Seismic Damage and Fracture Mechanism of Reinforced Concrete Beam-Column Joints

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Abstract: ***Seismic damage of Reinforced concrete (R/C) framed structures are significantly influenced by the performance of beam column joints. Most of the critical damages are happened in R/C. beam column joints and the extent of damage depends on integrity and redundancy of structural members associated with joint connectivity .Force transfer mechanism (FTM) in R/C joint is a key issue to be addressed for good seismic performance of a joint. Fragility of R/C joints are in the form of non ductile shear failure prior to beam yielding and ductile failure after beam yielding. This localized damage in joint significantly influenced the progressive collapse of global structure. This article provides necessary information about seismic vulnerability and fracture mechanism of R/C beam column joint and relevant stress field theories based on force transfer mechanism (FTM) due to synergistic effect of both external forces and internal reaction of materials are well established for joints. The reduction of joint reinforcement possible by consider joint strength as part of complete FTM, but not under independent shear strength of steel and concrete alone. This assessment helps to provide less conservative reinforcement detailing of a joint to mitigate constructability issues of fabrication and concreting of joint***.

Keywords: Beam column joint, Force transfer mechanism, Fracture conditions, Synergistic effect.

1. Introduction

The current state of seismic practice in R/C beam column joints is familiar with capacity design approach where the formation of plastic hinge is predefined. Plastic hinges are preferred in the beam adjacent to column .During seismic excitation high bond stresses developed at plastic hinge location of beam reinforcement and results considerable amount of bond slip in beam bars. During cyclic loads bond slip results deterioration of bond in anchored bars that is more significant as the compression steel subjected to tension and vice versa near the joint face. This will considerably reduce the flexural strength of connecting beams. Hakuto et al.,(2000)[28] studied these effects and concluded that the moment capacity of beam significantly reduced (10% for positive moment and 5% for negative moment of beam) due to bond deterioration of during reinforcement yielding [17]. Hence effective modelling of elastic stiffness is essential for good ductile design of beam column joint. A ductile joint establish plastic yield point in the connecting beam as per the requirements of capacity design. MJN Priestley et al(1978) [29], addressed seismic design philosophy of joints through force transfer mechanism (FTM) where strut and truss models (STM) are initiated. From the established literature, it is understood that the internal force transfer mechanism of beam column joints are in the form of strut and tie mechanism (STM). Since STM is a discrete representation of stress flow in a joint, it is necessary that connecting elements must locate at centre of respective stress path so as to improve stress distribution phenomena in the joints. Shear, bond, ductility and stiffness are the important parameters to be consider in the design of beam column joint. The in-plane action of seismic forces cause joint rotation at interface of beam-column and shear deformation within the joint core. Since STM is a discrete representation of stress field used to represent compression and tensile stress fields within a joint, the linear stress-strain distribution is not applicable. Formulation of comprehensive STM provides a reasonable prediction of elastic stiffness and strength components of beam column joint system[21]. Reduction of joint reinforcement may achieve by treating the shear strength of joint as part of complete force transfer across the joint but not considerable under independent action steel and concrete [18].Fragility of R/C joint system may reasonably assessed by moment curvature response of R/C joint system [23].

2. Importance of the study

Identification of fracture modes in beam column joint is essential for damage limitation at ultimate state of failure in beam column joint. Since STM is a discrete representation of stress flow in R/C joints, structural elements need to be placed at centre of the respective stress path in efficient joint models. Internal force transfer mechanism of R/C beam column joints are significantly influenced by detailing of reinforcement and support conditions of constitutive elements. This study provides necessary information about stress field and fracture mechanism of joints as per force transfer mechanism (FTM).This will helps to provide less conservative reinforcement detailing in beam column joints and to mitigate constructability issues related to the joint.

3. Fracture Mechanism of R/C Beam-Column Joint

Fracture mechanics of joints is related to the formation and propagation of cracks leading to failure of joint component or material assembly. The present state of engineering practice follows material tensile strength as basic criteria but it is unable to fulfil objective results and fracture tests. Hence the approach is modified as energy releasing capacity in fracture mechanics. In this the joints are established by developed crack pattern (stress based criteria) and strain rate (energy based criteria) of joint element. This provides a realistic approach for analysis of cracked surface which is based on fracture toughness of material and releasing strain energy rate of joint core. Two types of fracture mechanisms are generally involved in joints. They are (i) Brittle fracture and (ii) Ductile fracture. This classification is based on catastrophic or steady state of crack propagation in joints. In the ductile fracture, plastic deformation of material taken place before crack nucleation and steady state of crack propagation is happened due to fracture failure stress is greater than yield stress of material. The state of stress and strain rate significantly influence the fracture mechanism of joint core. Under high strain rates the joint core behaves brittle even ductility imposed in the material[23]. Hence fracture toughness of joint core significantly influenced by the state of strains developed during seismic excitation.

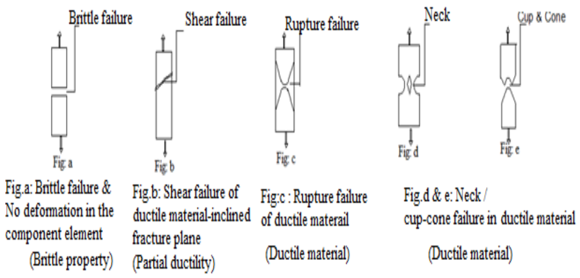
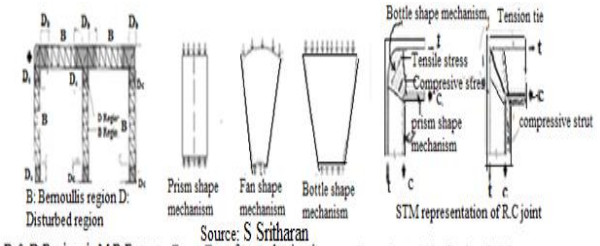


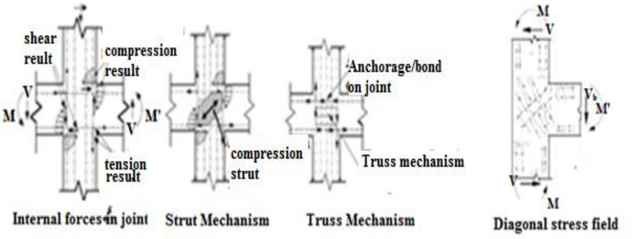
Fig : a, b, c, d, e: Shows Modes of fracture failures in component elements



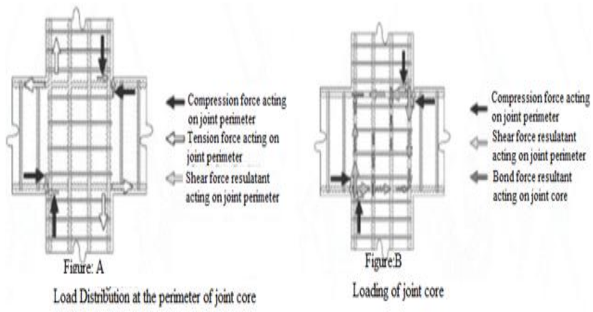
B & D Regions in M.R Frames Force Transfer mechanism in concrete Stress Distribution in joint

Structural response of R/C joints are basically categorized under B-region (Bernoulli region) and D-region (Disturbed region). This categorization is essential as the structural members distinctively respond in the above regions .The fracture mechanism of R/C joint in D-region is associated with a sequence of operations such as force transfer, stress distribution and failure mode in joint core.

From the past observations, Force transfer mechanism (FTM) in R/C joint is well established by strut and truss model (STM). Shear force is the most predominate factor in FTM of joint core. During in-plane action of shear force, the associated strut formation generates compressive force in the form of prism shape, fan shape and bottle shape mechanism as shown in figure. Prism shape stress fields expected in B-region and fan or bottle shaped stress fields developed in D-regions. Due to under confinement premature failure of concrete under crushing is quite obvious in bottle shaped stress field. To avoid this type of failures concrete in joint core should be adequately confined or reinforced. The strut formation in joint core may influenced by tensile strength, confinement and compression softening effect of concrete. Truss formation in joint core helps to accommodate tensile forces generated in the joint. During in-plane action of shear force, the truss formation associated with longitudinal reinforcement of beam and column bars coupled with shear reinforcement provided in joint core. For an effective STM a good bond must exists between concrete and steel in joint core.



Stress field distribution in joint core influenced by direction and intensity of forces acting on the joint. During in-plane stress conditions the joint core associated with the formation of compression strut and tensile truss at edges and center. Prism shape stress field occured at re-entraint corner of compression zone and bottle shape or fan shape stress field occur between the re-entaint corner of joint where the stress transformation happend between compression to tension vice versa. Fan shape and prism shape mechanism can avoid by good detailing practice and bottle shape mechanism can avoid by considering the contribution of concrete and transverse reinforcement in joint (Joh et al.[19], 1993). Due to in-plane shear conditions, cracks developed in the principal planes of weak zones in tension and crushing of concrete happend due to formation of compression strut..Formation of fracture planes are significantly influenced by geometric conditions,detailing of reinforcement and lateral confinement of joint core.



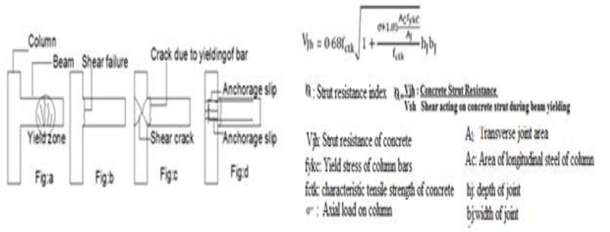
(Figure:A): From the figure, beam and column moments are transferred in to the joint through tension force resulatant carried by frame member longitudinal reinforcement of steel and compression force resulatant carried by frame member of concrete.The shear force is transferred in to the joint through concrete in the vicinity of frame member flexural compression zones shown by hatched arrows in the figure(loading distribution at perimeter of joint).

(Figure:B): Representing loading of joint core is an idealised action of loads on joint core. Here the compression and shear force directly acting on the perimeter of joint core, while tension forces carried by the frame member steel reinforcement are assumed to transfer in the joint core through distributed bond forces.

4. Conditional Assessment and Fracture Failures in Beam Column Joint

Failure of beam column joint is associated with shear deformation within joint panel and rotational distortion at outside of joint panel. The key mechanisms involved in joint failures are compression strut failure, truss failure due to insufficient shear reinforcement and bond failure of anchored beam bars. The internal action associated by framing members of joint panel is in the form of cumulative crushing of concrete by flexural action, tensile cracking of joint by shear, and bond slip of embedded bars plastic yield and stress reversal conditions. During seismic excitations the conditional assessment of joint failure and its connectivity system may study under four typical situations as followed.

1) Beam failure when beam develop plastic hinge (Fig:a)
2) Joint failure in shear without beam yielding (Fig:b)
3) Beam-joint failure when beam yielding precedes joint shear failure (Fig:c)
4) Joint-beam failure when joint loses its contribution of resistance followed by beam failure. (Fig:d)



Fracture failure conditions in R/C beam column joint   Strut resistance of concrete mentioned by Russo

1) **Beam failure when beam develops plastic hinge**: (Fig :a) This condition exists when strut mechanism of joint concrete not failed compressive forces generated during large in-plane shear conditions and existence of good confinement in joint concrete and sufficient anchorage of beam reinforcement in joint core. This is an ideal condition of seismic capacity design where strong column and weak beam conditions are persists. In this type of failure, the joint posses enough strength and stiffness and the connecting beam is ductile in nature. There is good transfer of forces exists between the joint and it's sub assemblage. According to Russo et al., [6] (2004) the strut resistance (Vjh) calculated by the empirical formulae mentioned above.
2) **Joint Failure in shear without beam yielding (**Fig: b) This type of failures are most frequently observed in beam column sub assemblage due to high shear conditions prevailed in non ductile joint system. In this type of failure, the connecting beams posses enough stiffness and strength but the force transfer mechanism from joint to beam was not effectively carried due to various conditions which was discussed below. Y.Goto and O.Joh (1996) stated that during the conditions of non yielding of beam, the joint shear strength was not influenced by the horizontal reinforcement as the diagonal strut action supported by both beam bars and joint reinforcement proportionately.

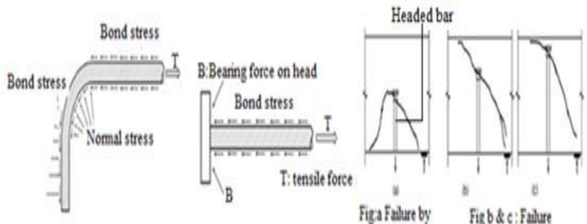
a) Failure of strut mechanism: This is due to strut failure in joint core. The nature of failure may categorized under confined or un-confined conditions of joint concrete. If the confinement persists, then concrete fails in compression with minimum deformation. If un-confinement persists in joint core, then joint fails due to both compression strut failure and tension yielding of shear reinforcement.

b) Failure of truss mechanism: If the connecting beam to the joint not reach its yield capacity due to truss failure and if stirrup yields then joint failure may happens in the form of strut failure, due to most of shear carried by concrete strut. However a portion of shear is taken by longitudinal beam bars as long as proper bond maintained between concrete and steel. The failure mode is summarized under concrete crushing by existence of high shear stresses

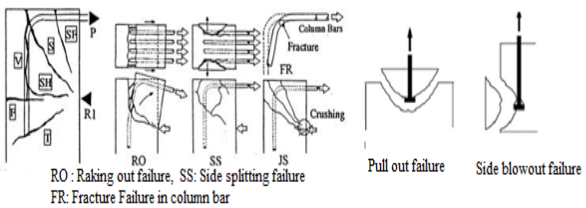
c) Slippage of beam bars: Slippage of anchored bars significantly influence the strength of joint and connected beam. In this type of failure, even there is good existence of strut and truss mechanism of joint core (strut mechanism contributed geometry and truss mechanism contributed by reinforcement detailing), the lack of bond existence between steel and concrete results slippage of beam bars. This results loss of truss mechanism in the joint core and strut mechanism only contribute transfer of shear forces in joint core. The slippage of bars significantly influence fixity conditions of beam column joint and results decrease in flexural strength of connecting beam as the fixed boundary conditions are changed to partial fixity. The failure in concrete may happened in mode of prism or bottle shape.

d) Anchorage failure in hooked beam bars: This type of failure happened when high a tensile force produced in anchored beam bars of joint region was not suitably compensated in joint core. If large number of longitudinal beam bars anchored into the joint then anchorage failure precedes shear failure due to lack of confinement and bond resistance in joint core. Three type of anchorage failures are observed due to anchorage failure. They are side split failure, local compressive fracture, fracture failure of column bars and raking out failure.

Side splitting (SS) failure occurred when concrete located adjacent side of bent radius is fractured due to the inadequate cover. Local compressive fracture is happened when concrete located inside the bent portion is fractured due to high bearing stresses when the bent radius is not enough large for smooth stress flow. The failure associated with development of split tensile stress inside bent portion of bars.



Transfer of forces in Hooked bar   Transfer of force in Headed bar
Failure modes of joint in Headed bars



Typical Anchorage failure in hooked bars   Typical Anchorage failure in headed bars

Raking out (RO) failure happened due to high tensile stresses exists by anchorage. To accommodate this tensile forces if enough cover not provided in front of concrete then concrete portion is raked out as single element and get separated from the joint.

The ultimate stage of this failure leads to opening of crack by bond failure at tail end of the bar. Fracture failure (F.R) in column bar happened at the bent portions of the column bars fractured due to reversal of bending stresses as the stress concentration happened at bent portion. As a result shear deformations increased in the R/C beam column joint.

e) Effect of confinement:

In adequate confinement of concrete in joint core significantly influence t.he transfer of stresses between steel and concrete. Shear deformation of joint is in the form of strut and tie mechanism. Due to ineffective confinement truss action nullified as the yield of stirrups taken place in joint core. Hence during high shear conditions, the failure of concrete happen by existence of principle tensile stresses developed in concrete. The mode of failure is in the form of prism or bottle shape mechanism and concrete is subjected to severe crushing or shear failure. The failure is pertained to joint only and does not make any contribution of sub assemblage elements.

iii. Beam-joint failure when beam yielding precedes joint failure: (Fig: c)

This types of failure occurred when the ductility of connecting beam is high compared with joint. Transfer of high shear conditions from joint panel to beam creates zones of high tensile stresses prevailed in beam reinforcement. This obviously creates tension softening effect in steel bars and subsequent plastic hinge formation in beam. Presence of high tensile and compressive forces during reversal stress conditions of cyclic loads further anticipate the yielding of beam reinforcement. Cracks are observed in the form of wide vertical shape initiated at bottom of beam and progress in upward. Interface stress transfer between beam and column is a critical issue in this type of failures. The failure is anticipated by slip of beam bars during non linear behaviour of joint. Considerable strength reduction of connecting beam results during this failure and ultimately results ductile failure of beam before joint failure. Slippage of reinforcement creates high drift conditions.

iv. Joint-beam failure when joint failure by shear after beam yielding: (Fig: d)

This type of failure represent failure of joint followed by beam due to high tensile strains developed by shear deformation of joint panel. This ultimately creates yielding of anchored bars of joint core. Yielding of joint reinforcement significantly influence the cracked concrete strength and shear strength of joint [16]. During this process, shear reinforcement in joint panel lost its contribution for transfer of shear due to plastic yielding of reinforcement taken place at high shear conditions. Due to ineffective shear transfer between joint and connecting beam leads, shear failure occurred at interface of beam and joint. During this process, the strength of beam significantly influenced by the boundary conditions of partial restrained or hinged conditions at this failure. Also the connecting beam lost its support conditions and proceeds sudden or brittle failure at interface of beam and joint connection. Lack of joint ductility and transfer of high shear and lack of continuity of beam bars due to yielding are the key parameters during this failure. These types of failures are more often in non-seismically detailed R/C beam column joints.

In this type of failure, large plastic rotations occurred at joint panel. The embedded beam reinforcement in joint core do not make significant influence on dissipation of energy during this failure. The studies of Hyogo-ken Nanbu earthquake (1995) in Japan experienced the situations where large displacements of joint shear failure occurred even the frame designed for ductility to meet capacity design requirements [7]. Joint concrete deterioration would occur, because of the shear cracking or bond deterioration by cyclic loading after beam yielding**.** To avoid this type of failures, the influence of joint shear deterioration on prior to beam yielding should consider first[l]. The joint shear strength may increase by presence of transverse beams.

V. Theories on Shear Transfer Mechanism of R/C Joints

Shear transfer mechanism of Reinforce concrete (R/C) beam column joints are associated with the following analytical theories based on the mechanism of crack pattern and stress distribution. In the performance based seismic joints, displacement theories are more appropriate than strength based theories for computing of joint forces. Some of the established theories are presented here for basic understanding of stress transfer in joint core. Principle stress, modified compression and strut-truss theories are force based and critical shear crack ,segmental approach are displacement based theories.

i) Principle stress theory
ii) Modified compression field theory
iii) Strut and truss theory
iv) Critical shear crack theory
v) Generic based segmental approach

In the principle stress joint models, the complex stress transfer in joint core due to application of axial, shear and flexural loads, results development of principal stresses (σ_1 and 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.

Modified compression theory provides a unified rational approach in the analysis of R.C joints at in-plane stress conditions. It provides conceptual model on behaviour of cracked concrete section under two dimensional stress conditions. Accordingly the cracked section treated as a new material with empirically defined stress strain conditions.

As per strut and truss theory, the internal force transfer mechanism in joint is in the form of diagonal strut and truss formation .The strength of concrete 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 truss mechanism associated with transfer of forces in shear reinforcement. The contribution of both mechanisms is involved for assessment of shear strength in joint core

Critical shear crack theory is based on the kinematic mechanism at failure rather than empirical formulae. In this approach, shear strength assessed by aggregate interlocking property. The residual tensile strains and doweling action in the cracked region calculated by fundamental constitutive laws responsible for critical shear crack opening. The transfer of forces is a function of crack width and directly related to rotation of the joint component.[0]

Generic based segmental approach [3] is more versatile shear modelling of a joint, where the shear fracture is associated with considering partial interaction mechanism such as tension stiffening ,confinement etc. This approach helps to prepare shear models of joints with innovative materials such as use of high strength materials, fibre-reinforcement, and geo-polymers etc, in the joint core. Segmental model simulate all mechanism associated with shear failure of joint. It is displacement based analysis approach

VI. Classification of Ductile Connection in Beam Column Joints

Based on type of mechanism and energy dissipation system involved during seismic excitation, ductile connections of beam column joints are classified under the following systems. From the past earthquake happenings it is observed from the literature study that in some situations joint failures may happened even after ductility of elements maintained. To avoid this type of failures, the author concluded that there must be a rationality maintained between the ductile capacity of joint and its sub-assemblage (Reduced beam section near joint called as "Dog bone") Dog-bone system improves the situations of plastic hinge formations in the selected locations, so as to improves collapse mechanism.

i) Tension or Compression yielding system (Figure :a)
ii) Shear friction system (Figure: b)
iii) Non linear elastic system (Figure :c)
iv) Shear yielding system.(Figure :d)

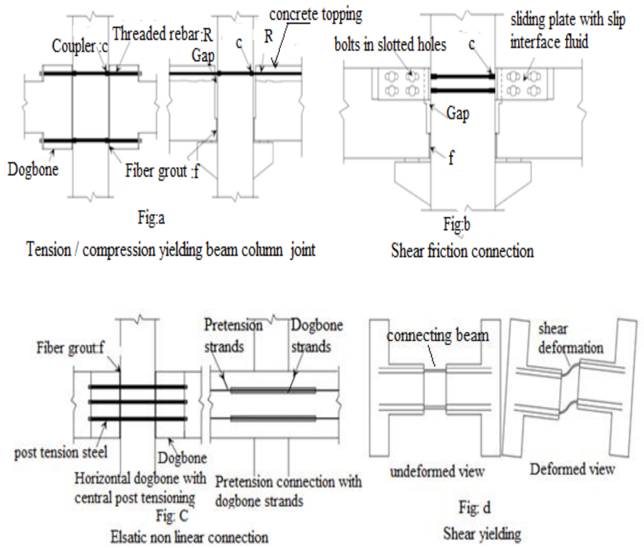


Fig:a
Tension / compression yielding beam column joint

Fig:b
Shear friction connection

Fig: C
Elsatic non linear connection

Fig: d
Shear yielding

In the tension yielding system (Figure: a) the energy dissipated by yielding of connecting elements, and the connecting elements are allowed to yield in both tension and compression. For some connections, tension/compression yielding takes place on one side of the beam (top or bottom) while the other side behaves primarily as a pivot point to permit only the rotation. To achieve yielding in both tension and compression in that location, a gap was left between the beam and column. This type of connection also called as "gap-joint" connection.

In shear friction connection (Figure: B) the energy is dissipated through friction when slip occurs between connecting elements. Special material can be used to enhance the slip behaviour. The advantage of this connection is reinforcing steel does not yield, resulting in cracking in the precast members that is relatively small even at large displacement level. This concept can be used as in the tension/compression connections where slip occurs on one side of the beam while the other side permits only rotation. A gap also must be provided to allow the slip to occur in both directions.

In the non-linear elastic connection (Figure: c) nonlinear behaviour achieved through crack opening and closing at the interface between each beam and column. This nonlinearity is related to geometric nonlinearity rather than material nonlinearity. Beams used in this connection type were pre-stressed with tendons un bonded through the joint and for some length on each side of the column. Cracks or joints at the column face open when bending moments produce flexural stresses large enough to exceed the pre compression stresses at the face of the column .pre-stressing steel does not yield if it is un bonded over an adequate length. The behaviour of this connection type is completely different from the first two types. In this connection type, energy dissipation is minimal. However, because of the pre-stressed beam, only small residual drifts are expected following strong ground movement. As a result, this connection also described as "self-righting. During shear yielding (Figure: d) the rigidity of concrete frame may promote to develop shear yielding in structural steel element. Consequently, energy is dissipated when yielding occurs in the steel element. This type of failure is with good consideration in capacity design of R/C moment resistance framed connections but the shear yielding should not promote tensile strains in joint core.

5. Parametric Influence on Shear Strength of Joint

As per the literature studies, the parametric influence on shear strength of R/C beam column joint is widely diversified. It is understood that the concrete compressive strength, normalized vertical joint shear reinforcement, normalized column axial stress and normalized horizontal joint shear reinforcement and beam bars are the most influential key parameters which effects the shear strength of joint[1]. The joint shear strength is little influenced by the axial load of column and the increment is proportional to column axial load[20]. The column load significantly influence the failure pattern of joint. Similarly joint shear increased with joint aspect ratio (h_b/h_c).The joint aspect ratio shows minimum effect on shear strength if the failure mode is pertaining to joint only. If the failure mode is related to beam joint failure, then the shear strength of joint reduced with increase in joint aspect ratio[13]. There is minimum and maximum limitation of transverse reinforcement in joint panel such as 0.30% and 0.40% respectively [21][10]. Accordingly the seismic design codes ACI318-02, NZS 3101-1995 etc implement limitations on nominal shear strength of joint panel (Taylor et al.,1974, Hamil et al.,2000 and Wong 2005). But to satisfy large anchorage, shear and confinement requirements of joint core, the reinforcement limitations are often obviated by the designers, and results brittle failure of R/C beam column joint.

6. Conclusions

The present seismic codes does not consider synergistic effects of joint mechanism during shear strength calculations of Reinforce concrete beam column joint. As per the existing codes, the shear strength of joint is a sum of shear contribution of concrete (strut mechanism) and shear contribution of steel reinforcement (truss mechanism) in joint core. Hence this approach under estimated the joint strength and develop incompatible stress conditions between th materials consumed in joint panel. From the past research it was identified that the present state of design calculations are not considerably representing the actual strength of beam column joint. Hence there is a need to reconsider the effect of interaction mechanism of forces (such as strut and truss mechanism) and interaction of material behaviour while assessing the joint strength. For example contribution of stirrup reinforcement has emphasised no meaning to improve shear strength of concrete in joint core, but many Researchers (TaoZan et al.,2015, Yu Basant et al.,2011 and Chabib EL.et al.,2011) stressed about the presence of stirrups in joints significantly improves shear strength of concrete through confinement and bond. During this process, the consideration of synergistic effects of both external forces and internal reaction of materials of joint is well established by force transfer mechanism (FTM). FTM provides useful means to identify threshold limit and boundary conditions of various shear theories and identifies the stress distribution, mode of fracture failure of joint under synergistic conditions. This ultimately helps to improve detailing requirements of reinforcement and provides less conservative reinforcement in R/C beam column joints.

References

[1] Francesco Cavagnis∗ , Miguel Fernández Ruiz, Aurelio Muttoni , A mechanical model for failures in shear of members without transverse reinforcement based on development of a critical shear crack, Engineering Structures, Elsevier publications-2018

[2] Minh Tung Tran, Influence Factors for the Shear Strength of Exterior and Interior Reinforced Concrete Beam-Column Joints, Procedia Engineering 142, pg 63-70, Elsevier publications, 2016

[3] Y.Goto, K NishimuraH.Yamazaki- Anchorage failure and shear failure of RC exterior beam column joint, proceedings of 15th world conference on Earthquake Engineering, Lisboa, Italy , 2015

[4] Tao Zhang, Phillip Visintin ,Deric john Oehlers, Shear strength of R.C beams with steel stirrups, Journal of structural Engineering, 2015

[5] Jalil shafaei, Mohammed Sajjad,2014, Effect of joint flexibility on lateral response of reinforced concrete frames, Engineering structures, pp412-431,Elsevier publications, 2014

[6] Angelo Masi, Study of Seismic behaviour of external R.C beam column joint through experimental tests and numerical simulation, Elsevier publications. 2013

[7] Giuliana Somma, Alessandro Pieretto, Tiziana Rossetto, Damian N Grant- A new approach to evaluate failure behaviour of reinforced concrete beam column connections under seismic loads, proceedings of 15th world conference on Earthquake Engineering, Lisboa, Italy -2012

[8] Goto Y, Nishimura K, Yamazaki H, Kitano A, Anchorage failure and shear failure of RC exterior beam column joint 15WCEE, Japan-2012

[9] Muhamad R Ali , MSM Oehlers, Griffith M , The tension stiffening mechanism in R.C Prisms, Journal of Engineering structures, Elsevier publications, 2012

[10] Muhamad R Ali , MSM Oehlers , Sheikh A.H , Load slip relation of tension reinforcement in R.C member, Journal of Engineering structures, Elsevier publications,2011

[11] Wong H.F ,Modeling the earthquake response of older reinforced concrete beam column joint , Ph.D dissertation , Hong kong University of Science and Technology. 2005

[12] Hitoshi Shiohara, Quadruple,Flexural resistance in R/C beam column joints, 13th World Conference on Earthquake Engineering,Vancouver, Canada,2004

[13] Bakir PG , Bonduroglu HM , A new design equation for predicting the joint shear strength of monotonically loaded exterior beam column joint, Engineering structures,(24) pp 1105-1117. 2002

[14] Kaung JS , Wong Sheikh A.H , Load slip relation of tension reinforcement in R.C member, Journal of Engineering structures, Elsevier publications,2011 HF, Effectiveness of horizontal stirrups in joint core for exterior beam column joints with non seismic design ,Procedia Engineering, pp 3301-3307. 2011

[15] Mergos, P.E., and Kappos, A.J., "Seismic damage analysis including inelastic shear–flexure interaction". Bulletin of Earthquake Engineering, 8, 27-46. 2009.

[16] Hamil, Stephen J(2000) , Reinforced concrete beam column concrete behaviour, Durham thesis, Durham university.

[17] Osamu JOH. Yasuaki GOTO , Beam column joint behaviour after beam yielding in R/C ductile frames, International conference, 12WCEE, Japan ,Elsevier publications, 2000

[18] Hakuto S, Park R, Tanaka H, Seismic load test on exterior and interior beam column joint with substandard reinforcement details, ACI struct Journal. 2000

[19] S.Sritharan [a]M.J Nigel Priestley[b] FriederSeible[b] Nonlinear finite element analyses of concrete bridge joint systems subjected to seismic actions. Elsevier publications.1999.

[20] Kamimura et al. 2000, Y. Goto and O.Joh 1996, An Experimental study on shear failure mechanism of R.C interior beam column joint, 11th World conference on earthquake engineering, Japan, Noguchi and Kurusu 1988, Blakeley et al. 1973, Lee et al. 2009, Joh and Goto 2000, Noguchi and Kashiwazaki 1992, Owada 2000, Kitayama et al. 1992, 1987, and 1991,.

[21] KITAYAMA K, Shunsuke OTANI and Hiroyuki AOYAMA, Design of beam column joints for seismic resistance,ACI-SP.123, pp97-123,Michigan- USA.1991

[22] Kitayama.K , Otani S , Ayoma H, Earth quake resistance design criteria for reinforced beam column

joints, proceedings of pacific conference on Earthquake engineering , Wairakei, New-Zealand,pp315-326, -1991
[23] Vecchio FJ , The modified compression theory for reinforced concrete elements subjected to shear , ACI journal pg 219-231, 1986
[24] Fracture mechanics of concrete: Structural application and numerical calculation, A. DiTommaso University of Bologna, Bologna, Italy, Martinus Nijhoff publishers-1985
[25] Shear failure in beam column joint occurred after beam yielding at large displacement in 1995 Hyogo-ken Nanbu earthquake
[26] Hillerborg A, Modder M , Petersson PE ,Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements, Cem concrete research pg .pp773-781, 1976
[27] Taylor H.P.J .The behaviour of in situ concrete beam column joints , London, Cement and concrete association, technical report.1974
[28] Hakuto S., Park R. *and* Tanaka H. 1995. *"*Retrofitting of Reinforced Concrete. Moment. Resisting. Frame*"*. Department *of* Civil Engineering, *University* of *Canterbury*, Research Report 95-94, Christchurch, New. Zealand
[29] Hakuto S, Park R., and Tanaka H. "Seismic load tests on interior and exterior beam-column joints with substandard reinforcing details." ACI Structural Journal, 97(1), pp 1125, 2000
[30] Paulay, T., Park, R. and Priestley, M. J. N. "Reinforced Concrete Beam-Column Joints under Seismic Actions," Journal of ACI, 75(11),pp.585-593, 1978.

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