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Seismic Design of Precast Component Beam-Column Joints using Headed Anchors

K. Padmanabham, K. Rambabu

Abstract *Precast construction system ensures high degree of quality, safety, and accelerated construction practice in R.C structures. It is well established in non-seismic conditions where gravity loads are predominated. But it is hesitated to implement during seismic conditions by the effect of lateral loads. Most of structural failures in precast framed structures are associated with beam-column joints as the integrated joint system experience high shear, and moments by cyclic action of seismic loads. In this context, researchers found that the joint distortions in precast system is well associated with its location of beam-column sub-assemblage. In beam-column joints the connections are attributed to locate in D-regions (D:Discrete) and B-regions (B:Beam) where the force transfer mechanism follows by strut - tie method (STM) or flexure beam theory(FBT) respectively. This paper analyzed the seismic performance of "Component Based Precast Joints"[CBPJ] located in D& B regions. To meet the convergence requirements, the connection systems are detailed by mechanical couplers and headed anchors. Five numerical models of exterior beam-column joints representing two models (BM1,BM2) of B-region and three models (DM1,DM2,DM3) of D-region are developed and verified their seismic performance with monolithic joint system by non-linear finite element analysis using ABAQUS software .The results indicated that the use of headed anchors in precast joints are effectively contributed to seismic requirements of shear, ductility, stiffness and energy dissipation. Also the precast joints located in D & B regions resembling good performance of joint sustainability during moderate seismic conditions as monolithic system.*

Keyword **:** ***Beam column joint, Coupler, Component joint, Headed bars, Precast system.***

I. INTRODUCTION

Seismic design of Pre-cast moment framed structures are often subjected to design failures and constructability issues. This is due to implicit behavior of critical components such as beam-column joints and explicit behavior of frame action under reverse cyclic loads. The frame action is attributed to (i) Finite size of joint, (ii) Shear deformation of joint and (iii) Rotational contribution against non-linear response. Hence the global structure response is based on members and location of joint connections to meet the cyclic response from earthquake forces. In this context, recent seismic failures R.C structures happened in China-1976, India-2000 and Nepal-2015 are typically associated with brittle failure of precast joints in beam-column assembly.

Although precise guidelines are mentioned in seismic design codes of fib-74-2014, ACI-550R, ACI 352-02R and PCI, but it was not addressed for detailing aspects of joints in D and B regions .Hence there is a need to establish sound solutions of connection mechanism in joints and establish the compatibility between these two states. Joint is a structural element subjected to high stress conditions of external forces and connection is an integral part of structural system and assemblage of members where the originated joint forces are safely transferred to principle members.

Component based design is a unified approach that provides efficient design philosophy of joints against non linear behavior. In this approach, the beam-column joints are discarded as individual elements and assembly of basic components contributes its structural performance for stiffness, strength and deformation capacity. The individual component members can be designed independently as per connection system and assemblage in later stage to meet the joint requirements [2]. The component system provides efficient design option as the joint behavior is optimized according to limiting components. The seismic connections of precast members are broadly classified under (a) Emulative design system (b) Component based design system. The Emulative technique of precast joints intends to design and detailed for seismic performance of structure which was similar to conventionally designed equivalent monolithic system based on ductility and strength of connection system [Ref: Ericson & Warne's 1990]. The ductile joints undergo flexural yielding and formation of ductile plastic hinge at selected locations. The strength based approach intends to establish strong elastic connections and flexural yielding at pre-selected locations of members and is away from joint. Researchers found that the configuration and location of joint significantly influence the global integrity of structural system during explicit performance structure. Hence it is crucial to consider the local joint response before global response of seismic structure [4]. The current practice of precast system intended to establish connection system near the column face of D-region (D: Discrete) or away from column face of B-region (B:Bernoulli's).The analysis of D-joints are described by strut-tie analogy and B-joints by Bernoulli's flexural beam theory. Studies related to location of joints in D & B regions of beam column assembly are rarely addressed in past research as the current practice often using this system due to constructability issues faced during erection of precast elements[8].Since headed anchor develop implicit strengthening mechanism of joint core and mechanical couplers develop continuous stress path in joint reinforcement, this study provides more construction feasibility of joints.

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In the limit state analysis of component system, the strength of each element is taken as isolation and establish the monolithic action of structural system by joints. Also the strength equations given by design codes are not considered the compatibility against integrity of global system. Hence most of the precast connections are unable to sustain at design loads. During the past, seismic joints of high raise and heavy R.C precast structures are unable to show good strength and ductility. In this context precast industry looking for design solutions to improve structural performance of joint assembly [12]. Inadequate transverse reinforcement and insufficient anchorage in joints are two major problems associated with seismic failures of precast joints. [9] .Joints of prefabricated structures should preserve the integrity of connecting members and to develop ultimate strength so that the deformability between the connecting members are compatible. Till date a very few research works carried on implicit strengthening of beam-column joint. Precast system intended to provide construction feasibility of structural elements located at constrained geometric locations. Since component based precast construction system provides more options to the designers for effective utilization of element strength, the lack of design approach of joints located in discrete or continuous regions of precast system is more significant in seismic design of beam column assembly.

This investigations focused on to provide design data of connections provided in D / B regions and to promote feasible construction practice in precast system.

II. OBJECTIVES

This study intended to give feasible solution of design practice for precast beam-column joints. The objectives are emphasized to give design methodology of component based beam-column joint system and connection detailing of joints located in Discrete region (D) and Beam region (B). Headed bars and mechanical couplers are used in this context. Numerical investigations are proceeded with ABAQUS program and generated five models at different D & B locations of component joints system. Seismic performance of this joints are evaluated and compared with monolithic casted joints.

III. PRECAST CONNECTION SYSTEM

Precast connections should able to meet the structural integrity of component members meeting at joint location and safely transfer the forces between the assembled members against progressive collapse of structural system. Seismic failure of stub beam-column connections located in Discrete (D) -region are attributed to shear deformation and slippage or yielding of beam reinforcement (beam-hinge) followed by yielding of column bars (column-hinge mechanism) (Ref: Kiran.R@al.,2014). Out of which, shear failure is the most obvious condition in special moment frames (Ref: Park & Mosalam.,2012).

Fig.1 Represents monolithic conventional (MCJ) joint with hooked anchorage system in beam-column connection .This type of joints used when gravity loads are predominated. During seismic action this joints are influenced by lateral shear, moments and results high shear conditions in joint core. In this context seismic codes addressed special detailing of reinforcement based on ductility. But in real practice this detailing aspects are unable to establish the force transfer mechanism with congested geometry .Hence brittle failures often happened at intersection of beam-column

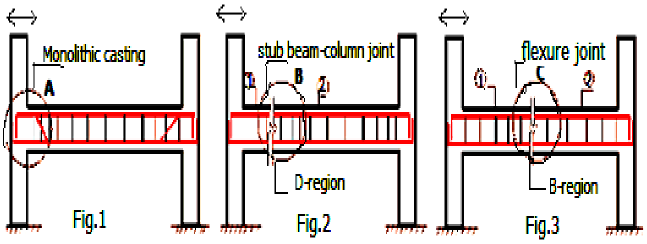


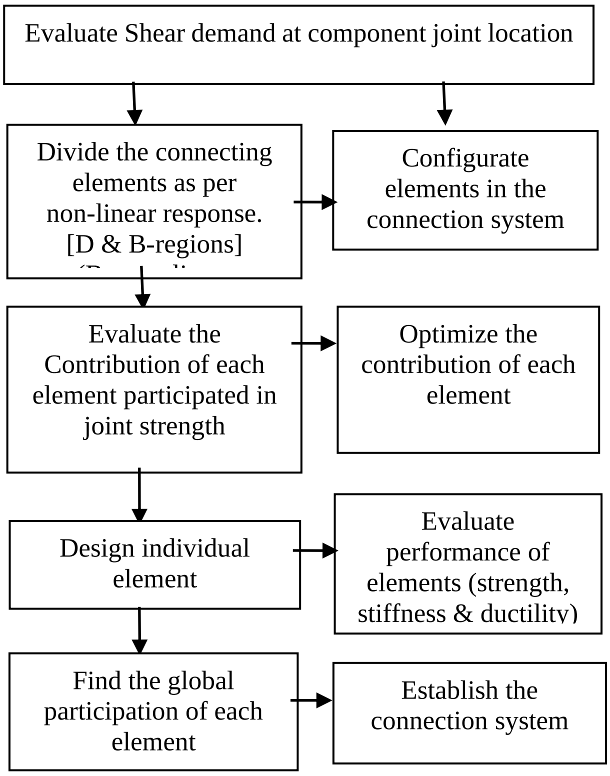
Fig.1 Conventional monolithic system
Fig.2 Discrete precast joint
Fig.3 Flexural precast joint

Fig.2 Represents the location of precast joint in discrete (D) region of beam column assembly. This joints are more prominent in segmental construction. ACI 352-02R impose flexure domination rather than shear if a member satisfies the ratio of effective length to depth should greater than 4 and ratio of its breadth to depth should be more than 0.30 .The maximum reinforcement allowed in joint section is 2.5% against joint ductility. Although design codes restricted the location of this joints, it may be intended to minimize the structural damages in connecting beams against inelastic conditions .Analysis of this joints are proceeded by STM approach. In the STM approach the compressive strength of concrete strut followed by node formation is the governing factor in deciding the strength of joint core. Effective provision of reinforcement detailing helps to establish compatibility conditions between joint concrete and reinforcement to attain sufficient levels of ductility in joint core. Fig.3 Represents Precast connection system in continuous beam region (B: Bernoulli's region) where the joint failures are predominated by flexural bending. The seismic design philosophy relies on sufficient ductility in the form of member ductility and its connection system so as to allow inelastic rotations of joint and plastic hinge formation in the associated connecting members. This intended joint system followed by beam yielding mechanism in precast connections are followed during strong column-weak beam where the ductile detailing of joints are more obvious during inelastic rotations of joints. This type of joints are more common in segmental construction (example: connection between the precast girders in balanced cantilever bridge deck). During seismic action, this joint are vulnerable against lateral shear and unbalanced flexural moments .Capacity design principle used to ensure strong connection mechanism between component elements where the failures are intended at preselected locations through plastic hinge mechanism. To meet beam yielding failure, design checks are required to verify the additional seismic shear imposed by cyclic loads on joint core. This ultimately leads to develop inelastic shear deformation and distortion of joint due to high shear conditions. The use of headed anchors and couplers typically contributed against to greater moment of resistance and energy dissipation by producing yield strain in the reinforcement. In this context joint detailing is more significant as the use of mechanical couplers gives rigid connection system and produce local strains in joint reinforcement.

IV. COMPONENT BASED PRECAST JOINTS [CBPJ]

This studies intends to give design methodology of CBPJ in flexible and rigid joints of BCJ. The principle mechanism is based on lower bound plasticity theorem. This system comprised by (i) Identification of basic components in structural assembly against compression, tension and shear factors. (ii) Characterize the properties of component elements based on joint location (D-region or B-region) (iii) Assembly the component parts to meet joint geometric configuration (iv) Establish connection mechanism (vi) Implement strengthening techniques of connection assemblage.

DESIGN METHODOLOGY



A) Discrete joint connections in D-region

Geometric configurations of D-connections are addressed in Fig.2a, Fig.2b, Fig.2c and represented by DM1, DM2, DM3 of numerical modeling . Analysis of this joint connections are followed by STM approach. Stub beam-column connection shown in Fig.2a, intends to provide beam reinforcement in component joint system connected by mechanical couplers and headed studs to receive high lateral shear conditions of discrete stub beam-column joint connection. Fig.2b shows shear stud splice connection of beam bars followed dowel anchorage. Fig.2c represents discrete joint connection with provision of shear key, as the joint subjected to high lateral shear followed by high transverse shear conditions. Analyses of joints are followed by STM (strut-tie method) approach under discrete joint conditions. The discrete location of joint connections are more appropriate when beam elements not intended for damage and the stress flow take diversion towards column as the structural system intended to provide enough redundancy about the columns. Through this connections damages are take diversion towards redundant columns in spite of beams as the stresses may intended to take diversion towards columns.

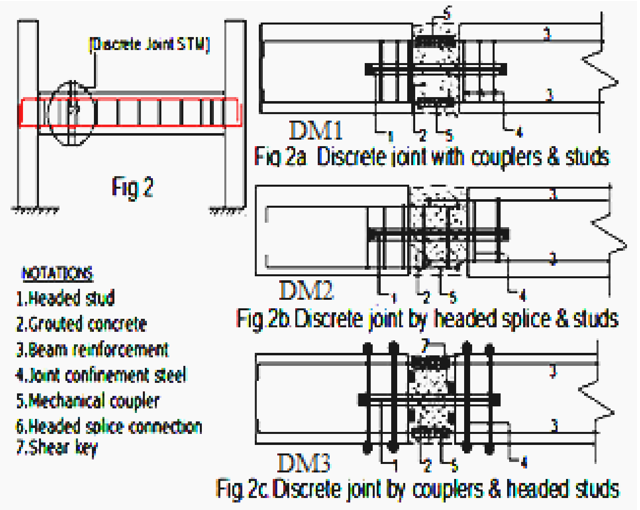


Fig 2a Discrete joint with couplers & studs

Fig 2b Discrete joint by headed splice & studs

Fig 2c Discrete joint by couplers & headed studs

FIG.2 DISCRETE BEAM COLUMN JOINTS BY HEADED ANCHORS/COUPLERS

- Design methodology of discrete connections are followed by Strut - Tie approach where the formation of compression strut, tension tie and nodal zones are crucial in strengthening mechanism of joint.
- Define and isolate the discrete (D) regions in connection assembly. Compute the force resultant on boundary of D-region.
- Based on load path select appropriate truss model to transfer forces in D-region.
- Select the dimensions of strut and tie and nodal zones based on loads. Verify the capacity of strut at mid length and nodal interface.
- Design the ties and anchorage system in nodal zones include design details. Check the minimum reinforcement requirement. Check the performance of joint for shear strength and serviceability

B) Flexural connections in B-region

Geometric configuration of B region connections (BM1, BM2) are shown in Fig.3a,&Fig.3b.Analysis of this connections are followed by flexure beam theory. The design procedure is as follows.

- Assembly the precast elements and locate the connections in B-regions and isolate the joint assembly.
- Compute the maximum shear and bending moment at connection and boundary elements.
- Using beam theory design the elastic connections in component joints. Also find the bending stress and bond capacity of joint concrete. Design the reinforcement which was compatible with grade of concrete.
- Assume stress conditions of concrete in compression and steel in tension are equal at joint core, calculate tension force generated in reinforcement of B-joint.
- Based on tension pull applied on joint reinforcement, find the required strength of joint concrete in the presence of headed bars.

- Design the headed bars against anchorage and confinement at component joint. Establish the reinforcement details and check joint capacity against ultimate loads .

V. MODELLING OF COMPONENT JOINT SYSTEM

Three dimensional Non-Linear Finite element Analysis (NLFA) carried out to evaluate shear response of beam-column joint. The analysis comprised with use of headed anchors and mechanical couplers in component joint system of precast beam-column assembly. Three models of DM1, DM2, DM3 in D-region and Two models of BM1,BM2 in B-region are analyzed and compared with monolithic casted joint (MCJ) in beam-column system. The investigations are followed to find stress-strain behavior, crack pattern, damage location and peak shear response of joint. Constitutive material modeling carried by Simplified Concrete Damage Plasticity (SCDP).Ref: [10] [11] [12]. In this context, the behavior of component joint system comprised by Elastic and Elastic-plastic response, that resembling pre and post failure conditions of joint assembly. In SCDP modeling, the concrete failure assumed to happen by crushing of concrete or development of splitting tensile strains. Effect of column axial forces are considered under $P_{axial} = 0.70 \times f'_{ck} \times A_{cg}$ [ ]. An increment of 10kN cyclic load applied at end of beam and Von-Misses stresses are verified against shear response of joint. The stress (σ) strain (ϵ) values in plastic region evaluated by true value of σ_{true}, ϵ_{true} (Fig4,5).

A) Modeling of Concrete

Concrete modeling is proceed with C3D8R (3-dimensional, 8-noded hexahedral element with 3 degrees of freedom in each node as solid material. The mechanical properties of simplified concrete damage plasticity (SCDP) model considered to elevate the properties of concrete at both tension and compression. M30 concrete grade selected to represent inelastic behavior of concrete with damage characteristics in the presence of embedded reinforcement. This modeling may analyze the reduction of stiffness and permanent damage of concrete during its fracture process. The compressive model (fig4b) of concrete for stress strain behavior is followed by Lopez-Almansa et al [6, 7] by concrete damage plasticity model. The damage parameters of dilation angle, flow potential eccentricity (e), ratio of initial biaxial compressive stress and uni-axial compressive stress fbo / fco, stiffness (k) and viscosity are chosen as default of CDP model as mentioned in Table.2

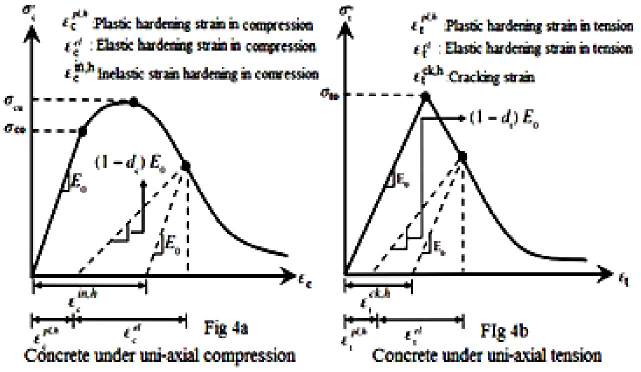


Fig 4a
Concrete under uni-axial compression

Fig 4b
Concrete under uni-axial tension

Fig.4 Stress- Strain behaviour of concrete
(Ref: Milad Hafezolghoram)

From the Fig 4a & Fig 4b following expressions are made

Total strain $\varepsilon = \varepsilon_{elastic} + \varepsilon_{plastic}$

Degraded elastic tensor $D^{el} = [1-d]D_0^{el}$

Stress $\sigma = (1-d_t)\,\sigma_{t\ effect} + (1-d_c)\,\sigma_{c\ effect}$

(d=0 for undamaged & 1 for fully damaged concrete)

$\sigma_c = (1-d_c)\,E_0\,(\varepsilon_c - \varepsilon_c^{pl,h})\ ;\ \varepsilon_c^{pl,h} = \varepsilon_c - \sigma_c / [E_0(1-d_c)]\ ;$

$\sigma_c = \sigma_{cu}\,[2\,(\varepsilon_c / \varepsilon_{c'}) - (\varepsilon_c / \varepsilon_{c'})^2]$

$\sigma_{true} = \sigma_{nominal}\,[1+\epsilon_{nominal}]$

$\epsilon_{true}^{Pl} = In\,[1+\epsilon_{nominal}] - \sigma_{true}$.

(d= damage variable, Do^{el}= initial elastic tensor, σ = nominal stress, σ_{effect} = Effective stress,)

B) Modeling of Reinforcement

Three types of steel reinforcement used for modelling of reinforcement. The main reinforcement is HYSD bars and M.S headed bars used for anchorage and steel couplers as connectors. The diameter of main reinforcement bars under tension is 12 mm and transverse reinforcement is 8mm followed by headed bars with 30mm diameter mild steel heads welded at end of 12mm steel bar. The main reinforcement at joint was connected by mechanical couplers of 12mm size to provide continuous stress path. Properties of steel reinforcement elements are shown in Table.3 which was taken from previous experimental tests. The elastic-isotropic option used to model the steel materials. The yield strength and the plastic strain values were modeled using the plastic-isotropic option. The material modeling comprises steel reinforcement as T3D2 truss element (2-Node linear truss) with linear interpolation used for position and displacement calculations. A bilinear model with strain hardening was used in the nonlinear analysis to consider the behavior of steel reinforcement. Steel reinforcement assumed to develop perfect bond with concrete. The composite action of modeling was justified by embedded technique that was programmed in the software.

C) Modeling of Composite action

Steel reinforcement represented by T3D2 truss model with 50 mm mesh size of implicit joint conditions. The joint concrete modeled given by C3D8R solid element with 50 mesh following both implicit and explicit conditions. The selected size of mesh verified by convergence test for obtain compatibility between the material modeling .The failure modes of joint comprised by shear damage of concrete and slippage or yielding failure of steel reinforcement by cyclic loads.

D) Damage parameters of concrete

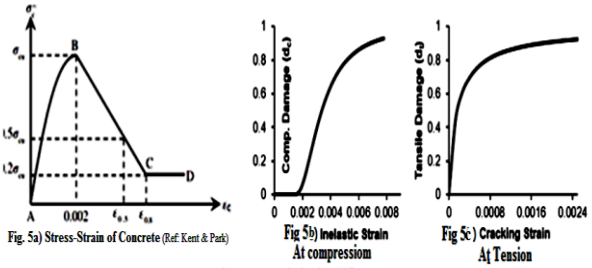


Fig. 5a) Stress-Strain of Concrete (Ref: Kent & Park)

Fig 5b) Inelastic Strain At compressiom

Fig 5c) Cracking Strain At Tension

Fig.5 Damage behaviour of Concrete

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E) Configuration and Testing of Component joints

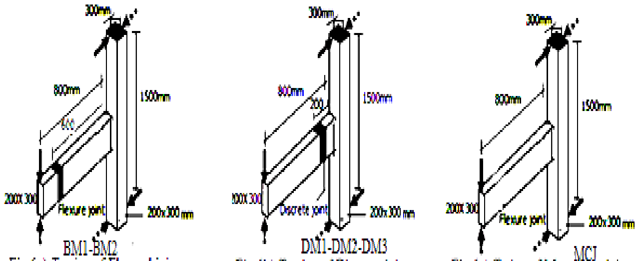


Fig.6a) Testing of Flexural joint Fig.6b) Testing of Discrete joint Fig.6c) Tsting of Monolithic joint

Fig.6 Boundary conditions and Testing of Component joint system

Table.1 Mechanical properties of Concrete: Grade M30

Density γ_c	Elastic modulus Ec	Poisons ratio μ_c	Allowble Strain ε_c	Confine ment factor K	Ultimate comp. strength f_{cu}	Tensile stress f_{ct}	Crack strain	Damage parameter T
N/mm^3	N/mm^2				N/mm^2	N/mm^2		
2.4x10^4	2652	0.30	0.0025	0.67	30	3	0.0011	0.99

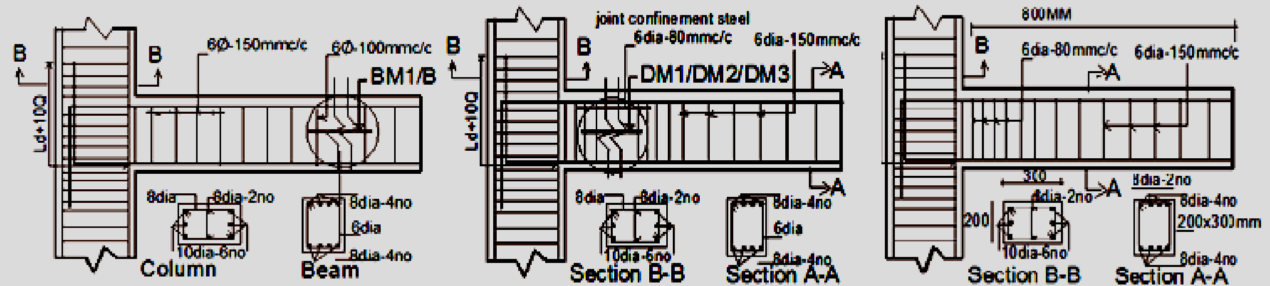
Table.2 Mechanical properties of steel reinforcement: Grade Fe410

Reinforcement Steel	Density	Bar-dia	Elastic modulus Es	Poisonratio μ_s	Yield stress fy	Ultimate stress fu	Plastic strain
	N/mm^3	mm	N/mm^2	0.30	MPa	MPa	N/mm^2
Mild steel bar	6.50x 10^6	6	1.8x10^5	0.30	310	560	0.30
HYSD steel	7.80x 10^6	10	2.0x10^5	0.30	530	610	0.20
Headed bar	7.80x 10^6	12	2.0x10^5	0.30	540	650	0.20
M.S Coupler	8.50x 10^6	12	2.4x10^5	0.30	570	680	0.20

Table.3 Damage Parameters

Dilation angle of concrete (β)	f_{bo}/f_{co}	Damage parameter= d		Stiffness recovery factor	
		Compression	Tension	Compression:	Tension:
35°	1.16	d_c =0.0011	d_t =0	ρ_c=0.67	ρ_t =0

VI. REINFORCEMENT DETAILING OF COMPONENT JOINT SYSTEM



Detailing of BM1 & BM2 joint Detailing of DM1,DM2,DM3 joint Detailing of MC joint

Fig.7a) Component Flexural joint Fig.7b)Component Discrete joint Fig.7c) Monolithic joint

Fig7. Reinforcement Detailing of Component Beam-Column Joints

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VII. STRESSES DEVELOPED IN COMPONENT JOINTS (B-REGION)

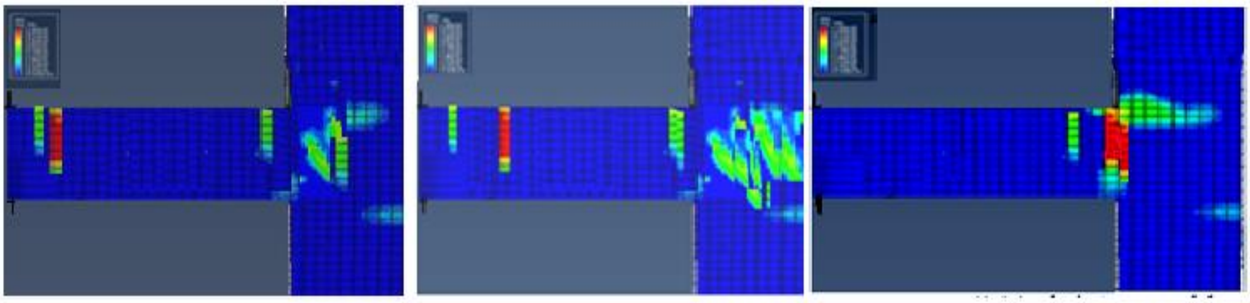


Fig.8a Component joint BM1 Component joint BM2 Monolithic Beam-column joint MCJ

Fig8a. Stresses Developed in Component Joints of B-region

BM1 represents critical stress condition of component joint located at flexure zone of precast system. The connection system comprised with use of headed bars and mechanical couplers to provide adequate stiffness and flexural rigidity. The connection detailing (Fig3a) establish sufficient joint anchorage and stress continuity of bars in the component joint element. This detailing intends to show moderate elastic response (44kN) and ductility with ultimate failure load (56kN). The stress contours indicates narrow gap between the connection and failure location. The column section possess less degradation of joint stiffness and shear strength and it possess same strength at par with monolithic joint system.

BM2 represents typical properties of BM1. The connection intends to show good elastic response (48kN) and ductility with ultimate failure load (50kN). The joint failures are attributed by intensified stress conditions near beam-column intersection. The developed stress conditions indicating that this connection is more critical than rest of joint system. Component joint MCJ (Fig.8a) gives critical stress condition of monolithic beam column system modeled under conventional hooked anchorage system. This system comprised by shear failure at intersection of beam column face due to development of principle stresses .Brittle shear failure happened at joint core during peak load (62kN) and the joint possess moderate ductility. The connection details (Fig3a) established sufficient joint anchorage and stress continuity of bars in the component joint element. This detailing intends to show moderate elastic response (48kN) and ductility. The stress contours indicated narrow gap between the joint failure and connection location. Also the column section possess less degradation of joint stiffness and shear strength.

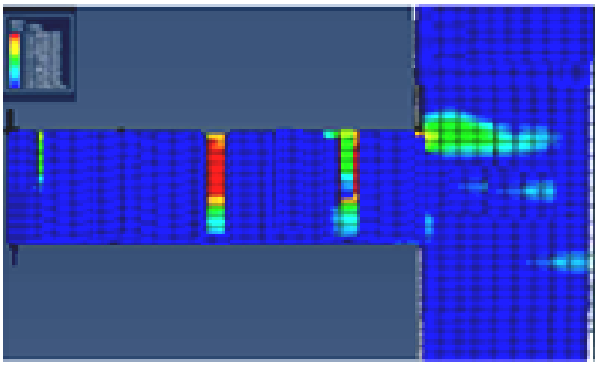


Fig.8b Discrete Component joint DM1

DM1 represents critical stress condition of joint located high shear zone of precast system. The connection system comprised with use of headed bars and mechanical couplers with suitable transverse confinement by headed bars .The connection detailing (Fig2a) establish sufficient joint anchorage and stress continuity of bars in the component joint element. This detailing impose good elastic response (50kN) and large in-elastic range before ultimate failure (64kN). Further it is noted that maximum stresses developed away from discrete joint connection in beam element and face imposed by less contribution of column stress concentration and stiffness degradation in beam-column intersection. DM2 represents critical stress condition of joint located in precast system .This joint comprise use of headed splice and studs to provide doweling effect between the component elements (Fig2b). Cyclic loads applied at beam end against shear strength. The stress contours shows that plastic hinge located near to joint connection and little away from column face. The joint possess considerable degradation of stiffness and moderate ductility. The results indicate good elastic response (48kN) and moderate ductility with ultimate load (56kN). Stress contours indicated that beam column junction receive high stress concentration compared with connection detailing DM1 & MCJ.

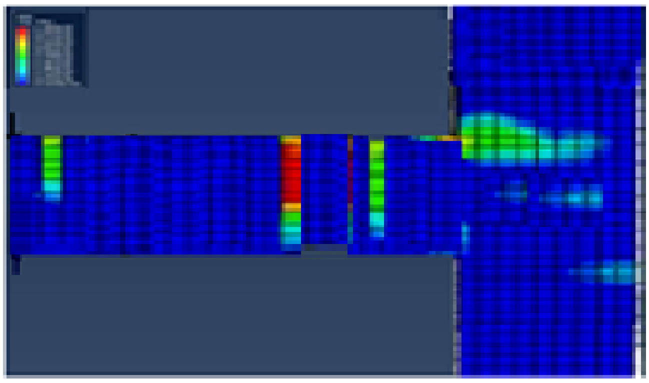


Fig 8b. Discrete Component joint DM2

DM3 represents critical stress condition of joint. The loads on joint component applied by transverse and lateral directions. The design of connection system comprised by use of headed bars, mechanical couplers, and provision of transverse shear key on concrete face confined by use of transverse reinforcement (Fig2c).Observations found that the development of high stress conditions are away from connection system. The results indicated that (DM3) possess good elastic range (58kN) and ductility with ultimate failure load (76kN).

The stress contours shows increased length of plastic range and hinge formation is away from discrete joint. The connections system possess moderate degradation of stiffness, strength and good ductility with reduced stress concentration at beam-column intersection. This joint system provides improved efficiency at par with monolithic beam column joint system.

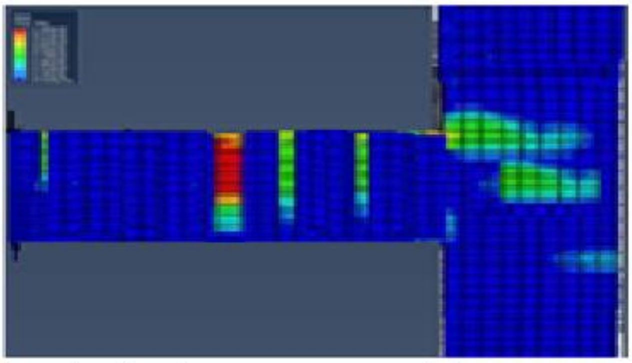


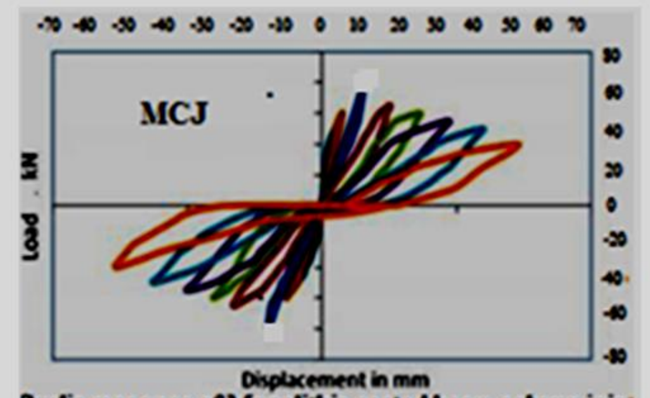
Fig 8b. Discrete Component joint DM3

VIII. SEISMIC RESPONSE OF JOINTS

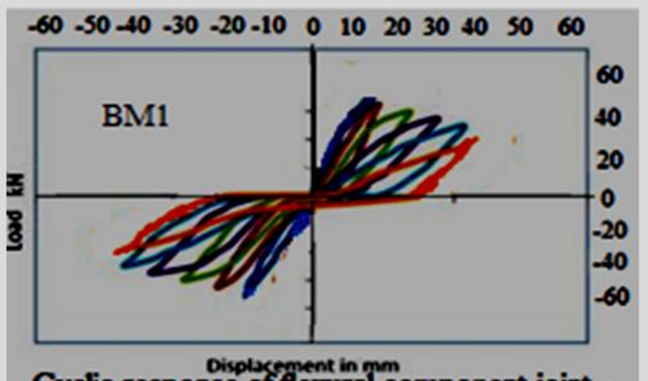
The seismic response of Discrete (DM1,DM2, DM3) and Continuous joints (BM!,BM2) are verified under peak load response of component system, cyclic response , crack location and ductility of the system.

A).Ductile performance

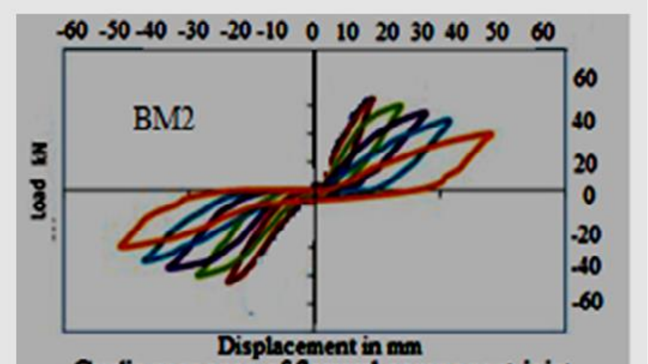
The hysteresis curves of monolithic beam-column joint (MCJ) shows ultimate load 62kN at lateral displacement 58.40mm with elastic limiting load 48kN.Flexural component joints of BM1, BM2 shows failure at ultimate loads 56kN, 50kN and the corresponding lateral displacement 48.30mm, 52.10mm. The limiting load of this joints are observed at 46kN, 44kN. Locations of joint failures in flexural component connection system are shown in Fig10a.



Cyclic response of Monolithic casted beam-column joint
Fig.11a- MCJ



Cyclic response of flexural component joint - Fig.11b-BM1



Cyclic response of flexural component joint
Fig.11c-BM2

Fig 12a,b,c shows discrete connections of DM1, DM2 and DM3 are fails at ultimate loads 64kN, 56kN,76kN and the corresponding displacements are noted as 54.30mm, 46.20mm, 57.10mm. Elastic limit of this joints are observed as 52kN, 48kN, and 59kN respectively. It is worth mentioned that DM3 exhibit higher failure loads (22.5%) than MCJ and DM1 shows same level of failure with MCJ .The location of discrete joint failures are shown in Fig10b and their performance was noted in Table 4.

From the observations, DM3 and BM1 exhibit maximum ductility 57.10mm and 48.30mm corresponding to ductility of monolithic joint MCJ of 58.40mm. Subsequently this joints are intends to fail @ 8th& 6th cycle corresponding to MCJ failure @ 8th cycle. Hence DM3 and BM1 are convergent with monolithic joint system and gives adoptable solutions in precast connection system.

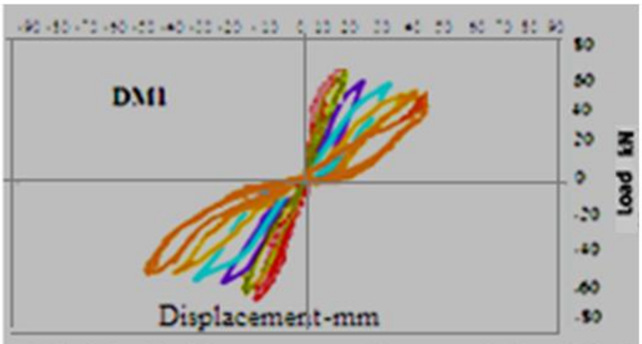
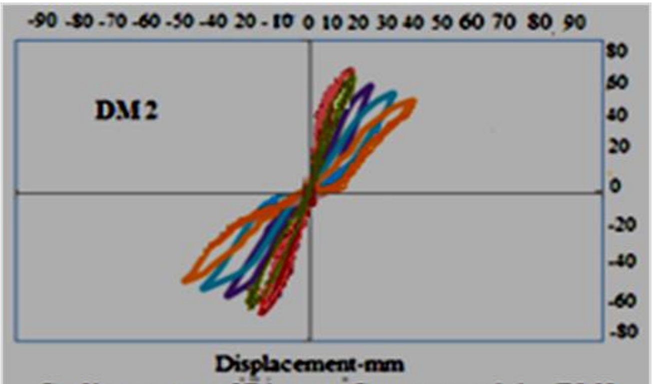
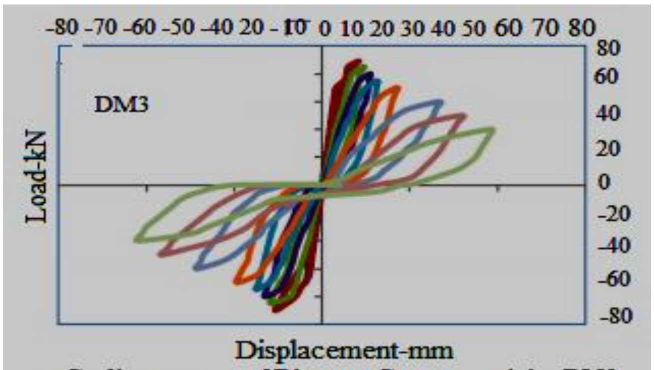


Fig-12a Cyclic response Discrete joints-DM1



Cyclic resonse of Discrete Component joint DM2
Fig.12b-DM2



Cyclic response of Discrete Component joint DM3
Fig.12C-DM3

B) Peak Load Response

Peak load response is a graphical representation of joint system by drawing each peak load and its corresponding deflection when a joint is subjected to cyclic loads. This ultimately indicate the stiffness degradation of joint (stiffness= load/deformation). In this process the component assembly ensures two types of stiffness degradation which are mentioned by elastic and in-elastic stiffness. This is an important phase of design as the inelastic deformations result loss of stiffness from elastic stage only.Fig13 shows elastic stiffness of different component assembly

C) Cyclic Response

The cyclic response of joints are verified under constant axial load of 800kN on column and identified the failure location in component joint system of B and D regions. The observations indicated that DM3 exhibit highest cyclic response at par with monolithic joint system. Hence the presence of Headed bars, Mechanical couplers and Shear heads of concrete in joint surface are much effective

Table 4. Cyclic Performance of Component Joint system

No	Component joints	Moment capacity Kn-m		Moment Ratio	Shear Capacity of joint kN		Capacity of factor-BCJ	Stiffness @ failure	Joint failure
	Joint model	Mu .Theory	Mt. Tested	Mu/Mt	Sf: @CJ	Sj. @ BCJ	Sj / Sf	kN/m	Type
1	MCJ	57.60	52.40	1.10	62	86.40	1.40	1.06	shear
2	BM1	57.60	55.20	1.04	56	86.40	1.54	1.15	flexure
3	BM2	57.60	51.60	1.10	50	86.40	1.72	0.95	flexure
4	DM1	57.60	51.20	1.12	64	86.40	1.35	1.18	flexure
5	DM2	57.60	44.80	1.28	56	86.40	1.54	1.21	shear
6	DM3	57.60	56.10	1.02	76	86.40	1.13	1.33	flexure

No	Component joint	Applied Load (kN)		Deformation (mm)		Ration of Stiffness de-grade	Ductility factor	Inelastic strength factor	Failure of Joint
		Elastic kN	Ultimate kN	Elastic mm	Ultimate mm	Ku /K e	ρ	R	@ Cycle number
1	MCJ	48	62	42.10	58.40	0.92	1.38	1.29	7
2	BM1	46	56	36.40	48.30	0.91	1.32	1.22	6
3	BM2	43	50	32.30	52.10	0.72	1.61	1.16	5
4	DM1	52	64	38.60	54.30	0.87	1.40	1.23	6
5	DM2	48	56	37.20	46.20	0.94	1.24	1.16	5
6	DM3	59	76	41.60	57.10	0.93	1.37	1.29	8

Table.5 Strength of Component Joints

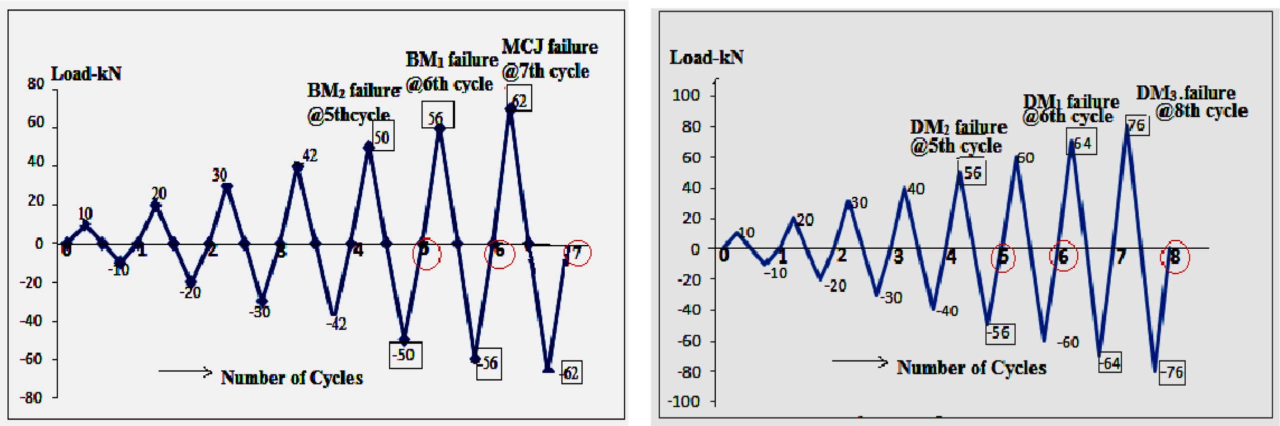


Fig.9a Cyclic response of Flexure joint (BM1-BM2-MCJ)

Fig.9b Cyclic Response of Discrete joint (DM1-DM2-DM3)

Fig.9. CYCLIC RESPONSE OF COMPONENT JOINTS

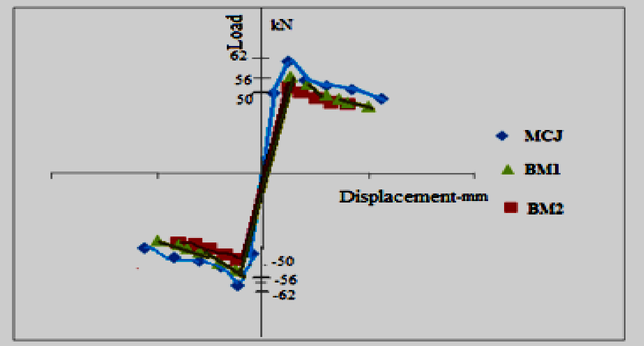


Fig 13a. Peak response of Load-Displacement Component jointsMCJ-BM1-BM2

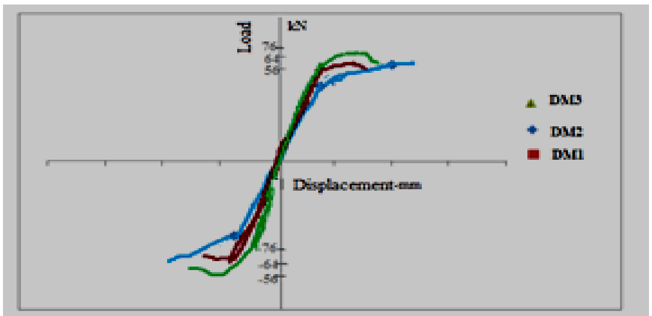


Fig.13b Peak response of Load-Displacement Component joints DM1-DM2-DM3

IX. PRINCIPLE OBSERVATIONS

Numerical analysis carried on different component joints modeled under Continuous and Discrete conditions of precast component joint system. During the testing, constant axial load of 800kN applied on column.

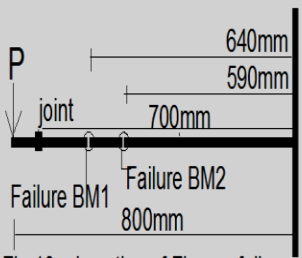


Fig.10a. Location of Flexure failures BM1, BM2

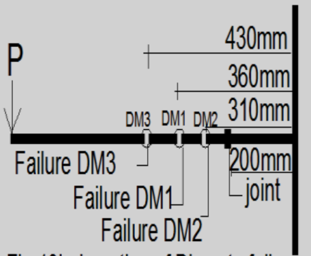


Fig.10b. Location of Discrete failures DM1,DM2,DM3

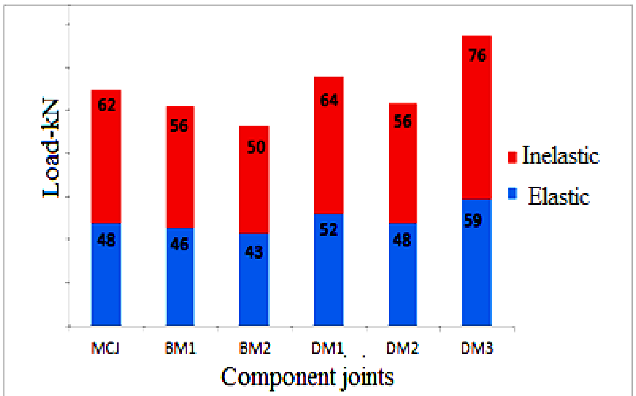


Fig 14a. Elastic & Inelastic response of joints

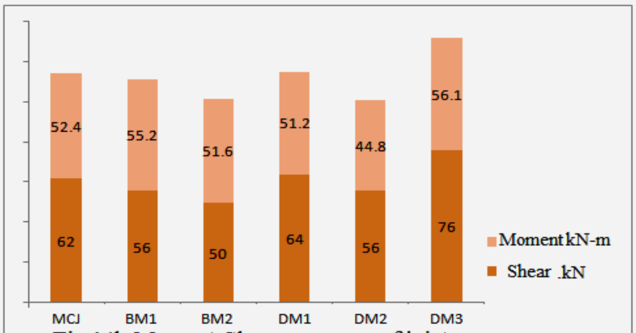


Fig.14b Moment-Shear response of joints

X. RESULTS

As mentioned in Table15 the final results of the developed precast component beam-column joints by using headed anchors and mechanical couplers shows good seismic joint efficiency of 97% , 89% of DM3, BM2 of component joints respectively. The results shows that a good improvement on seismic behaviour at par with monolithic BCJ .

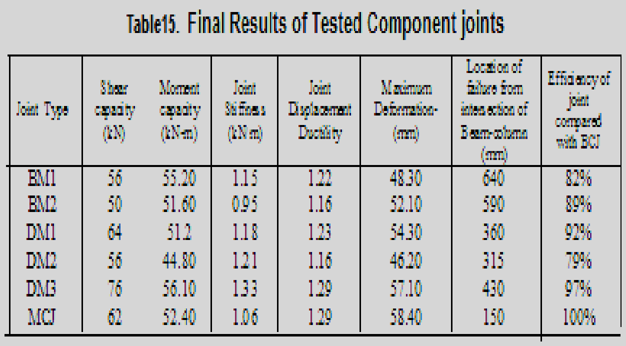


Table15. Final Results of Tested Component joints

Joint Type	Shear capacity (kN)	Moment capacity (kN-m)	Joint Stiffness (kN m)	Joint Displacement Ductility	Maximum Deformation-(mm)	Location of failure from intersection of Beam-column (mm)	Efficiency of joint compared with BCJ
BM1	56	55.20	1.15	1.22	48.30	640	82%
BM2	50	51.60	0.95	1.16	52.10	590	89%
DM1	64	51.2	1.18	1.23	54.30	360	92%
DM2	56	44.80	1.21	1.16	46.20	315	79%
DM3	76	56.10	1.33	1.29	57.10	430	97%
MCJ	62	52.40	1.06	1.29	58.40	150	100%

The improved design system shifted the plastic hinge location from beam-column junction to beam portion with flexural yielding.

Shear failure of component joints can be avoided by using the new design approach mentioned of CBCJ

The new system is much effective and constructible and easy to implement of joint detailing at construction site during erection of precast members.

The established components joints of B and D regions designed by headed anchors and mechanical connectors are significantly influence the seismic performance of segmental precast construction system.

XI. CONCLUSIONS

1.The tested series of flexural joint connections explained that, BM2 exhibit highest ductility ρ=1.61 as compared with monolithic joint system MCJ (ρ=1.38). This indicates the presence of headed bars and mechanical couplers are much useful to establish flexural component joint system in precast connections. Also BM2 fail at 90% ultimate load of MCJ .The failure is attributed in beam and away from the established component joint system. Also BM1, BM2 shows identical shear capacity and 10% moment capacity than MCJ. And the inelastic response of BM1 and BM2 are intended to 10%, 15% less than MCJ.

2.Tested series of discrete joint connections observed that, DM3 exhibit highest ductility ρ=1.37 at par with monolithic casted joints of MCJ (ρ=1.38). This indicates the presence of headed bars, concrete shear heads and mechanical couplers are much efficient to establish discrete joints in precast connections and improved ductility.

3.The ultimate failure of DM3 is 121% greater than MCJ and the nature of joint failure is flexural yielding of reinforcement in beam and located away from the established component joints

4.The failures of Both discrete and continuous joints, are attributed to locate in flexure region rather than shear location of beam-column junction or component joints. Also the joint DM3 posses highest cyclic failure loads at 8th cycle than MCJ. This indicates DM3 shows good resistance against fatigue loads and suitable in high seismic conditions.

5.Inelastic strength factor of DM3 and MCJ are typical and indicates that DM3 connection system in discrete locations behave similar to monolithic cast in-situ beam-column joint system with improved joint stiffness (more than 25%).

6.Except component joint DM2(combination of headed splice and shear studs), all the rest of component joint systems developed in Discrete and Continuous joint locations are failed under flexural action. This indicates component joints developed by couplers and headed bars are efficient to relocate the damage in beams rather than in beam-column junction.

7. The Key observations of DM3 indicated that joint indicates that 22% improved shear capacity, and 7% moment improvement and identical stiffness compared with MCJ.

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