-assemblage. The rigid joint assumption gives an over estimation of structural stiffness and under estimation of storey drift [7]. The present seismic practice restricts elastic response of joints during moderate earthquakes and inelastic ductile response at severe earthquake conditions .The inelastic response of joint significantly reduce strength and stiffness of joint unless it was suitably controlled by ductile property. The ductile joint system effectively dissipate seismic energy during and after inelastic joint behavior and develops full design strength of the joint assembly and its connecting members[38]

As per the seismic theories, more than 50% of the Indian sub-continent exposed to moderate and severe earthquakes. Major cities like Bombay, Calcutta, Madras, and Delhi, are located in moderate and high seismic zones with growing intensity of high raised R/C structures. During this scenario, the present design codes need to emphasize basic design aspects of R/C beam column joints where the configuration, strength, stiffness and ductility plays an important role during and after seismic action. The seismic damage of joints are attributed to inadequate shear, anchorage and ductile reinforcement detailing. This may leads to sudden and brittle failure of joint system.

Capacity design is an advancement in the design of beam column joints, where due considerations are given for ductile performance of joint of failure. But this method is unable to find failure modes of joint [5]. As per Bernoulli's hypothesis, linear deformation valid for continuous boundary conditions but not for discontinuous boundary elements such as joint .Strut and Tie method (STM) is useful to analyze the elements of discontinuous boundary conditions.

STM provides easiness of application and understand the structural behavior of Reinforced beam-column joint.[4

2. Literature review of seismic design code

International design codes of ACI/NZS/EU/BS are silent or partially addressed on certain design aspects of R.C beam column joints. The codes express conflicting views about shear transfer mechanism, interplay between shear-bond and confinement effect of joint core. The codes given high importance about anchorage and confinement to enhance shear and bond strength of the joint system .Design provisions of joints under partial fixity or restrained conditions of beam column joint connections and eccentric joints are not addressed in codes and still they are envisaged. Also codes are silent about design provisions of R/C precast and pre-stressed beam column joint system. As per the literature studies ductile performance of joint significantly influenced by the size of reinforcement and codes must able to address the optimum size strength and reinforcement area of joints. Concepts on relative slippage of bars under cyclic loading conditions and parametric influence on stirrup confinement in joint core need to address by codes .Moment capacity ratio of joint sub assemblage significantly influence the performance of joint, which is partially addressed by the codes. Design codes are uncertain about nominal shear capacity of high strength concrete (>50MPa) and effect of column axial load on shear strength of joints. Till now the experimental studies are permitted to find the influence of joints when columns experienced moderate loads (Ref: ACI 352-02R) Column Tension $T \leq 0.07$ fck. Ag and Compression $C \leq 0.25$ fck. Ag) but the effect of joints due to higher axial column loads ($C > 0.25$ fck. Ag) are not established [30] [34]. But from the literature it was that axial load significantly influence the failure pattern of joint. In spite of better anchorage and shear strength, design codes implemented certain limitations on usage of headed bars in the joints due to non availability of design information.

Indian standard code of seismic practice [44]not include specific design guide lines for efficient performance of beam column joints .As per the code ,seismic provisions are mandatory for structures located in seismic zone III onwards, but in many aspects the explicit guide lines of joints are not mentioned in the code. The code restricted to the anchorage provisions of beam bars in joint, but the poor performance of joint often noticed due to high shear demand imposed by adjoining flexural members such as beams and column due to their inelastic behaviour during dissipation of seismic energy[8]. In this context ductile detailing of monolithic R.C joints are suggested by the code (I.S 13920-2002) but for precast structural system code expressed design provisions applicable only if the structural system shows same level ductility as in monolithic construction. Repair and retrofitting techniques of individual R/C members are emphasized in I.S 13935, but the same for global performance such as shear wall or framed structural system with joint connections are not addressed. Design codes unable to address recent innovations such as use of fiber reinforcement, high strength concrete, headed bars, couplers, structural implants and parametric influence on confinement of joints , effect of high axial loads on joint shear and nominal shear strength of concrete under uni-axial and bi-axial stress conditions. Geometric configuration of beam column joint and effect of confinement plays an important role during shear transfer mechanism of beam column joint, but limited parameters are mentioned in the codes. As per IS 1893-2002, it is possible to correlate joint shear stress, anchorage , and effect of bar diameter by reduced bond conditions of shear cracking during peak shear stress and over strength of connecting members. I.S code not discussed about shear friction concept, wide beam column joints, deep beam joint connections and detailing concepts related to partial fixity conditions of beam column joint. As many improvements need to address by I.S code of seismic design codes practicing for reinforced concrete joints, these uncertainties are partially obviated in I.S codes related to structural steel design codes.

3. Postulated theories

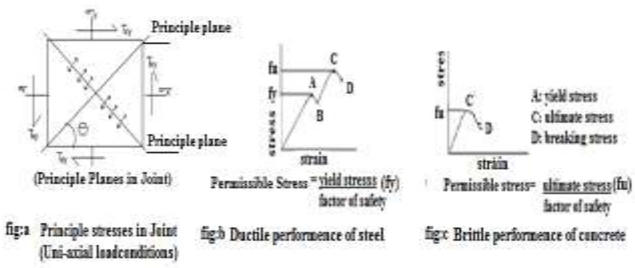
During experimentation of R.C beam column joints, the designers often implement certain limitations on formulation of mathematical models. Without appropriate modeling, designers are deprived of using rational methods to understand joint behavior as the codified procedures may not offer best solution. In this context postulated theories helps to identify the influential parameters and provides evidence for appropriate joint behavior based on the conceived models. This ultimately helps to proceed experimental works in right direction rather than producing wealth of data.

The postulated theories are developed as per the basic assumptions expressed by Park R & Paulay T [38]. Accordingly the strength of joint should not be less than the maximum demand corresponds to develop structural plastic hinge mechanism of connecting members. This eliminates need for repairing of joint at inaccessible region. During seismic excitation, many failures of tall structures observed by soft storey effect and shear failure. Since the joint considered to be an integral part of the column, deformations in joint should not increase storey drift and it should respond within elastic range during moderate seismic disturbance. During high seismic and cyclic loading the performance of joint significantly influenced by degradation of strength and stiffness due to in elastic joint deformation and energy dissipation.

Based on the above conditions, the joints analyzed under elastic, plastic and fracture failures by considering initial elastic modulus, plastic strains and fracture parameters. Cracks in joint core are not appear until the principal tensile strains reach to limit strain of concrete. Design methods of un-cracked joints often studied by using rotational spring model, component model and finite element model. Modeling of cracked concrete joint sections are based on, Tension stiffening, Compressive stiffness, Bond slip strain, and Shear displacement modes and analyzed during and after failure conditions .Damage simulation in RC concrete is followed by (i) Concrete smeared cracking, (ii) Cracking model for concrete, and (iii) Concrete damaged plasticity [CDP]. CDP modeling considered degradation of elastic stiffness by development of plastic strains in tension and compression. It also consider stiffness recovery effect under cyclic loads (tension stiffening effect). The joint models can effectively formulated by finite element analysis. In tension stiffening method, concrete continues to support a part of tensile strength of R.C section even after cracking which results higher stiffness in the R.C section. As per empirical formulas, σ_t = Average tensile stress in concrete, f_t = Tensile strength of concrete and ϵ_t is corresponding strain, ϵ_{tu} = ultimate tensile strain in concrete, then $\sigma_t = f_t\,(\epsilon_{tu}/\,\epsilon_t)^c$ where c=coefficient(c=0.40 for HYSD bars). In compressive stiffness model the stiffness of cracked sections is considered less than un-cracked sections. In bond slip strain models, the relative displacement between steel bars and surrounding concrete identified very large at beam column face due to plastic hinge formation. Influence of bond slip on entire structure is considerably high. In shear displacement model (low and high shear conditions), the shear stress applied on joint models solely in terms of shear displacement and crack width by ignoring the effect of elastic deformation in crack plane . [If φ= shear stress or shear strain, β=shear displacement or crack width, then $\varphi = \beta^2/(1+\beta^2)$ then, $f_{st}=3.8(f_c)^{0.33}$ where fc = cylindrical compressive strength].

As per studies made by Fergusson (1973), Park & Pauley (1975) and Waren et al., (1976) , post cracking behavior of joint models are well established by considering strength conditions under plane strain conditions and un-cracked joint models are analyzed by geometric conditions of plane stress conditions of elastic joint system. In this context the relevant postulated theories used in the analysis of beam column joint are (i) maximum principal stress theory, (ii) strut and tie method (truss analogy) (iii) modified compression theory, (iv) energy distortion theory (v) shear friction theory. Maximum principal stress and truss analogy theories are used in the analysis of un cracked sections (stress based) and modified compression and shear friction theory used for cracked sections (strength based) .A brief description is given as follows.

(i) Principal Stress theory (Rankine's theory)**: [PST]**
This theory used in the design of brittle or inelastic joints of un-cracked sections at impending failure. The complex stress transfer in joint core due to application of axial, shear and flexural loads, results development of principal stresses (σ_1 , σ_2) in two orthogonal directions of principal planes .Since concrete is a brittle material and weak in tension, the impending failure of joint at elastic limit may occur due to maximum and minimum principal stresses developed in concrete (tensile and compressive).Once a diagonal crack developed, the effective sectional properties get altered and stress distribution is no longer maintained .Hence this theory well identified the influence of tensile strength of concrete at failure. Based on this theory capacity design of R.C joints well established in which due considerations for ductile performance of joint in the form of arrange ductile links at predetermined locations. This plane stress theory not well established if the joint possess large tensile cracks [43].



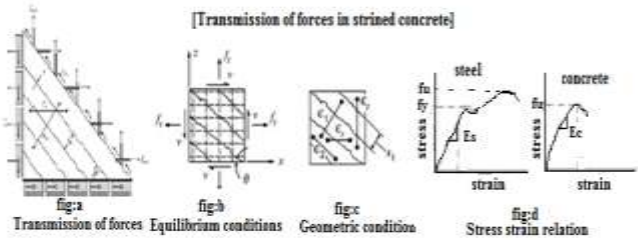
Principle Stress Theory

For two dimensional stressed body, if σ_1 and σ_2 are the major and minor principal stresses developed under combined action of flexural tension (σx , σy) and direct shear (τ_{xy}) on joint core.

Then the principle stresses = $\sigma_{1,2} = (\sigma x+\sigma y)/2 \pm [(\sigma x-\sigma y)/2)^2+\tau_{xy}^2]^{1/2}$ and maximum shear stress $(T_v)max = (\sigma_1 - \sigma_2)/2$ and tan $2\Theta = 2\tau_{xy}/(\sigma x - \sigma y)$. Within elastic limit ($\sigma_1$ and σ_2) < f where (f=working stess of material). Since concrete is brittle material and weak in tension, tensile cracks developed in the joint in the direction perpendicular to the major principal tensile plane.

During the design practice of R/C beam column joints the tensile strength of concrete(f_{ct}) considered between
$f_{ct} = 0.22[f_{ck}]^{1/2}$ & $0.37[f_{ck}]^{1/2}$.
Empirically we may consider the following in R/C joints
$\sigma_t^2 \leq 1/12C. [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]$.
[σ_t= allowable tensile stress of concrete & C=shear modulus].

(ii) Modified Compression Field theory: [MCFT]
This theory provides a unified rational approach in analysis of R.C joints at in-plane stress conditions , and provides conceptual model on behavior of cracked concrete section under two dimensional stress conditions . Accordingly the cracked section treated as a new material with empirically defined stress strain conditions[3]. Myoungsu Shin et al., (2004) developed this theory to evaluate hysteretic shear behavior of joint and its subassemblies during cyclic loads.



Modified Compression Field Theory

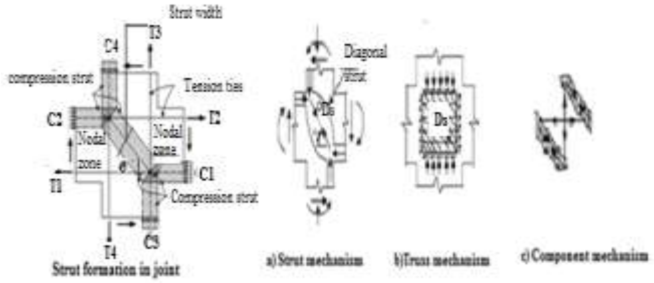
Modified compression field theory provides shear capacity of cracked sections through strain compatibility. Figure represents transmission of forces in a cracked concrete section at equilibrium conditions. The method provides shear strength calculations of cracked section based on allowable strains and compatibility conditions between steel and concrete of cracked section. The average strength of un-cracked concrete and principal strength of cracked concrete section will considered for evaluation of shear stress conditions in cracked concrete. The shear force can be carried through broken concrete zone by inclining the main reinforcement through hinge zone toward point of contra flexure [50]

(iii) Shear strain energy theory (Energy distortion theory): [EDT]
This theory provides a good approximation in the design of ductile material. Accordingly failure of a material occurred when the total shear strain energy per unit volume (modulus of resilience) of a stressed material will reaches maximum tensile stress at elastic state. Empirically this theory can expressed in a stressed material. If σ_1, σ_2 and σ_3 are the principal stresses in three dimensional body, then total shear strain energy/unit volume must satisfy the following relation.
$\sigma_t^2 \leq 1/12C. [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]$. [σ_t= allowable tensile stress of concrete & C=shear modulus].

(iv) Strut and Tie theory: [STM]

Pauley et al.,[38] proposed that shear transfer in joint panel is in the form of strut -tie and component of truss mechanism. As per this theory joint models are best suitable in discrete regions where plane sections not remain plane after bending. [example: pile caps, discontinuity regions of joints, changes in cross sections, corbel and bracket connections, abrupt change of cross sections]. Efficient structural models can produce by STM but unique solution cant arrive by single solution instead of several iterations. Due to easiness of application and understanding the structural behavior STM is more acceptable to implement in the analysis[38].

In general design considerations, horizontal joint shear (Vjh) is taken as sum of joint shear due to (Vch) strut mechanism and (Vsh) truss mechanism ie; [*Vjh= Vch+Vsh*]. To prevent shear failure by diagonal tension along failure plane both horizontal and vertical shear reinforcement contribute to generate diagonal compression field and feasible load path. The real behavior of joint is due to the combination of diagonal strut and truss mechanism with bond deterioration of longitudinal bars to certain degree during cyclic loads(Source: N.Subramanyan) . A brief explanation of this mechanism as follows.



Shear Transformation-Strut & Tie method

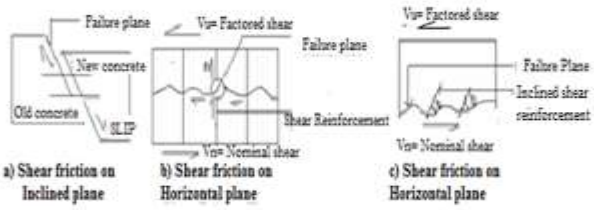
Figure (a): The Internal forces in concrete is in the forms diagonal strut. In strut mechanism diagonal compressive force (Dc) developed along the corner of joint which contribute substantial part of shear in joint core. However the strength of the strut reduced by development of tensile stresses perpendicular to the direction of strut (compression softening effect) where the confinement of joint core takes crucial part to compensate tensile stresses. The standards such as ACI 318-02 and NZS 3103 require (prEN 1998-1-3:2003) & Kunnath. K.S., Hoffmann. G, Reinhorn. A. M and Mander. J. B, 1995) stated that the shear stresses in joint core are kept below a maximum permissible value. The stress strain model proposed by Mander et al., (uni-axial confined concrete) used to determine the stress components of diagonal strut by considering the effect of compression softening [1]

Figure (b): The truss mechanism mainly associated with transfer of forces through bond stress of column and beam longitudinal reinforcement. These forces are transferred through four boundaries of joint and form compression field with diagonal cracks in the joint and generate total diagonal compression force (Ds) in joint. The internal forces transferred from adjacent members to the joint creates diagonal compression and tension stresses in the form of strut and tie mechanism. This tie mechanism well supported by use of transverse reinforcement in the joint.

Figure (c) : Component truss mechanism associated with the situation when concrete is thoroughly cracked such that no more tensile stresses are transferred through concrete and transverse reinforcement contribute its part to resist the tensile stresses. The contribution of truss mechanism is more significant in this situation and provision of good bond is required between concrete and steel.

(v) Shear Friction theory: [SFT]

Shear friction theory applicable when direct shear transferred across a defined plane of weakness and slip may occur rather than diagonal tension failure. For example, planes of existing or potential cracks, interface between dissimilar materials, interface between elements such as webs and flanges, interface between concrete placed at different times etc are the situations where shear friction model is adoptable. The correct application of this concept depends on proper selection of assumed crack location or slip. This type of failure often happened at in-situ concrete when column concrete over laid after beam concrete during casting. To establish shear friction design, the reinforcement must be well anchored to develop full yield strength of steel and provide in the form of hooks or bends of reinforcement bars and properly anchored welded studs etc. As per ACI 318-02 and Euro-code EN 1998 , design requirements are well established , but Indian code not addressed any guide lines on shear friction theory. As per the studies of S.G Hong *et al*,.[24] shear friction truss model able to accommodate the contribution of dowel action by longitudinal bars, aggregate interlocking, and un-cracked compression zone .The model also able to predict the balanced failure between stirrups and longitudinal beam reinforcement. Shear friction resistance is proportional to concrete strength and contact area and is more effective in normal strength concrete.



SHEAR FRICTION THEORY

Figure shows an idealized cracked concrete specimen loaded in shear where the clamping force between two contact surface is provided by shear friction reinforcement A_{vf}. Hence the clamping force in vertical surface.(Fc)= force against slip= μ ($A_{vf.}$ f_y).During shear friction of inclined planes , if reinforcement placed at angle φ with shear plane, then nominal shear V_{sn}.Nominal shear resistance due to transverse reinforcement $\sigma_v = \gamma .\ f_y .\cos\varphi + \mu\ \gamma\ .\ f_y \sin\varphi$.

($\gamma = A_{vf} / A_{cv}$ and σ_v = Vsn / A_{cv} and Acv= area of concrete @ interface shear transfer)&Vsn= A_{vf}.f_y [cos φ + μ sin φ]

Based on the above discussed postulated theories, the authors proposed following shear models for shear calculations of beam column joints. They are (i) Ortiz strut model(1993), (ii) Parker & Bullman strut model(1997),(iii) Hwang & Lee strut and tie model(1999), (iv)Tsono's maximum principle stress model(2002) and (v) Empirical model proposed by Hegger et al [40] (2003). Ortiz model states that joint shear strength based on strut angle, strut width and limitation of maximum

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stirrups based on strut formation[33]. Parker & Bullman model consider based on critical inclination of strut based on provide maximum stiffness against shear displacement based on the considerations of strength of diagonal strut, stirrups, and strength of struts between the stirrups. Hwang & Lee considered strut and tie model based on equilibrium conditions, strain compatibility , and constitutive laws of materials. The author suggested three load paths in the joint region and joint shear force must able to resist forces in horizontal, vertical and diagonal mechanisms. Based on Mohr's principle stress theory, Tsono's *et al* .,considered uniform distribution of normal compressive stress and shear stress at middle section of joint. Hegger *et al*., considered shear strength of joint influenced by joint slenderness, column reinforcement ratio, normal stress on column and efficiency of beam anchorage and stirrups.

IV. Seismic Analysis of R/C beam-column joint

The basic principle mechanisms involved in failure of beam column joints are, (i) Shear failure within joint core (concrete), (ii) Anchorage failure of beam bars projected inside the joint (steel) and (iii)Bond failure of beam bars (horizontal shear) or column bars(vertical shear). Since joints are the smallest structural elements, it is essential to consider localized stresses in the analysis of joints. The analysis of joints are based on geometry and structural response of joint system. Accordingly joints are classified on the basis of geometry conditions and discrete boundary conditions in the moment resistance framed system. The discrete regions are one where the Bernoulli's hypothesis for linear deformation is not valid. The behavior of joint significantly influence the moment–rotation capacity of the connecting system.[10] The analysis of beam column joints classified according to geometry and structural response of the under which the connecting system of beam column sub-assemblage respond against the external force.

A. Geometric classification

As per the geometry, joints are classified as external, internal, and corner joints under continuous and discrete (knee joint) conditions of their locations with respect to plane frame and space frame models.

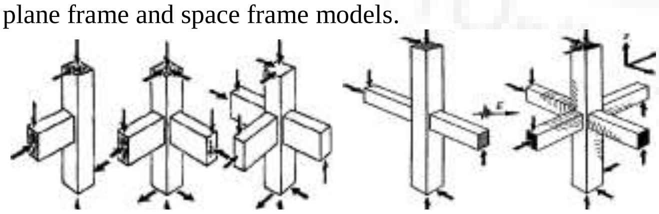
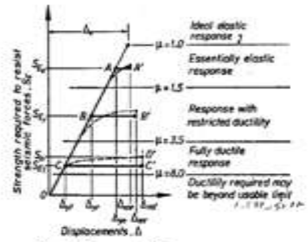


Figure shows Continuous beam column joins and forces acting

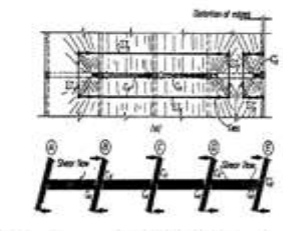
Figure shows Discontinuous beam column joins and forces acting

B. Classification based on structural response

Structural response of joints assessed under transfer of forces, shear, and failure modes when the joint shows elastic or inelastic response under gravity (Type-I connection) and seismic load (Type-II connection) conditions respectively. Type-I joint connection are the one which possess enough design strength and stiffness without significant inelastic deformation (un-cracked) during and after application of critical loads treated under elastic joints. During moderate seismic conditions this joints are respond within elastic range and deformation not increase significant storey drift.



Ductile Response of Joint



Flange Response of Joint (During Cyclic Loads)

Figure represents flange mechanism of joint during cyclic load conditions. During this process beam reinforcement subjected to compression in one side and tension on other side of joint induce steep force gradient in joint followed by excess shear and drift conditions. To sustain the force gradient, high amount of bond stresses required in joint core. During cyclic loads the degradation of moment capacity followed by excessive joint drift conditions may effectively controlled by joint detailing [Park & Pauley-1975]

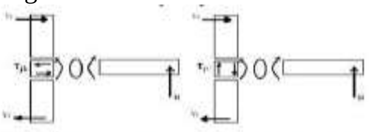
Type II joint connections are the one which sustain strength and ductility at in-elastic deformation and able to dissipate strain energy through reversal of deformation .This joints are analyzed under cracked section with appropriate strain control. In seismic design practice, assumptions are made such that plastic hinges expected to form in beam adjacent to joint. During seismic excitation of cyclic load conditions (cyclic loads apply alternate tension and compression) inelastic strains passed through external joint by yield penetration of embedded beam bars into the joint, causing yielding and slippage of bars which is responsible for anchorage failure. This result splitting development of cracks at beam column joint face and propagates up-to the tail of anchored bar which cause pull out of bars and lost flexural strength and leads to brittle failure of joint.

(i) Analysis of Exterior Beam Column Joint

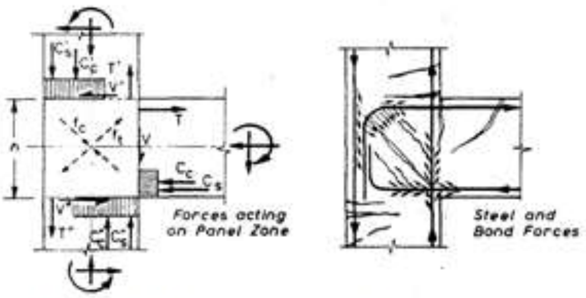
External beam column joints are often fail by shear and bond conditions due to inadequate anchorage length of bars persist which represent poor hysteresis conditions of cyclic loads [38].

Figure shows schematic representation of shear transfer mechanism in external beam column joint .The joint subjected to elastic deformations under quasi static loading conditions (gravity and wind) under moderate seismic conditions and the expected failures are in the form of shear and anchorage. Due to inadequate anchorage and stress concentration at anchorage location concrete wedge brittle failure may happen in joint core. From the position of stress resultant, it is apparent that diagonal tension and compressive stresses (f_t and f_c) are induced in the joint core. The diagonal tension is high when the adjoining members reached ultimate capacity which results extensive cracking.
The exterior beam–column joint is usually subjected to large shear forces due to lateral loading (Mohammad Shamim and

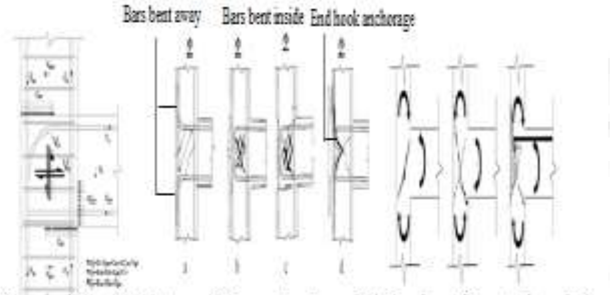
Kumar.V., 1999). The bending moments and shear forces acting on the joint give rise to both horizontal and vertical shear forces at the joint core . The situation becomes critical under large cyclic reversals of ground shaking, possibly causing extensive damage to the joints. In the ductile design approach, 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. The external forces acting on one face of the joint develop high shear stresses within the joint. Extensive cracking occurs within the joint during reversal loads which affects both strength and stiffness. Hence the joint becomes flexible enough to undergo substantial shear deformation. [28] &[29]



Horizontal shear Vertical shear
Forces acting on the Exterior Joint
(Source: ACI 318-02, 2005)



FORCE ACTING IN JOINT CRACK PATTERN



Shear transfer in exterior joint Development of cracks End hook anchorage-Concrete wedge mechanism

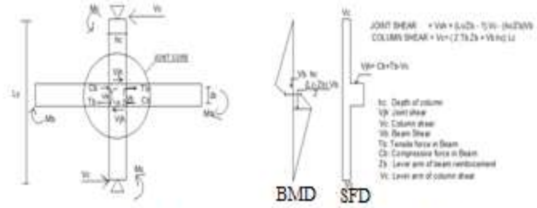
SHEAR TRANSFER AND STRESS DISTRIBUTION IN EXTERIOR JOINT

(Source: Park.R & Paulay.T)

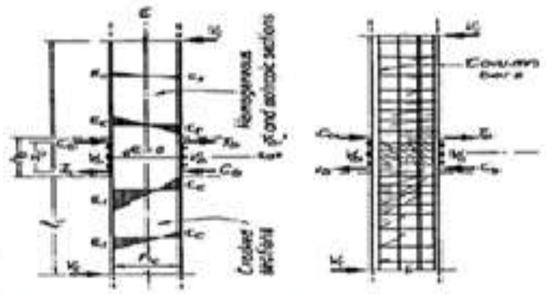
Notations: V_{col} = Vertical Column shear;
Vjh= Horizontal joint shear;
l_c = Effective length of column under shear]

ii) Analysis of Interior Beam Column Joint

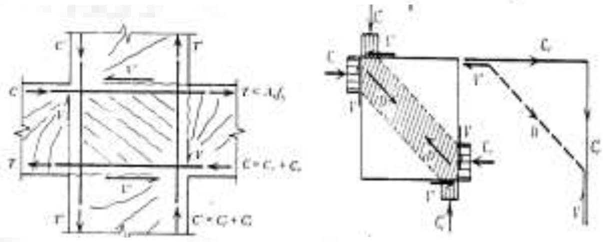
In the interior joint, the beam bars are subjected to push and pull effect by adjacent beams, which transfer forces upto strain hardening range in tension . In most practical situations, bond stress required to transmit bar forces to concrete in joint core, consistent with plastic hinge development at both sides of Joint. This could be very large and well beyond limits considered by codes for bar strength development. Bond slip seriously effect hysteretic behavior of ductile frames. About 15% reduction of bar strength result 30% reduction of total energy dissipation of beam column joint . The stiffness of frame is sensitive against bond performance of anchored bars which are passing through interior joint. Hence anchorage failure of beam bars is unacceptable at any stage as it result complete loss of beam strength. The shear demand of joint is influenced by ratio of flexural strengths of column and connecting beam.[43]



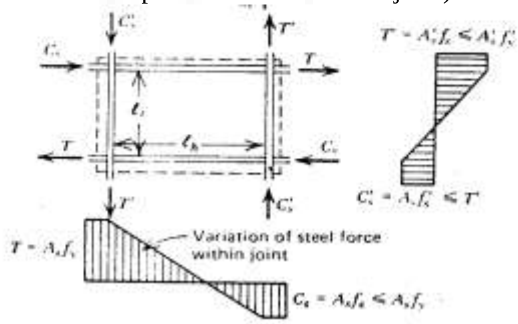
Equilibrium conditions-Type-II Internal joint



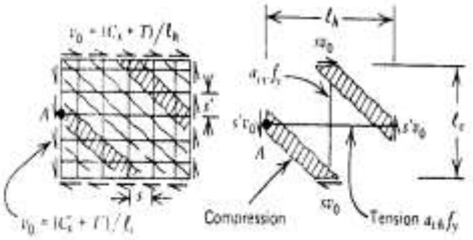
Forces acting on column Crack pattern in joint



(Internal forces & crack pattern) & (shear transfer by compression mechanism of joint)



(Forces acting in steel reinforcement of joint)



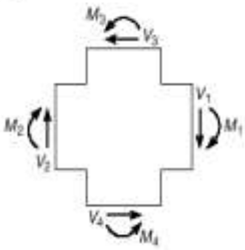


Figure d: (Transfer of loads in interior joint)
Stress distribution- Internal joint
(Source: Park.R & Paulay.T)

(iii) Analysis of Knee Beam Column Joint

Failure of open joint primarily due to formation of diagonal tension crack across the joint with outer part separated from rest. During seismic action stress reversal likely to occur in corner joints. Hence the joints should conservatively designed as open joint with appropriate detailing to show ductility. Stresses resulted from framing members transferred through bond along longitudinal beam bars and flexural compressive forces acting on joint face. Hence the joint must show enough strength and stiffness to resist induced stresses and to control undue deformations respectively during large deformations.

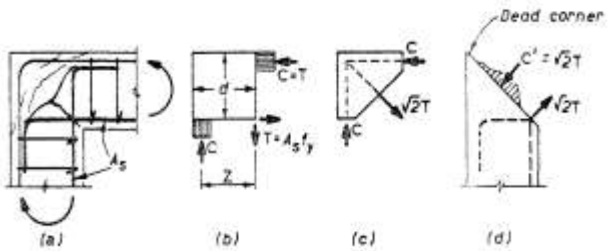


Fig i (a,b,c,d)

Force action and failure of open corner Knee joint

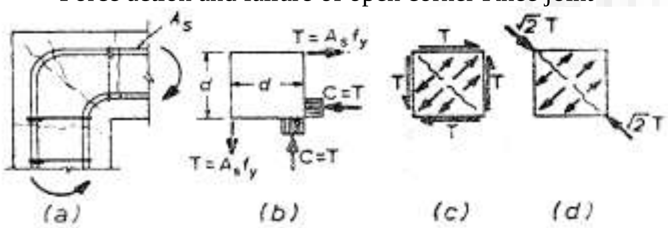
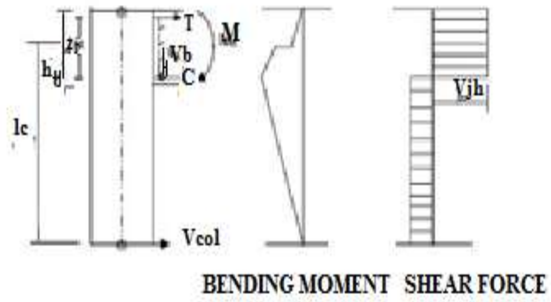


Fig ii: Failure in closed Corner joint



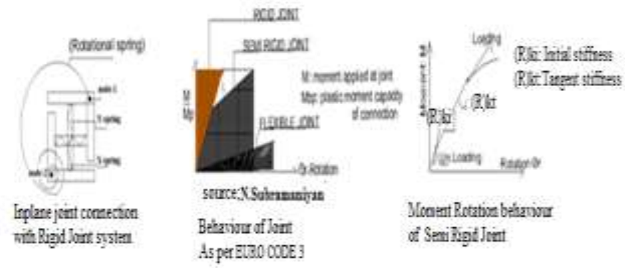
Notations: Figures representing
a) open corner joint b) internal forces
c) force pushing off joint d) force in joint diagonal

IV. Critical observations at impending failure of R/C beam-column joints

Unsafe joint conditions jeopardized the entire structure even the structural members fulfilled seismic requirements. The failure mechanism of beam column joint attributed to shear ,anchorage and bond failure as it was identified as weak source of energy dissipation. Typical damages of R.C beam column joints observed in the form of diagonal tensile cracks, crushing failure of concrete, outward buckling of stirrups, and yielding or bond slippage of reinforcement in the joint. Shear cracking and bond slippage are the major contributors of lateral storey drift in non-ductile beam column joints, which severely effect global performance of structure [1]. As per Shiohara, H., et al., 2001 [22] joints shows complex interaction between shear and bond. The bond performance of anchored reinforcement effects shear resisting mechanism to a significant extent. During cyclic loads , repeated yielding of longitudinal bars and diagonal cracking of concrete results spall of concrete results progressive slippage of beam reinforcement and anchorage failure in joint core. Use of high strength concrete, and design of smaller sections for high cyclic or gravity loads significantly influence the performance of joint at congested steel reinforcement.

i)Instability of moment resistance frame due to seismic behavior of joint

Application of seismic loads significantly influence the storey drift and soft storey effect. Usually storey drift leads to three types of global failures such as storey mechanism, intermediate mechanism and beam mechanism .As far as joints are concerned, three basic aspects influence the behavior of moment resistance frames. They are (i) Finite size of joint, (ii) Shear deformation of joint, (iii) Rotational deformation of joint at beam column connection. To evaluate frame instability, joint connections need to model directly in the analysis where the effect is significant. Such analysis is feasible through combination of rigid end links and internal spring elements. If P= direct force or moment applied on joint, k= stiffness of spring and δ= movement in the direction of force P, then [P=k.δ]. In the semi rigid frame analysis .The joint modeling with rotational spring and rigid links to beams and columns can be implemented as standalone element in RC structural system (Mazzoni-2010)



To assess the effectiveness of joints, the damage index proposed by Park & Ang (1985) [35a] more realistic compared to other seismic index proposed by the researchers. As per the literature studies seismic damage can be expressed as linear combination of damage caused by excessive deformation and damage accumulated by repeated cyclic loading effect.[11]

During second order analysis of inelastic joint design, yielding properties of material need to considered. Three methods of inelastic analysis are in use. They are (a) plastic zone method, (b) elastic plastic hinge method and (c) modified plastic hinge method. Through this material properties, residual stresses, geometric imperfections and second order effects and may improve erection sequence of joint system.

ii) Influential parameters at impending joint failure

1. As per Kuntz & Browing et al.,2003 [21] full structural mechanism of seismic joints develops only under strong column and weak beam conditions. To fulfill this condition, the ratio of sum of moment resistance capacity between column and beam ($\frac{\Sigma Mc}{\Sigma Mb}$) at joint must be greater than unity. Accordingly seismic design codes mentioned different values

(a) In view of economical design, future studies required to develop rational approach need to find the strength of joint for different moment capacity ratios of column and beam.

(b) The strength and stiffness of joint seriously effected by seismic loads. To avoid brittle failure, joint must ensure sufficient flexibility to substantiate the shear deformation. For retrofitting of joints in strong beam and weak column sections, there is a need for future studies about the proportionality of stiffness between column (Kc), beam (Kb) with respect to joint (Kj)

(c) There is a need to find moment curvature ratio of joint under partial fixity conditions to develop efficient joint system.

2. Distress in joints attributed to shear, bond and anchorage failure of beam bars which passing through joint core .This failures considered as brittle conditions due to weak source of energy dissipation. Hence the joint should posses enough strength and enable to develop ultimate loads in the connecting flexural members .Also the deformation should not increase storey drift. In view of safety aspects of joint, future studies need to know about how far the strength degradation of joint must allowed , such that the capacity of column should not effected to carry design loads.

3. The design of un-cracked joints influence development of tensile strength in concrete is more significant than compression as the initial failure of joint is attributed to tensile stresses at major principle plane. Shear reinforcement of the joint contributes to take tensile stresses only after formation of initial tensile crack in the joint .This phenomena directly influence stiffness of concrete specifically when joint system subjected to cyclic load conditions. Hence there is a need to improve initial tensile strength of concrete of joint core suitable means such as use of fiber reinforcement, high strength concrete and confinement of concrete etc.

4. During elastic behavior the effective sectional area of joint dimension required to support strut mechanism and adequate transverse reinforcement required to support truss mechanism. Increase of joint dimension reduces the effect of nominal shear stress of concrete. Hence most of the design codes considered the compressive strength of concrete during strut formation is reliable source to calculate nominal shear capacity of joint. Accordingly the codes restrict the nominal shear capacity based on compressive strength of concrete and axial loads acting on the column. But seismic design codes are uncertain to decide nominal shear capacity of joint for high strength concrete (fck > 50MPa) and light weight concrete.

5. Non linear behavior of joint system cause relative slip of anchored beam bars in joint and flexural cracking may results due to fixed end rotations at interface of beam column joint. Effect of this fixed end rotation is certainly high in precast concrete system as the design assumptions mentioned in codes are belongs to monolithic behavior of cast in-situ concrete (rigid joint system). Due to slippage of beam bars basic assumptions of rigid joint system and fixity conditions of sub assembly are partially obviated and partial fixity conditions developed in the connecting beam system which may subsequently enhance deflection of connecting beams, storey drift and P-δ effect under global scenario.

6. Flexible joint connections reduce beam end moments and increase span moments, which may results higher moments on column. As per the literature study , the semi rigid behavior of joint under partial fixity conditions reduce beam section and subsequently overall frame weight decreased by 7.2% compared with rigid frame, but the lateral drift increased by 18.5%.

(a) Hence drift limitations need to re-consider in frame analysis, as the joint is not in rigid conditions.

(b) The designer need to take absolute care to balance the overall building drift and connection stiffness for economic framing system.

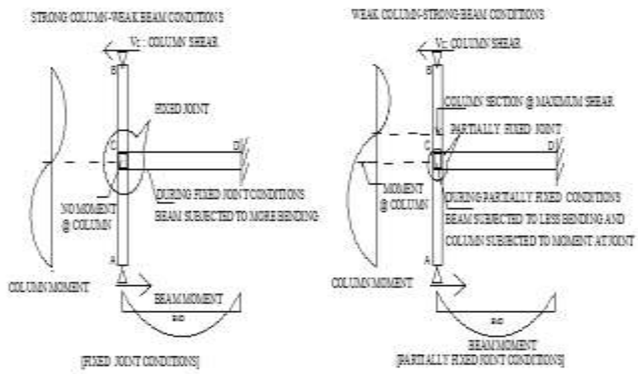
7. External beam column joints, inelastic cyclic loads cause bond deterioration at the face of the column. Due to yield penetration of beam bars, splitting cracks progressed towards the joint core aggravate further up to beginning of bent .This creates progressive loss of bond between steel and concrete and the longitudinal reinforcement bar get pulled out if terminating straight or loss of anchorage strength if bars are hooked inside the joint core. This ultimately leads to loss in flexural strength of beam and brittle failure of joint, which is an unacceptable situation. Hence, proper anchorage of longitudinal reinforcement of beam bars in the joint core is utmost importance for efficient joint performance.

8. The amount of horizontal joint shear reinforcement required in joint is more than normal conditions of large lateral loads of low axial load of column. As per the experimental studies, the function of joint hoop or spiral reinforcement is to carry shear as a tension tie so as to constrain the crack width but not to confine the concrete core [5], [38] Due to insufficient hoop reinforcement, inelastic strains ($\epsilon_s > 0.003$) occurred in stirrup ties makes further contribution of tensile strains. This leads to drastic loss of joint stiffness at low shear, specifically after a force or displacement reversal .The reduction of joint stiffness subsequently reduce ability of joint against dissipation of seismic energy.

9. Hooks are helpful to provide adequate anchorage when furnished with sufficient horizontal development length and a tail extension. Due to yield penetration in 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 by 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, provision of horizontal ties in the form of transverse reinforcement in the joint provides effective restraints against the hook when beam bars is under compression.

10. When the joint suffers inelastic rotations, ductility of adjoining members shifted towards the joint and makes a state of probable plastic hinge formation towards joint core. This ultimately results flexural yielding within joint core and global collapse of joint assembly. The phenomena stressed to maintain ductile property in R.C joints irrespective of loading conditions. And also concludes that joints should not accept transfer of ductility from connecting members. Hence during design phase of joint, considerations must given for ductile properties of joint with respect to its sub assemblage [2]

11. Shear strength of joint comprises three forms such as shear strength of plain concrete, shear strength of longitudinal steel of framing members, and shear strength due to web steel provided in joint by transverse reinforcement. Due to insufficient transverse steel, inelastic strains occurred in lateral ties and makes further contribution of the ties only when tensile strains imposed in joint system is larger than earlier developed. This leads to drastic loss of joint stiffness at low shear conditions, specifically during force or displacement reversal .The reduction of joint stiffness subsequently reduce its ability against dissipation of seismic energy[44].
12. Structural ductility essentially comes from member ductility through which inelastic rotations and deformations occurred. Plastic hinges are the allowable locations through which inelastic rotations of structural damage allowed in beam (beam yielding mechanism) rather than column (storey mechanism) or any part of the structure. If storey mechanism allows, then the resultant inelastic rotational demand is very high and very difficult to cater by any possible detailing. Through proper detailing hinge formation in beam mechanism can be promoted during inelastic response of structure.
13. Incorrect bending of reinforcement in joint core prevents diagonal strut formation, which results diagonal crack formation in joint and ultimately leads to shear failure. When the internal load path in joint assessed in the form of truss system, then steel takes tension and concrete in compression, which shows good working safety in design of joints.
14. As per the failure theories, behavior of un-cracked R.C beam column joints may consider under maximum principle stress theory or maximum shear stress theory. Failure mechanism of cracked joint is in elastic conditions associated with modified compression field theory and strut-tie methods (CCT model). The non linear behavior of joint can acceptably studied under moment rotation curves (which shows lower complexity, easiness of application and good prediction of experimental behavior) through which joint behavior can be studied with the help of stress strain curves drawn between concrete and steel (include tension stiffening effect). For more realistic approach of joint behavior, bond slip between steel and concrete at interface of joint region need to consider.
15. Designers are often taking care about seismic detailing of beam, column, foundation and other structural elements to show ductile behavior of structural system but they often neglected or unable to give proper detailing about R.C joint system. This results formation of weakest link at joint and suspected brittle failure may happened.[38]
16. Joint shear demand increase with high axial load on column. At lower axial loads of column, joint shear increase with beam load. In both case, increment of joint shear is independent of the beam and column loads respectively[12] [4]. Effect of column axial load (P< 0.3 fck) does not show any influence on bond resistance of joint and axial load less than 0.5 fck does not influence joint shear strength.[18]
17. During moment reversals of frames, identical connection at end of the beam may not always behave identically. The lateral loads the lee-ward joint connection of beam-column bent continues to hold higher load and acts as a pinned joint and windward joint connection is unload and acted as a linear elastic connection with stiffness equal to initial stiffness. Hence the stiffness of joint connections are different. The shear strength of joint degrade during multiple inelastic deformation reversal specifically when the column axial loads are low. In such cases contribution of shear by concrete is (Vc=0) negligible and shear reinforcement in joint takes the total shear.[NIST-GCR]



Influence of Fixity conditions in beam column joint

18. The current state of design practice assume fixed joint conditions of beam column joint, which ensure more bending moments in beam and less bending moments in column at joint location. But in real practice, due to the partial fixity conditions the exhibit less beam moments and more column moments are produced at joint, which leads to soft column and weak beam conditions. In this situations, maximum shear occurred away from beam column joint location , where the column section not designed to take lateral shear. This phenomena significantly influence the performance of R/C column and leads to brittle failure

4. Conclusions

Indian subcontinent experienced growing seismic activity from the past decades. But the present Indian seismic codes are unable to fulfill the seismic design requirements of R/C beam column joints in the moment resistance framed structures. Most of the seismic design standards are still envisaged. From the comprehensive studies it was found that there is a considerable technical gap existing between the present design codes and available research data. In this context, most of the high raised R/C framed buildings in the country which are already constructed and proposed to construct in seismic zones (Zone III,IV, and V) are more susceptible to failures during moderate and high seismic conditions and the designers are deprived and uncertain about the various influential parameters to be consider in the seismic design of beam column joints. Lack of design information about key influential parameters in design of joints are the important consideration for improper design. And without appropriate modeling, designers are deprived to use even rational methods and the codified procedures may not offer best solution to analyze the R/C beam column joint under constrained geometric conditions. In this context postulated theories helps to identify the influential parameters and provides good evidence of joint behavior based on the conceived models. This ultimately helps to proceed for experimental works in the right direction rather than producing wealth of data. Hence this article focused on relevant postulated and empirical theories on R/C joints and how to correlate influence of analytical theories with experimental data for evaluate most appropriate behavior of reinforced beam column joints and related key influential parameters

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