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DESIGN AND CONSTRUCTION ASPECTS OF REINFORCED CONCRETE BEAM-COLUMN JOINT UNDER SEISMIC CONDITIONS

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Abstract - The dynamic action of earthquake excitation introduce high shear and bond stress conditions in reinforced concrete beam column joints. This ultimately leads to brittle failure of joints and non seismic performance of structural system. Due to constrained geometry and congestion of reinforcement in joint core, the beam column joints and its associated members are unable to fulfill seismic design requirements. The constructability issues of reinforced concrete (R/C) beam column joint often elevates poor compaction, confinement, detailing and anchorage system in the joint panel. This creates formation of weak links in joint core and often leads to brittle failure of joint system.[6][4] Since all the available seismic design codes recommends monolithic action of R/C joint system, these design uncertainties are more established in precast R/C beam column joints. As a result most of the precast R/C joint connections are seriously damaged in the past earthquakes. In view of the above construction and design uncertainties, this paper discussed about the associated defaults of joints in the present construction practice and proposed an innovative design methodology by introducing integrated prefabricated R/C joint element. The integrated joint element effectively satisfies high shear, anchorage and bond conditions of joint core. The design approach is based on account of material constitutive properties, equilibrium and compatibility conditions of joint forces. This will establish realistic behavior of joint under critical action of service loads.[15] The new system provides acceptable solutions in the design and construction of R/C beam column joint system. It provides good means of adoptability in precast as well as in-situ concrete joint system.

Key Words: **Beam - column joint, Construction aspects, Constructability issues, Integrated joint element, Hypothetical assumptions**

1. INTRODUCTION

Traditional separation of structural steel and Reinforced concrete (R/C) construction practice in India is not effectively improves the design guidelines of seismic beam column joints. The current seismic practice is versatile with capacity design approach where the ductile performance of beam-column joint and its associated connecting system is recommended[3]. However plasticity and damage in beams are rare combinations and if any structural damages in joints may seriously influence the functionality and jeopardize the structural system[8][11].Due to constructability issues, most of the R/C structures in India are still proceeding with non seismic detailing of R/C beam column joints .The construction difficulties are associated with confined joint area and congestion of reinforcement in joint core .This significantly influence the performance, strength, stiffness and ductile property of joint system. Irrespective of vast experimental database and scientific approach available about parametric influence on seismic beam column joint system, the present construction practice unable to fulfill seismic design requirements of joints. This is due to poor confinement, compaction, congestion of reinforcement, and deficiency of anchorage in the joint core. Moreover the present seismic design codes are unable to address important design aspects and considerations of joints and still they are envisaged in the design. Pauley et al.[15], identified that during severe earth quakes the joint deformation significantly influenced by storey drift in both seismic and non seismically detailed joints. In seismically detailed R/C joint, the deformation may cause diagonal shear cracking and leads to storey drift [13].and in non seismically detailed joints this effect is more catastrophic and leads to entire structural collapse. In this context, sustainability of high raised buildings under lateral loads need to verify as the joints are more susceptible by shear deformation through slippage of joint reinforcement. The reinforcement slip in joint overestimates strength and stiffness of joints and global framing system[1] . During seismic excitation the overall performance of a structure significantly influenced by the storey drift and soft storey effect, both of which are considered as brittle failures .Hence there is a need to reconsider the construction aspects of R/C joint

II. RESEARCH SIGNIFICANCE

The existence of technical gap between seismic design practice and constructability issues of beam column joints are widely discussed at present. To accommodate high shear, bond stress and ductility conditions, the detailing part of congested reinforcement in joint is much difficult and unable to comply with seismic design standards of beam column joints. As a result, poor confinement and compaction of concrete exists within the joint core and leads to brittle failure conditions.[10] To ensure minimum safety and acceptable performance of R/C beam column joint system, the current design provisions need to modify for ease of joint construction and reliability.[2]. In this context a new design philosophy and structural element introduced to develop "Integrated joint system". It is an innovative system useful for both precast and in-situ R/C joints.

III. DESIGN PROPOSAL OF INTEGRATED R/C BEAM - COLUMN JOINT ELEMENT.

A Brief review on Integrated joint system

Present design practice of R/C beam column joints considered the contribution of only joint element for transformation of lateral loads. But in many situations, the joint element is unable to transform these critical loads due to constrained geometric conditions and congested reinforcement provisions[4]. A new design approach is proposed in this study known as "Design of integrated joint element". In this method, design of component joint element is initiated with a distinguished prefabricated element and extended arms in the direction of beam and column. The integrated effect of joint panel element and associated system contributes effective load transfer mechanism in R/C beam column joint. The contribution of extended portions of beam, column portions increase the net sectional area of joint core, and the system improves efficient load transfer mechanism in joint.

This innovative design proposal developed from the recommendations of Indian seismic design code I.S 13920-2008.The code expressed that the performance of R/C beam column joint system may significantly improved by the provision of special confinement hoop reinforcement at effective structural parts of beam, column and joint sections[16].The newly proposed discrete R/C joint element with extended parts of the sub elements (beam and column) is made with high strength, stiffness, ductility and confinement so as to meet the .The extended arms of the joint element is connected to beam and column portions subsequently to show monolithic action of joint system. The seismic design proposals of plastic hinge formation in beam portions are precisely valid in this new system as the joint connection (flexible connection) is proposed in beam portion. Similarly the connection between column and extended arm of joint is made with rigid joint connection. Prediction of joint loads, high shear conditions and transfer of unbalanced moments induced within the joint are more precisely evaluated in new design approach. The strength loss due to anchorage zone damage, and anchorage response of beam and column reinforcement may effectively compensated in the new approach due to enhancement of cross sectional area of joint. This new hybrid or integrated joint element is much compatible with Pre-fabricated construction system, It allows segmental construction process as practice in prefabricated system. Since the modified joint element is considered as one of the primary structural element of structural system, shear transfer mechanism in joint may predict more accurately with high sensitivity in the connecting structural system

i. Design assumptions of Integrated joint system

Design of R/C integrated joint element is based on Strut and Tie method and versatile with capacity design method. Both strut and truss formations are well defined in the current system. The anchorage provisions of embedded beam reinforcement and shear transfer mechanism in joint core are well addressed in the new system. Provision of mechanical anchorage in the joint system is more adoptable in the new system.

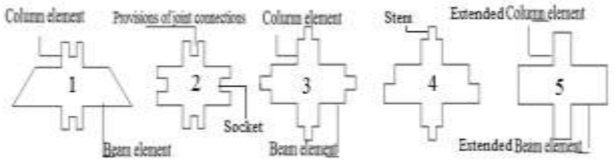
The extended portions of beam and column elements in the integrated joint element should be confined for high stiffness and not allowed for flexural deformation. The sectional enhancement and geometric proportionality of extended beam and column portions of integrated joint element is to accommodate high shear and anchorage requirements of joint core.

Sectional enhancement of integrated joint element is considered through include the partial segments of connecting beam and column sections. Hence the joint system provides partial contribution of beam and column geometry to fulfill high shear conditions. The new approach provides contribution of extended beam and column lengths in integrated joint element is based on strength and confinement of capacity. Hence the design philosophy varied with current system.

Failure conditions of joint is precisely addressed in this new approach. Accordingly the strength and stiffness of integrated joint element is more than the connecting elements (beam, column and slab) and has to satisfy elastic conditions under critical loads. The inelastic response of joint element is not allowed in general practice and where it is inevitable, the joint failure is considered under truss mechanism due to sufficient concrete sectional area of joint concrete. Hence detailing of reinforcement is more comfortable in joint core.

The integrated joint element satisfies basic principle of strong column and weak beam conditions of seismic design. Accordingly sectional failures are more anticipated in beam rather than any other part of joint element or its sub-assemblage .Accordingly ductile connection detailing allowed between integrated joint element and beam element such that inelastic yielding occurred during post failure conditions of joint. Similarly rigid connection detailing allowed between the integrated joint element and column section such that no part is under influence of plastic hinge formation and the joint core is safe against shear deformation.

ii. Proposed Geometric shapes of Integrated joint model (Precast joint element):

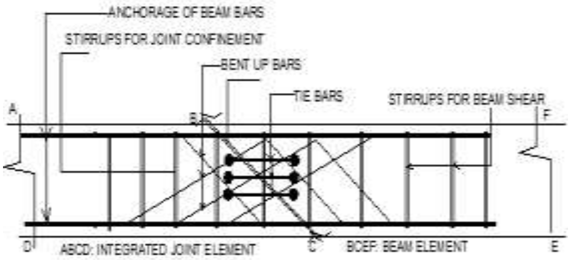


GEOMETRIC SHAPES OF INTEGRATED R.C. BEAM COLUMN JOINT ELEMENT

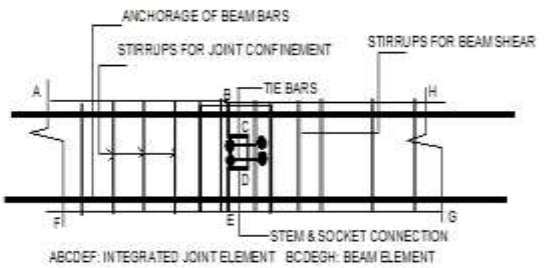
iii. Reinforcement detailing between Integrated joint element and connecting beam

(Ductile provision)

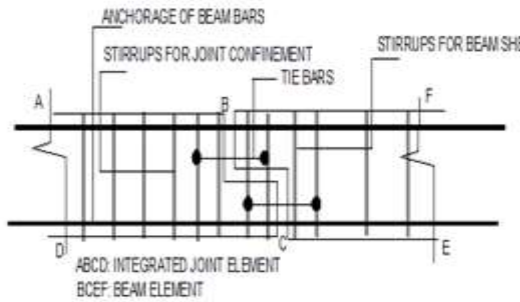
(Integrated joint Element: ABCD, Beam Element: BCEF as shown in the following figures)



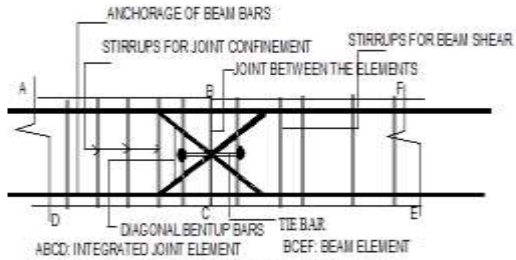
DUCTILE DETAILING OF JOINT ELEMENT (ABCD)AND BEAM ELEMENT(BCEF)
(CONNECTION FOR ELEMENT 1&2)



CONNECTION DETAILS OF JOINT ELEMENT :3

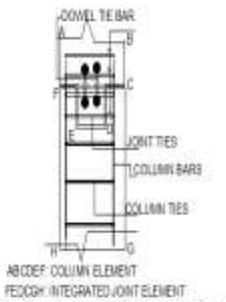


DUCTILE DETAILING OF JOINT ELEMENT (ABCD) & BEAM ELEMENT (BCEF)
(CONNECTION DETAILS OF JOINT ELEMENT 4)

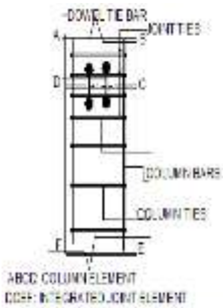


DUCTILE DETAILING OF JOINT ELEMENT: 5

iv. Reinforcement detailing between Integrated joint element and column (Rigid joint system

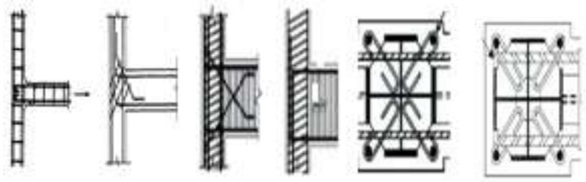


RIGID JOINT BETWEEN COLUMN AND JOINT (STEM & SOCKET CONNECTION)



RIGID JOINT BETWEEN COLUMN & INTEGRATED JOINT(ELEMENT 5)

v. Reinforcement detailing of beam column joint system proposed in the past research studies



vi. Advantages of Integrated joint panel system

- Hybrid joint element is effectively reduce the reinforcement congestion in joint core due to availability of more sectional joint area
- It provides more stiffness and strength to the joint element
- It improve and facilitates the compaction of concrete in joint core due to construction of joint element under factory conditions
- More quality standards may ensure due factory made conditions of Integrated joint element
- It provides enough ductility, stiffness and flexural rigidity apart from high shear resistance
- The role of shear, anchorage and confinement reinforcement are precisely addressed in the new

design system. Hence detailing of reinforcement is more comfortable during design and construction.

- Experimental research works suggested that hybrid joint element won't allow brittle joint failure at high shear conditions. If failure is inevitable in joint element then it may confirm to ductile mode. Due to good confinement effect of precast joint element. and ductile joint connections failure may avoid in joint sections in the new proposal.

- The integrated joint element ensure innovative joint assembly and adoptability to establish connections between composite sections and precast or pre-stressed elements. Assembly of structural implants ,high performance, high strength, fiber reinforced and self compacted concrete, are more feasible during the implementation of integrated joints.

vii. Disadvantage of Integrated joint panel system

- The design philosophy is under developing stage and experimentally not verified .Whatever the views expressed so far is based on hypothetical assumptions based on past research and experimental studies.

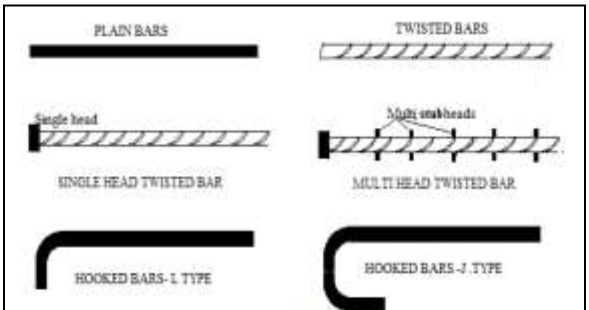
- Issues related to connection details between R/C integrated joint element and beam or column elements need to establish.

- Influence of design parameters in joint element need to establish for monolithic action of the joint system.

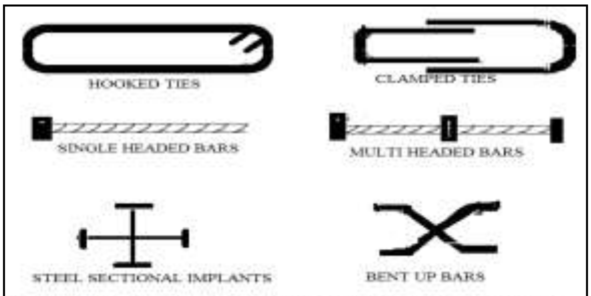
- Engineering and technical skills required to establish joint connection in the integrated system between joint element and its sub assemblage.

- Establishment of rigid joint assumptions is appropriate in the new approach but the connection between the sub assemblage of joint elements is more appropriate.

- **viii. Configuration of different Re-bars used for anchorage and shear in R.C beam column joints**



RE BARS USED IN ANCHORAGE SYSTEM OF R.C JOINTS



SHEAR REINFIRCEMENT USED IN R.C JOINTS

IV.CONSTRUCTABILITY ISSUES IN R/C BEAM COLUMN JOINTS

1 Quite often seismic beam column joints are subjected to insufficient ties or stirrups due to congestion of reinforcement. Most of the situations, bottom beam bars are not extended through continuous or discontinuous conditions of joint. This leads to non ductile performance and brittle failure of joint.

2 Incorrect detailing practice of beam column joint such as incorrect bending of beam reinforcement within the joint prevents diagonal strut formation which leads to diagonal cracking and leads to tensile shear failure of joint. As per past experimental studies the normal detailing of open joints provides flexural efficiency of joint between 25-40% and the provision of diagonal stirrups in joint enhance efficiency by 75%.[3]

3 Large ductility demands high energy dissipation (ductility factor>4) which demands detailing of congested reinforcement in joint core. This practical difficulty unable to satisfy the seismic design requirements and shear failure of joints by slippage of anchored beam bars. Geometric considerations of joint significantly influence the detailing part. In adequate anchorage of beam bars in joint results splitting failure of concrete due to requirement of high bond stresses. [7]

4 Kinking of column bars in joint core ultimately leads to stress concentration and early distress of joint specially when a joint is subjected to lateral forces by earth quakes. Splicing of main bars should not encourage in joint region as it results brittle failure due to high and congested steel reinforcement and poor confinement of concrete. [8]

5 Use of large diameter of bars and high yield strength steel in joint core cause early breakout of bond (between steel and concrete) before development of full yield strength of adjacent beam bars, which may result brittle failure of joint. There must be limitation in use of large diameter bars and its yield while used to satisfy anchorage requirements.[15]

6 In most of the situations, rigid joint assumption of joint is not appropriate as it over estimate the joint stiffness and

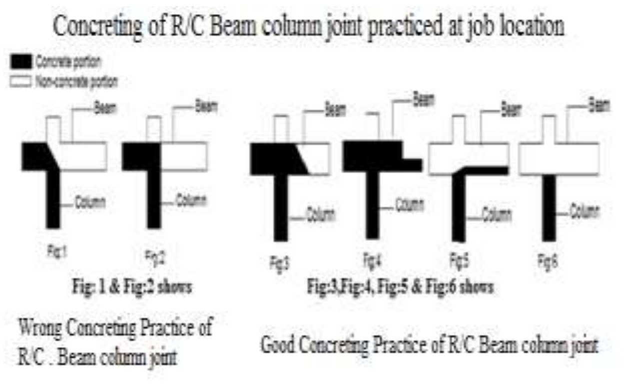
under estimate lateral drift of structure. Pauley et al., addressed that the joint deformation significantly influence storey drift and more than 20% of inter storey drift may happened in R/C moment frames during severe earthquakes [12].Hence no allowance should made for rigid joint ends that are subjected to lateral seismic response.

7 Use of hooked bars, clamped and hoop reinforcement often used to accommodate high shear and confinement conditions in joints .Arrangement of this shear reinforcement include bar bending and fixing in the constrained joint core is much difficult and sometimes not followed as per detailing.

8 As per design codes maximum limitations are allowed on provisions of joint reinforcement (<0.40%). But due to the requirements for anchorage, shear, ductility and confinement joint reinforcement exceed maximum limitations [13].This significantly influence compaction of concrete and creates weak zones of poor compact concrete and dense reinforcement and ultimately leads strut failure of joint core.

9 The role of confinement reinforcement and shear reinforcement in the joint core are not precisely identified in the design codes. Due to this reason, seismic detailing of joints becomes more complex and unable to fulfill design requirements of a joint.

10 Use of headed bars, structural implants and other mechanical systems against high shear and anchorage requirements of joint panel are not sufficiently addressed in the seismic design codes[11][16].This may significantly influence the prospects of design developments in R/C beam column joint.

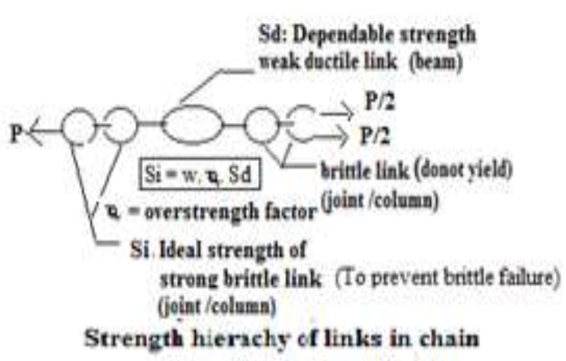


V. DESIGN RECOMMENDATIONS OF R/C BEAM COLUMN JOINT

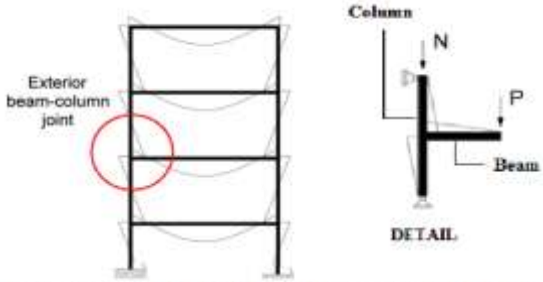
The recommendations are based on the assumption that critical section formed immediately adjacent to the joint and located in the part of connecting beam. Prior considerations required for secondary stresses such as effect settlement, fatigue loads, creep, shrinkage, and temperature stresses on joint. The direction of casting significantly influence bond strength of joint and slip of anchored reinforcement. There is an upper limit to joint confinement.[5] After fully confined environment of joint, the maximum bond strength attained and failure of joint attributed to crushing of concrete. The compression strength of concrete is not only a significant parameter as most of the codes implied in joint design. Under cyclic loading conditions, the tensile strength of concrete shows significant influence on local bond strength of joint.[15].

1. Capacity design is an advancement in seismic design of reinforced concrete where the joints promote ductile performance and inelastic behavior in the form of flexural yielding of beam[14]. In the capacity design elements of primary load resisting system are chosen and suitably designed and detailed for energy dissipation under severe inelastic deformations. All other structural members are provided with sufficient strength so that the chosen means of energy dissipation maintained. Other design factors involved in capacity design are dependable strength of material, strength reduction factor, and ductility. Accordingly, high raised buildings are analyzed under design loads to determine the required flexural strength for formation of plastic hinges at beam ends.

2. Seismic design considerations of joint may follows that, if beam column joint is unable to show ductile performance, then it remains elastic and provide ductile links between joint and its sub assembly. This ensure efficient behavior of joint at reversal loads and joints are cable to effectively dissipate energy under inelastic deformation with minimum degradation of stiffness and strength. As a part of capacity design (Ref: ACI 318-02R) the probable moment strength (Mpr) calculated to establish beam strength and beam column joint and column strength[17]



Capacity design of joints
(Source: Pauley & Priesltly)

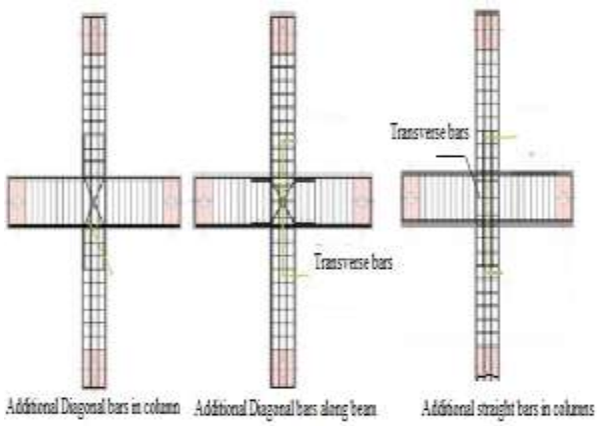


Experimental Test setup-External joint

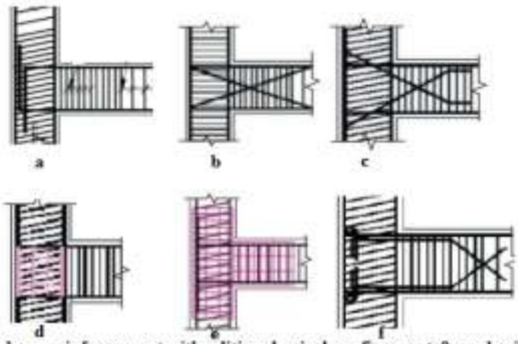
3. The beam column joints need to perform resistance against moment and shear in addition to axial loads. Moment resistance provided in the form of fixity through anchorage, bond, confinement and bearing strength .Under post yielding conditions inelastic ductile behavior of joints ensured by proper detailing of reinforcement, and confinement of concrete by lateral ties. The minimum distance between lateral ties should not less than 4φ (φ: Anchorage bar diameter) otherwise bond strength reduced to maximum 20%.[15]

4. Design of efficient joint system includes use of high strength and self compacted concrete, fiber reinforcement, and mechanical anchorage system such as couplers, headed bars, and mechanical implants in joints. The detailing of reinforcement and configuration of joint are significantly influence joint performance.[2]

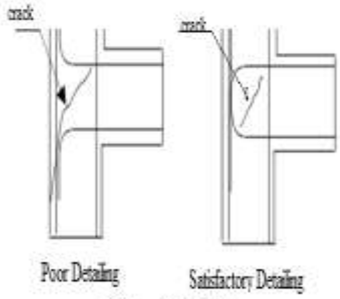
5. Joint core involves three types of shear transfer mechanism. They are shear strength of plain concrete (strut mechanism), shear strength of longitudinal reinforcement of framing members (truss mechanism), and shear strength of web reinforcement in the form of transverse reinforcement (vertical and horizontal ties). The joint need to ensure minimum dimensions to allow strut mechanism and good bond to ensure truss mechanism.



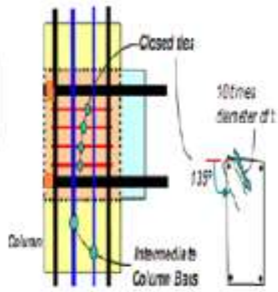
Joint Shear with additional bars in joint- proposed by Lu et al (2011)



Joint shear reinforcement with aditional spiral confinement & anchoring
(Source:Asha & Sundrajan)



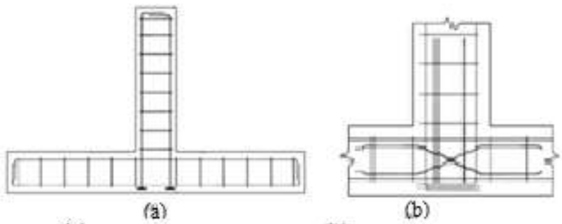
Detailing of Exterior Joint
(Source: Somer villey G & Taylor)



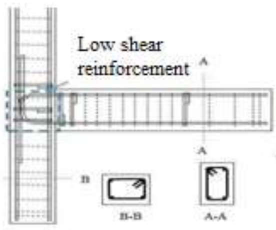
Closed ties in beam column joint
(Source : CVR Murthy)

6. In the design of beam column joints, material constituency properties need to consider as it impacts compatibility conditions during post failure conditions of joint. Constitutive modeling of joint material improves plastic deformations character.[13].To accommodate high shear, bond and confinement properties at joint core, use of high strength concrete, fibers, and composite materials are some of adoptable solutions

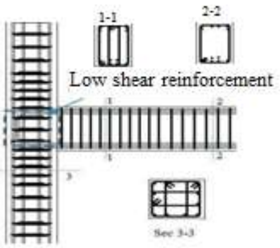
7. During inelastic deformations, joints are subjected to shear deformation and slippage of beam bars which results significant drift and brittle failure of joint. This phenomena, effects the stiffness degradation of joint. Hence the joint should enable to fulfill sufficient bond length.
   Limitations on tensile reinforcement or increase of compression steel may certainly enhance ductile performance and energy absorption of joint. Experimental studies in this connection established the same. Hence the ratio of steel reinforcement should keep subsequently low to improve ductility of joint for post yielding performance.The proportion of beams meeting at joint should arrange such a way that they must allow ductile characteristics of tensile failure



Joint Shear with T- Type Mechanical anchorage & hair clip
(Source: S Rajagopal & S.Prabavathy)



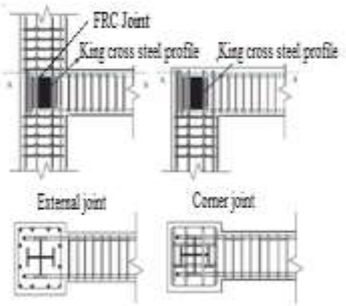
Joint Shear proposed by Park & Pauley



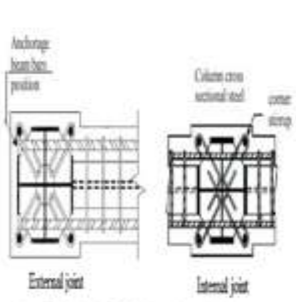
Joint Shear by Paulay &Scarpas

8. Splicing and kinking of main bars in joint core adversely effects the structural performance of a joint. Splicing of bars in high shear zones anticipate brittle failure of joint and kinking of column or beam bars obstruct uniform stress distribution in the reinforcement.

9. High degree of structural redundancy always helps to create many zones of energy absorption before failure mechanism developed in joint. Hence indeterminate joints are more advisable than determinate joints. Talaat & Mosalam (2004)[5] expressed concern about limitation on drift is significantly influenced by redundancy. Progressive collapse analysis necessitates the development of element removal criteria for unreinforced joints. This requires the type of connectivity and internal degree of freedom of beams and columns associate with the removed joints.



Joint Shear with King cross steel profile implants
(Source: CC Chen & B Suswanto)



Use of H-Section in FRC joints as shear reinforcement
(Source: CC Chen & KT Lin)

10. Shear capacity of non seismic or sub standard joints are not mentioned in seismic design codes. Torsion forces significantly influence the shear deformation of external beam column joint. From the experimental studies, it was observed that shear deformation of a joint increased by 50% and shear strength of joint reduced by 20% due to torsion effect[7].This may specifically observed in eccentric joint connections and out plane stress conditions of the joints.

11. Composite joints has more toughness and reduced problems associated with reinforcement bar congestion and concrete placement. On the other hand the use of structural steel in joints associated with welding and fracture resistance of joint connection and may impose difficulty during construction.[9]

12. Brittleness of high strength concrete is a matter of concern in the design. Pauley & Pristeley (1992) specified that increase of grade of concrete will decrease strains at peak stress and at first crushing. Hence designers must aware when used high strength concrete in joints

VI. CONCLUSIONS

During the recent past, Indian sub continent is prone to moderate and high seismic excitations. Most of the reinforced concrete (R/C) structures are seriously influenced by the dynamic action of seismic forces. In this context ductility and damping coefficient of structures need to reconsider in design stage. Also design philosophy of joints need to reconsider such as cross sectional area of joint and reinforcement diameter and detailing are critical issues need to address due to congested geometric conditions and fabrication problems. For example provision of hoop reinforcement is not always possible in the congested joint. To promote good dissipation of seismic forces, the performance level of structure need to re-establish based on joint ductility for which detailing is key issue. This paper discussed about various constructability issues and design recommendations of R/C beam column joint. Accordingly specific conclusions made referring to joint panel system, reinforcement arrangement in joint core, joint fabrication and constructability are discussed. Accordingly design improvements are mentioned. Based on the comprehensive review of previous research work , a new design philosophy is proposed for R/C beam column joint system .This comprised with implementation of prefabricated joint panel in joint core with segmental beam and column extensions. The segmental extension portions enhance the joint strength and enable to fulfill high shear and bond conditions in joint core. Different joint models with design considerations are discussed in this paper and summarized the conclusions as follows.

(i) Integrated joint panel system:

Failure conditions of beam column joints are precisely addressed in the new integrated joint panel system. The design of new system is based on Strut and Truss mechanism. The integrated joint panel system follows basic principles of seismic design such as strong column and weak beam conditions, rigid joint conditions and plastic hinge formations in beams. The new joint panel system provides less congestion of panel reinforcement, high strength and confinement with good constructability .They are more adoptable against innovative construction materials such as fibres, structural implants, headed bars and composite construction techniques in the preparation of joint core concrete. Due to factory made environment the new prefabricated joint panel system, ensures good quality standards, ease of construction and structural safety. The design strength of joint panel strength is much varied from the strengths of beam and column. Since the beam and columns are considered under Bernoulli's principle and the associated joint element is considered under strut and truss mechanism, strength coefficients of the beam column joint system and force transfer mechanism are well proposed in the new system.

(ii) Constructability issues:

Constrained geometry and congestion of reinforcement in joint panel are often mitigate the seismic detailing joint panel. Under this conditions joints may allow poor level of compaction and confinement.

Due to mismatch of structural alignment of columns, seismic beam column joints are often practiced with kinking of column bars and splicing of bars in joint, which leads brittle failure of joint.

Anchorage of beam bars and provisions of hooks or clamped bends in joint core is a difficult issue due to limitations of joint area and congestion of reinforcement. This ultimately results anchorage failure of beam bars in joint panel.

In the wide beam column joints, the bars are generally allowed to bend near column for insertion of bars in joint panel and to fulfill anchorage requirements. If the detailing requirements are inadequate at the junctions then joint may subjected to brittle failure.

In most construction practices, the designers often fail to guide the construction standards of beam column joints. In construction practice, the specifications of joints are similar considered with other structural elements for design mix preparation, form work, compaction, workability and concreting. In most of construction practices, the general specifications not fulfill the design standards

Indian seismic code I.S 13920-2009 recommends confinement of joint reinforcement by provision of hoop reinforcement. This is difficult and unable to establish in most of construction practices due to limitations of joint area. Also there is no methodology in the design code to emphasize strength of hoop reinforcement. The deign default imposes low shear resistance of joint core.

(iii) Design recommendations:

Ductile behavior of joint dampens the structure and reduces the system resonance during seismic excitations. When the structure becomes inelastic, then the ductile joint dissipates high seismic energy through hysteretic damping and reduces the effect of external forces on the structure

The location of yield points should be carefully selected as it creates undesirable location of failures such as shear cracking in concrete

The beam column joint panel must ensure minimum dimensions to fulfill strut mechanism and satisfy good bond between concrete and joint reinforcement to satisfy truss mechanism.

The designers are responsible to provide both construction methodology and design specifications for implementation of effective joint system.

Slippage of beam bars in joint core results degradation of stiffness in joint core. Hence the anchorage requirements of beam bars must improve by headed bars, hooked or clamping bars or by new innovations. Both compression and tensile strength parameters of concrete are equally responsible for good performance of beam column joint during cyclic load conditions.

Performance of R/C beam column joint improves with structural implants, headed bars, joint couplers and integrated panel elements in joint core.The parametric influence of the mentioned implementations are in research stage This paper contributes the same for improvements in joints.

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Biography

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