AN INVESTIGATION OF BEHAVIOUR OF BEAM COLUMN JOINTS USING RPC

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ABSTRACT

This paper presents results of the studies conducted on beam-column joints. Experimental as well as analytical results are interpreted and are followed by discussions regarding the behaviour of beam-column joints considering various structural parameters. The half scaled models of beam-column joints were tested in a loading frame and the load along with deflections at four positions as given in the experimental setup were noted with the help of proving ring and dial gauges respectively. Development of first crack and failure patterns related to the propagation of cracks is noted for each specimen.

Keywords: Normal beam column joint (NBCJ), full RPC beam column joint (FRBCJ), Vertical RPC & Normal concrete beam column joint (VRNBCJ) and Inclined RPC & normal concrete beam-column joint (IRNBCJ)

INTRODUCTION

The development of RPC was based on two distinct approaches which emerged in nineties I order to achieve higher compressive strength. The first approach is creating compact granular matrix concrete designated as dense small particles (DSP). DSP matrix contain a higher super plasticizer, silica fume and also may incorporate quartz sand or even steel aggregates. The principle of DSP is related to the density of the matrix. Greater the packing density of matrix, higher compressive strength of concrete is achieved.

The second approach of researchconcerns with macro-defect-free(MDF) polymer pastes,which are having very high tensile strength, thereby generating crack free matrix. Research using these two approaches together was carried out by technical division of Bouygues, in France in early nineties & resulted in development RPC. This was first reported by Pieere Richard & Marcel Cheyrezy (1995). Since RPC was introduced in 1994, it has received considerable attention worldwide. Since then further development of the material along with its application in structural field has continued throughout the world at a frenzied pace. RPC is characterised by extremely good physical, mechanical, and durability characteristics. Thereby this material will have significant impact on construction industry related to use of high performance concretes. It will facilitate the material use in optimised way, and enable the industry to build strong and durable structures.

RPC has special combinations of the ingredients and its mix design include very high content of ordinary Portland cement, exceptionally low w/c ratios accompanied by high dosages of super-plasticisers. It has presence of a high reactive pozzolanic material (typically silicafume). Conventional coarse aggregateis completely removed and replaced by fine quartzsand having particle size b/w 150 & 600 µm, thereby RPC approximates a mortar rather than concrete. It is very necessary to have dense matrix formation and one of the basic requirement in RPC that the coarse particles (quartz sand) should not be in contact with each other. This will happen when the volume

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of the binder in RPC matrix will be more than at least 50 percent the void volume of the aggregate. By achieving this, the probability of inelastic deformation is significantly improved upon in response to the stresses developed. Thus the storage of strain through the formation of micro-cracks is discouraged. The name 'reactive powder' reveals fact that all powder componentsin RPCreact chemically following addition of water: cement by conventionalhydration, silica fume reacts with calcium hydroxide formed through pozzolanic reaction. The quartz sand is also to some extent reactive, as it provides dissolved silica for formation of CSH gel. Further if RPC is subjected to highpressure steam curing, then additional reactive silicaalter CaO/SiO_2 ratio & formation of calcium silicate hydrate mineral (tobermorite) takes place as an end product of entire hydration process.

MATERIALS USED IN RPC

RPC is a cementitious matrix that supports straight steel fiber reinforcements (optional) by combining unique constituent materialssuch as cement, silicafume, and quartz sand with a high range waterreducer.

CEMENT

The selection of cement can be an importantfactor in performance ofRPC as it comprises of very high cement content. Ordinary Portland cement (OPC) is used in RPC. OPC is obtained by mixing calcareous materials like limestone, chalk, marl and argillaceous materials like clay, shale. Materials containing silica, alumina or iron oxide can be added during mixing. The mixed materials are burned at a high temperature, and the resulting intermediate product, clinker is ground along with gypsum. This cement should conform to physical & chemical properties of 53 grade of Ordinary Portland Cement given in IS 12269:1987. Generally, ideal cement has ahigh Tri-Calcium Silicate & Di-CalciumSilicate content (C3S and C2S) & very little Tri-Calcium Aluminate (C3A). This is for the reason, C3A plays primary role to act as a flux during calcination process and has no so significant role to play as a binding agent.

QUARTZ SAND

Crushed quartz powder in crystalline form is an essential ingredient for RPC. Quartz is the +most important sand-forming mineral. Quartz sand is made upof a continuous suctural framework of mn silicon-oxygen tetrahedral (SiO_4). Each oxygen atom is shared b/w two tetrahedral, thereby giving an overallformula SiO_2. Since RPC belongs to the class of compact granular matrix concretes designated as dense small particles (DSP), mean particle size ofquartz sand is defined with reference to the criteria of homogeneity along with separation of granular classes' criterion. In RPC, after quartz sand, next lowestgranular category is that of cement, whose meandiameter varies between 11-15 µm. Therefore sand with a mean particlediameter of about 250µm is selected. Maximum particle size is restricted to 600 µm, and particle sizes of sand below 150 µm are not considered. This would prevent interference of sand particles with largest cement particles (80-100 µm). Quartz offers following advantages with respect to the mineral composition:

1. Very hardmaterial
2. Excellent paste-aggregateinterfaces
3. Readily available

The other more important properties of quartz sand are described below.

It should be clean with a low or negligible silt, clay & organic matter content. Colour should be white. This property is related to mineral composition and is an index of purity e.g. a brownish colour indicates presence of iron oxides. The specific gravity of quartz sand is about 2.65. A lower

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value of specific gravity may signify the presence of impurities or porosity and a higher value may specify the presence of heavier minerals such as carbonates, iron oxides etc. Quartz sand should contain 95 % quartz (silica). The grain size should fit the concept of DSP. The sands should meet a precise grain-size distribution.

SILICA FUME

One of the important and essential constituent of RPC is a highly reactive silica fume, performing three vital roles

- It fills voids b/w next larger class of particles (cement). To achieve this, silica fume must be appropriately fine to pack around cement particles closely, thereby improving packing density of resulting matrix. This also ensures minimizing possibility of voids between the particles.
- It produces of secondaryhydrates by pozzolanic reaction with lime produced from primary hydration,thereby strengthening binding capacity of the resulting composite. To achieve this, it should possess considerable pozzolanic activity
- It enhances rheological characteristics due to the lubrication effect

Since silica fume particles is basically of a spherical shape which helps it to act as a lubricant within fresh mix so that the flow is improved upon. Traditionally, reactive silica used for RPC is silica fume (an amorphous form of silicon dioxide), which is an ultra-fine powder collected as an industrial by-product of manufacturing of silicon & ferrosilicon alloys in submerged-arc electric furnaces. The gaseous form of SiO escaping from furnaces oxidizes & condenses as very tiny spherical amorphous silica particles. The following are the qualities of silica fume. Silica fume is a powder that is very fine. The spherical particles have diameters less than 1m, with an average of 0.15m. The typical cement particle is roughly 100 times smaller in size than silica fume. The bulk density of silica fume ranges between 130 and 600 kg/m3. The specific gravity ranges between 2.2 and 2.3. The specific surface area varies between 15,000 and 30,000 m2/kg. Because of its great fineness & high silica concentration, silica fume is a very efficient pozzolanic substance. Silica fume acts on the pozzolanic reaction in cementitious compounds, where hydration of Portland cement creates a variety of compounds, including calcium silicate hydrates (CSH) & calcium hydroxide (CH). The CHS gel is in charge of generating strength in concrete. When silicafume is mixed with fresh concrete, itchemically interacts with the CH to form more CHS gel. This reaction has the advantage of increasing compressive strength while decreasing porosity and therefore increasing chemicalresistance. The interfacial zone bond b/w binder paste & aggregate is strengthened, resulting in high compressive strengths. The extra CHS gel formed by silica fume improves durability because it is more resistant to assault by strong chemicals than the weaker CH. The primary function of silica fumes in RPC is to produce high-quality densified systems in the absence of particle aggregates. As a result, non-compacted silica fumes are used. Pozzolanic silica in the required quantity when added, reactswith all Ca $(OH)^2$ that would be produced during process of cement hydration. The hydration reaction in simplified form can be represented as:

$$2C_3S + 6H = C_3S_2H_3 + 3CH$$

$$2C_2S + 4H = C_3S_2H_3 + CH$$

[Where $C = CaO$; $S = SiO_2$; $H = H_2O$]

The product $C_3S_2H_3$ formed is poorlycrystalline. It is morecommonly referred to as CSH or calcium silicatehydrate. The CH produced byhydration of cement nearly occupies about 25-30 % of cement paste byvolume. CH is inert and has no role in development in strength. It is the addition of

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amorphous silica (which is formed due to the pozzolanic reaction) which helps in formation of CSH at the cost of calcium hydroxide.

CH + S + H = CSH

As mentioned earlier, it is desired that the volume of the binder in the RPC matrix should be at least double than void volume of the quartz sand so that the aggregate particle remains separated in the matrix. In a conventional concrete there is contact of the aggregates. Due to this, there is formation of a strong matrix. Silica fume is the most influential ingredient of in RPC and it is responsible for the improvement in its properties.

SUPER PLASTICIZER

In RPC, very low w/c (water/cement) ratios are used, which is possible because of addition of high-quality thirdgeneration super-plasticizing agents. Generally, there are four main categories of super plasticizer such as Formaldehyde condensates,Sulfonated Naphthalene-Formaldehydecondensates, modified lignosulfonates and others such as sulfonic-acid esters & polycarboxylate ethers. In orderto have proper workability of RPC mix, new generation plasticizer used is polycarboxylate based. Polycarboxylate Ether (PCE) super plasticizers have been very effective as they impart tremendous workability without the undesirable effects of retardation and segregation with up to reduction in water by 40 %.

The dosage ofsuper plasticizer depends on water/cement ratio (w/c) & type of cement used. The effectiveness increases when w/c ratio decreases. Thesuper plasticizer used should becompatible with cement used in mix. The utilization of super plasticizer ensures positive effect on the behaviour of concrete, both in fresh and hardened states.

In freshstate, there is reduction in the tendency tobleeding due to reduction in w/b ratio or watercontent of concrete. However, if w/c ratio is maintained, then there is a tendency that super plasticizer will increase setting time of concrete as more water is available. With use of super plasticiser, it is seen that in the case of hardened concrete, compressive strength is increased as it enhances the efficiency of compaction to produce denser concrete. PCE admixtures are also compatible with mineral additives such as GGBFS, silica fume and fly ash.

OBJECTIVE OF THE RESEARCH

To investigate the behavior of beam column joint using reactive powder concrete in terms of first crack failure pattern

LITERATURE REVIEW

Halit Yazici et al. (2010) investigated mechanical properties byreplacing cement with highvolumes of GGBFS. The percentage replacement was 20, 40, and 60 %. For different mixes quartz, sintered bauxite and granite were used. The effect of high volume of GGBFS was that the compressive strength of RPC obtained was over 250 MPa with autoclave curing. The compressivestrength of 400 MPa was obtained with application of an external pressure of 30 MPa.

A. Pimanmasa and P. Chaimahawan (2011) adopted the technique of joint expansion for the enhancement in behaviour of beam-column joint. Interiorreinforced concrete beam-column joint was expanded in two dimensions along the length of the beam keeping width of beam intact. The expansion was cast-in-situ around the corners of the joint. Monotonic loading was applied to interior beam-column specimens with expanded joint zone. The results demonstrated an enhancement in the shear capacity of joint. The energy dissipation and ductility also increased. This could also be thought of as a retrofitting technique to increase the strength of the joint and thereby

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avoiding the failure of the joint. Also, the failure takes place in the beam portion and hence undesirable shear failure is converted to ductile flexural failure of the beam.

Gregoria Kotsovou and Harris Mouzakis (2012) proposed use of inclined bar rather than the horizontal stirrup for enhancement of the behaviour of joint. For the seismic design of externa beam-column joints, a design method was proposed on the basis of the fact load which is transferred from beams to the joint is resisted by means of a diagonal strut action. This action is affected as cited before, by the bond characteristics b/w concrete and that portion of reinforcement of the beam which is extended into the joint. It also depends on the how the beam reinforcement and the joint reinforcement are anchored together effectively.

A. E. Abalaka and O. G. Okoli (2013) determined mechanical properties of concrete with samples cured in water & air for 3, 7, 14, 28 and 90 days. The mechanical properties tested were compressive & split tensile strength, sorptivity and coefficient of water absorption). Here the specimens were initially water cured for 1, 2, 3, 4, 5, 6, 7, 14, 28 days and later air cured for the remaining days to complete the period of 28 days. Compressive & split tensile strength properties of concrete specimens were found at end of 28 & 90 days. Water cured specimens showed better mechanical properties than air cured specimens. Conversely, the maximum compressive strength was found to be recorded for the samples which were water cured for 4 days & then air cured for remaining 24 days.

Chithra S. & Dhinakaran G. (2014) studied the effect of hot water curing & hot air oven curing on admixed concrete. GGBFS was used to replace cement in percentages of 20%, 30%, and 40%, and specimens were cast and cured under various curing conditions. Hot water and a hot air oven are examples of these circumstances. The specimens were treated to four hours of hot water curing at temperatures ranging from 40°C to 50°C. The specimens are next subjected to compression and split tensile tests. These experiments were carried out on concrete cubes and cylinders. When compared to specimens treated to simply normal curing, test findings showed that a few hours of thermal curing prior to normal curing resulted in better strength. The effect of heat curing on tensile strength was greater than that on compressive strength of control concrete and GGBFS admixed concrete. Hot water curing was shown to be more successful than hot air oven curing among two techniques of thermal curing.

C. Shi, M. Long, and C. Cao. et al. (2017) used a large eccentric compression test of 22 RPC columns to investigate bearing characteristics of RPCcolumns during eccentric compression with varying section diameters, reinforcement ratios, and circumstances with & without steel fibers. The distribution patterns of stresses across the segment of the RPC columns under substantial eccentric compression were investigated under cracking loads. A simple analytical method for cracking loads was also devised. When cracking loads are calculated, the thickness ratio of the elastic tensile zone to the whole tensile region may be 0.4 (with steel fibers) or 0.5 (without steel fibers). In the tensile area, the tensile stress distribution on the RPC columns was an isosceles triangle. A simple mathematical technique was used to compute the ultimate loads of RPC columns under strong eccentric compression. According to the test results, the RPC column's equivalency coefficient in tensile regions might be 0.6 (with steel fibers) or 0.4 (without steel fibers).

The failure characteristics, deformational properties, ductility, and energy dissipation of reinforced reactive powder concrete internal beam-column joints were explored by Zheng et al. (2018). Joint shear strength was measured in line with GB5001-2010 and ACI 318-14. The results show that reactive powder concrete beam-column joints have higher shear-cracking strength and shear bearing capacity, with no apparent loss in strength or stiffness. Furthermore, using RPC for beam-column connections aids in reducing stirrup congestion in the joint core. The diagonal strut mechanism bears the majority of the shear stress in the RPC joint; the ACI 318-14 design equation

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may be used to compute the shear strength of RPC joints in this test, which has a safety margin of 22%38%.

HUSSEIN M et al. (2019) investigated the performance of reinforced normal (ordinary) (NC) concrete & Reactive PowderConcrete (RPC) of Beam-Column Joints under reversedcyclic stress. For this objective, full-scale three m high reinforced beam-column joints fabricated with NC and RPC were examined. The appliedload for the RPC joint increasedby 26.5% as compared to the NC joint. The current study found that RPC structural joints can withstand vertical and lateral loads better than NC joints, which is due to improvements in the mechanical characteristics and overall behavior of RPC joints. Furthermore, the fracture pattern, load-deflection trend, and quantity of stresses improved the overall behavior of RPC Beam-Column Joints.

Zi-Yu Zhang (2020) provides cyclic testing offour internal precast UHPC/RC composite beam-column joints to quantify effect of substituting regular concrete in joint zone with UHPC. Given thatsteam curing is difficult to obtain in real building environment, non-steam-cured UHPC was used & demonstrated acceptable compressive (>120 MPa) & tensile strength (>7 MPa) with an ultimate tensilestrain more than 1 percent. The anchoring techniques, anchorage lengths, & stirrup ratios in joint zone are the important factors in this study. The cyclic load tests demonstrate that the cast-in-place UHPC works well with precast concrete and that stirrups are unnecessary in the UHPC joint zone. By utilizing UHPC instead of conventional concrete, the anchoring length of the beam straight and headed bars may be lowered to 16db and 8.1db, respectively. As a result, using UHPC in the joint zone is practical and can significantly simplify the production process, especially when headed bars are employed.

Nafees A, et al. (2021) investigated finite element modeling & analysis of a beam columnjoint made of reactive powderconcrete. According to the findings, the application of RPC at the joint region increased the total strength of the structure by more than 10%. It also helped with fracture width management. The use of RPC at the joint region increased the ductility of the structures. To conduct comparisons, different mesh sizes and viscosity parameter values were employed. Raising the mesh size and viscosity parameter value lowered analysis time and the number of steps taken during analysis. This work describes a unique modeling approach based on RPC beam-column joints for forecasting structural behavior and reaction, as well as increasing shear strength deformation under diverse structural loading circumstances.

A steel hysteretic is utilized to simulate the experimental response of steel strand anchored precast concrete frame joints exposed to reversed cyclic stress testing, according to Jianbing et al. (2022). According to the examination, the plastic hinge at the end of the beam had migrated outward in the case of the failure morphology of RPC beam-to-column couplings with friction dampers. Furthermore, the RPC inner beam-column joints' energy dissipation capacity and ultimate bearing capacity have been improved; the ultimate load of PC2 is 28.8% larger than that of PC1. Based on the aforementioned results, a parametric study of the RPC inner beam-column junction was performed. The influence of a variety of parameters on the mechanical properties of the joint was then investigated by varying the friction coefficient of the friction damper, the stirrup spacing in the panel zone, and the different axial compression ratios.

Jianhua Liu et al. (2023) examined the seismic performance of the innovative beam-column joints by constructing two full-scale components and subjected them to modest cyclic stresses. From fracture formation through component failure, the entire process was comprehensively investigated, and seismic performance indicators such as the hysteresis curve, skeleton curve, and stiffness degradation curve were compared and evaluated. The finite element simulation results are exceedingly accurate, correctly representing the seismic behavior of the components. Cast-in-place joints are shown to have stronger energy dissipation capability than test joints, while having a

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higher ultimate bearing capacity. Based on the experimental stress characteristics of the nodal core zone, a mechanical analysis model of the nodal core zone of the new assembled concrete beam-column joints is proposed, and shear force calculation equations for the core zone of the new assembled concrete beam-column rigid joints and semi-rigid joints are derived.

EXPERIMENTAL ANALYSIS

NBCJ SPECIMEN

The NBCJ specimen developed the first crack at joint face of beam at a 4.35 kN load which propagates in the joint area. Subsequent cracks are developed at the core section of joint and minor cracks are observed in beam and column sections until load reaches it maximum value of 11.02 kN at which the specimen fails.

FRBCJ SPECIMEN

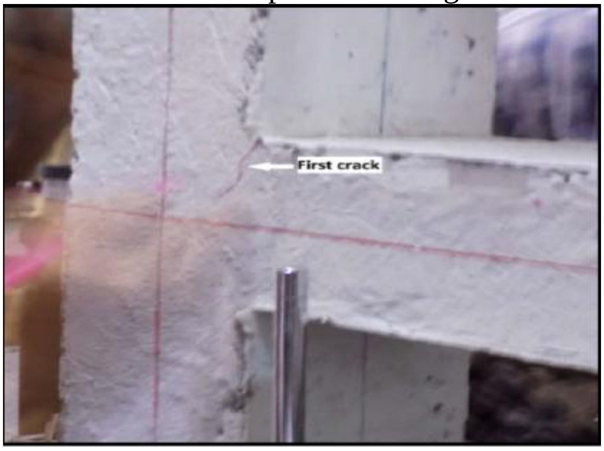
It is observed that first crack at 6.33 kN is developed vertically in beam at the column face on both faces of joint. Second minor crack is observed in the beam section near to the joint. As the load increased, subsequent major tensile crack is observed in the main core region of the joint diagonally, along with some minor cracks in the joint region with further increase in loading till failure load of 11.85 kN.

IRNBCJ SPECIMEN

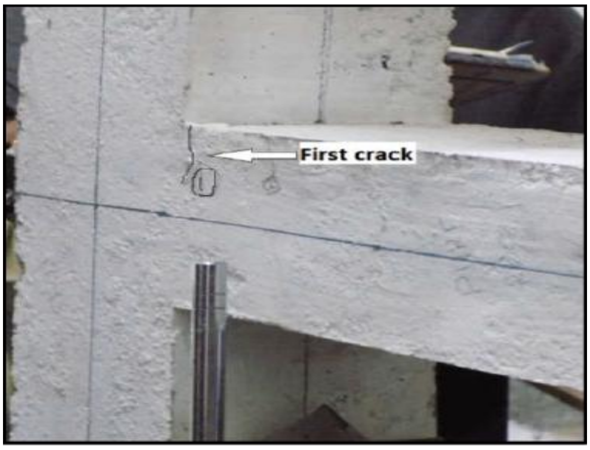
First crack is developed at the column face in the beam section at loading of 5.81 kN. With increase in loading, last crack is developed at the junction of RPC with conventional concrete with nearly same inclination of 30° at loading of 11.44 kN showing bond failure.

VRNBCJ SPECIMEN

First crack is developed vertically at junction of beam and column at both faces at loading of 4.54 kN. Crack is developed in core region at failure load of 11.02 kN.



(a) NBCJ (FCL-4.35 KN)



(b) FRBCJ (FCL-6.33 KN)

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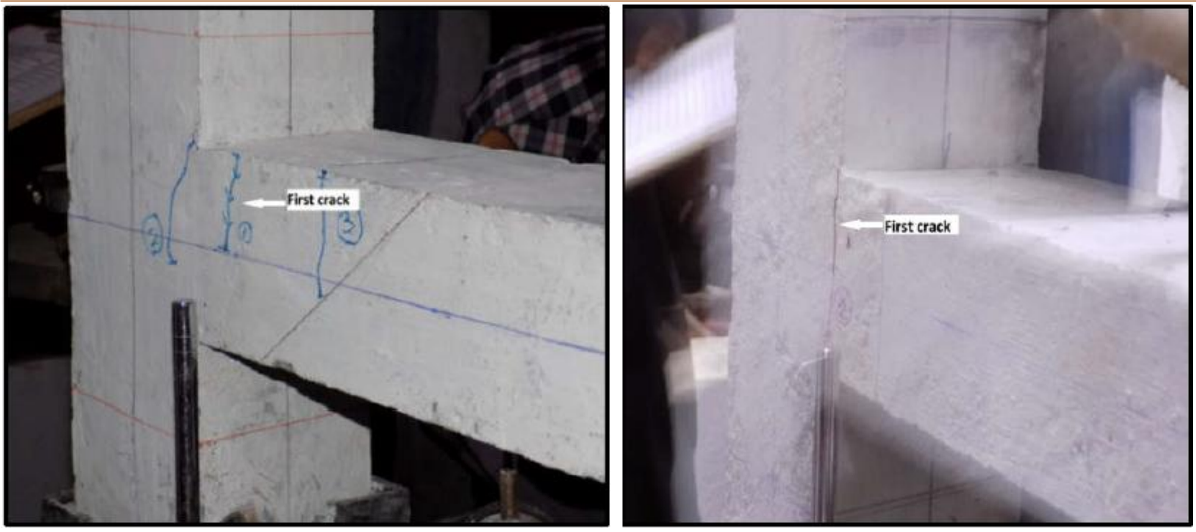
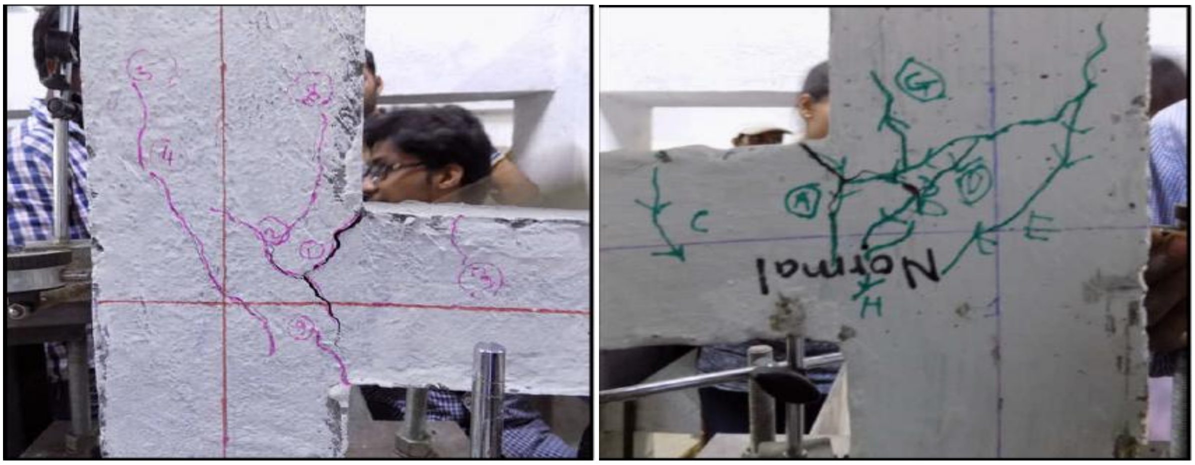


(c) IRNBCJ (FCL-5.81 KN) (d) VRNBCJ (FCL-4.54 KN)

FIGURE 1: FORMATION OF FIRST CRACK IN BEAM-COLUMN JOINT SPECIMEN



(a) CRACK PATTERN ON FACE A (b) CRACK PATTERN ON FACE B

FIGURE 2 CRACK PATTERN AT FAILURE-NBCJ SPECIMEN

(a) CRACK PATTERN ON FACE A (b) CRACK PATTERN ON FACE B

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FIGURE 3: CRACK PATTERN AT FAILURE-FRBCJ SPECIMEN

(a) CRACK PATTERN ON FACE A (b) CRACK PATTERN ON FACE B

FIGURE 4: CRACK PATTERN AT FAILURE-IRNBCJ SPECIMEN

(a) CRACK PATTERN ON FACE A (b) CRACK PATTERN ON FACE B

FIGURE 5 CRACK PATTERN AT FAILURE-VRNBCJ SPECIMEN

TABLE 1: EXPERIMENTAL RESULTS FOR NBCJ SPECIMEN

SR. NO.	PROVING RING READING	CALIBRATED LOAD (KN)	DEFLECTION (MM) AT POSITIONS OF				CRACK OBSERVATION	
			DIAL GAUGE 1	DIAL GAUGE 2	DIAL GAUGE 3	DIAL GAUGE 4	FACE A CRACKING	FACE B CRACKING
1	0	0.00	0	0	0	0		
2	0	0.19	0.5	0.25	0	0.01		
3	0.05	0.60	0.85	0.52	0.2	0.44		
4	0.1	1.02	1.75	0.72	0.48	0.84		
5	0.15	1.44	1.95	0.9	1	1.51		
6	0.2	1.85	2	0.95	1.38	2.04		
7	0.2	1.85	2.5	1	1.65	2.54		
8	0.25	2.27	3.1	1.2	1.98	3.101		
9	0.25	2.27	3.75	1.25	2.3	3.602		
10	0.3	2.69	3.95	1.5	2.58	4.05		

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11	0.35	3.10	4.1	1.7	2.97	4.55		
12	0.4	3.52	4.25	1.72	3.3	5		
13	0.4	3.52	4.55	1.78	3.72	5.51		
14	0.45	3.94	5.2	1.9	4.28	6.05		
15	0.5	4.35	5.49	2.2	4.58	6.62	Crack 1	
16	0.55	4.77	6.2	3	4.12	7.12		Crack 1
17	0.6	5.19	6.35	3.175	5.2	7.75		
18	0.65	5.60	6.45	3.225	5.46	8.3	Crack2	Crack 2
19	0.7	6.02	6.79	3.395	5.72	8.94		
20	0.75	6.44	6.8	3.4	6.02	9.63		
21	0.85	7.27	7.25	3.625	6.28	10.19		
22	0.9	7.69	8.05	4.025	6.55	10.78	Crack 3	Crack 3
23	0.95	8.10	8.15	4.075	6.88	11.49		
24	1	8.52	8.15	4.075	7.05	12.13		
25	1	8.52	8.35	4.175	7.32	12.79		
26	1.05	8.94	8.35	4.175	7.5	13.26		
27	0.9	7.69	8.35	4.175	7.75	13.73		
28	1	8.52	8.35	4.175	8.04	14.31	Crack 4	Crack 4
29	1.05	8.94	7.95	3.975	8.04	15.09		
30	1.1	9.35	7.75	3.875	8.04	16.17		Crack 5
31	1.15	9.77	7.5	3.75	8.04	16.9		
32	1.2	10.19	7.4	3.7	8.04	17.65		
33	1.2	10.19	7.3	3.65	8.04	18.33		
34	1.2	10.19	7.8	3.9	8.04	19.59		
35	1.25	10.60	8.25	4.125	8.04	19.73		
36	1.25	10.60	8	4	8.04	20.64		
37	1.3	11.02	8	4	8.04	21.63		
38	1.3	11.02	8.05	4.025	8.04	22.46		Crack 6
39	1.3	11.02	8.05	4.025	8.04	23.1	Crack 5	
40	1.3	11.02	8.05	4.025	8.04	23.83	Crack 6	Crack 7

TABLE 2: EXPERIMENTAL RESULTS FOR FRBCJ SPECIMEN

SR. NO.	PROVING RING READING	CALIBRATE DLOAD	DEFLECTION (MM) AT POSITIONS OF				CRACK OBSERVATION	
			DIAL GAUGE 1	DIAL GAUGE 2	DIAL GAUGE 3	DIAL GAUGE 4	FACE A CRACKIN G	FACE B CRACKING
1	0	0	0	0	0	0		
2	0.1	1.03	0.01	0	0.18	0.28		
3	0.15	1.44	0.06	0	0.28	0.65		
4	0.2	1.85	0.2	0	0.51	1.07		
5	0.25	2.27	0.64	0	0.68	1.46		
6	0.3	2.69	0.98	0	0.78	1.74		
7	0.33	2.99	1.09	0	0.92	2.01		
8	0.35	3.1	1.22	0	1.02	2.26		
9	0.4	3.52	1.43	0	1.09	2.8		
10	0.43	3.74	1.59	0	1.54	3.48		
11	0.47	4	1.78	0	1.77	3.74		
12	0.48	4.48	2.06	0	2.01	4.22		
13	0.52	4.87	2.24	0	2.22	4.56		

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14	0.57	5.04	2.43	0	2.32	4.78		
15	0.58	5.29	2.58	0	2.45	5.02		
16	0.63	5.63	2.76	0	2.68	5.56		
17	0.65	5.81	2.93	0	2.81	5.82		
18	0.67	6.09	3.1	0	2.96	6.16		
19	0.68	6.33	3.2	0.4	3.08	6.53		
20	0.71	6.79	3.32	0.4	3.36	6.92	Crack 1	
21	0.73	6.98	3.48	0.6	3.51	7.26		
22	0.75	7.06	3.67	0.6	3.64	7.48		
23	0.78	7.81	3.88	0.62	4.03	8.28		
24	0.82	8.01	3.95	0.62	4.26	8.62		
25	0.87	8.41	4.03	0.62	4.39	8.94	Crack 2	Crack 1
26	0.87	8.86	4.12	0.92	4.46	9.05	Crack 3	
27	0.91	9.11	4.3	0.92	4.75	9.56		Crack 2
28	0.93	9.32	4.41	0.92	4.96	10.02		
29	0.95	9.56	4.92	0.92	5.28	10.68		
30	0.96	9.95	5.44	0.92	5.58	11.24		
31	0.99	10.14	5.62	1.2	5.99	11.98		
32	1.02	10.31	6.37	1.2	6.15	12.38	Crack 4	
33	1.04	10.58	6.49	1.8	6.42	12.86		
34	1.07	10.88	6.93	1.8	6.64	13.32	Crack 5	Crack 3
35	1.09	11.05	7.63	2	6.89	13.84		
36	1.13	11.24	7.9	2.4	7.66	15.42		Crack 4
37	1.15	11.44	8.12	2.6	8.01	16.08		Crack 5
38	1.17	11.62	8.39	3	8.39	16.82	Crack 6	
39	1.2	11.85	8.62	3	8.82	17.68		
40	1.2	11.85	8.62	3.3	9.06	18.19		

TABLE 3: EXPERIMENTAL RESULTS FOR IRNBCJ SPECIMEN

SR. NO.	PROVINGRING READING	CALIBRATEDLOAD (KN)	DEFLECTION (MM) AT POSITIONS OF				CRACK OBSERVATION	
			DIAL GAUGE 1	DIAL GAUGE 2	DIAL GAUGE 3	DIAL GAUGE 4	FACE A CRACKING	FACE B CRACKING
1	0	0	0	0	0	0		
2	0.15	1.44	0.09	0	0.04	0.13		
3	0.15	1.44	0.15	0	0.18	0.42		
4	0.2	1.85	0.28	0.06	0.32	0.94		
5	0.25	2.27	0.35	0.2	0.48	1.05		
6	0.3	2.69	0.42	0.28	0.61	1.31		
7	0.35	3.1	0.53	0.32	0.81	1.79		
8	0.4	3.52	0.66	0.44	1.08	2.78		
9	0.45	3.94	0.8	0.54	1.36	2.91		
10	0.5	4.35	1.05	0.7	1.44	3.08		
11	0.5	4.35	1.12	0.7	1.62	3.41		
12	0.55	4.77	1.35	0.9	1.82	3.78		
13	0.55	4.77	1.48	0.98	1.96	4.09		
14	0.6	5.18	1.65	1	2.09	4.33		

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15	0.65	5.81	1.85	1.14	2.26	4.74		
16	0.67	6.09	2.05	1.26	2.42	5.02	Crack 1	Crack 1
17	0.67	6.09	2.13	1.36	2.58	5.39		
18	0.7	6.44	2.24	1.46	2.9	5.96		
19	0.7	6.44	2.39	1.52	2.98	6.17		
20	0.73	6.98	2.51	1.52	3.28	6.68		
21	0.75	7.06	2.64	1.64	3.41	6.99		
22	0.77	7.49	2.72	1.72	3.52	7.22	Crack 2	Crack 2
23	0.78	7.81	2.9	1.72	3.65	7.51		Crack 3
24	0.82	8.01	3.05	1.78	3.82	7.83		
25	0.87	8.41	3.32	1.88	3.98	8.13		
26	0.87	8.86	3.4	1.88	4.15	8.49	Crack 3	
27	0.9	8.94	3.52	1.9	4.4	8.98		
28	0.9	8.94	3.6	1.92	4.64	9.42		Crack 4
29	0.93	9.32	3.75	1.94	5.01	10.13		
30	0.95	9.56	3.9	1.98	5.31	10.75		
31	0.95	9.56	4.01	2.02	5.63	11.43		
32	1	10.18	4.12	2.02	5.96	12.08		
33	1	10.18	4.2	2.04	6.3	12.71		
34	1.05	10.6	4.3	2.06	6.6	13.29	Crack 4	
35	1.05	10.6	4.38	2.08	6.96	14		
36	1.1	11.02	4.5	2.12	7.09	14.29		
37	1.1	11.02	4.6	2.12	7.09	14.79		
38	1.15	11.44	4.6	2.16	7.55	15.16	Crack 5	
39	1.15	11.44	4.63	2.16	7.84	15.74		Crack 5
40	1.15	11.44	4.65	2.16	8.14	16.33		Crack 6

TABLE 4: EXPERIMENTAL RESULTS FOR SPECIMEN VRNBCJ

SR. NO.	PROVING RING READING	CALIBRATE DLOAD (KN)	DEFLECTION (MM) AT POSITIONS OF				CRACK OBSERVATION	
			DIAL GAUGE 1	DIAL GAUGE 2	DIAL GAUGE 3	DIAL GAUGE 4	FACE A CRACKING	FACE B CRACKING
1	0	0	0	0	0	0		
2	0.1	1.03	0.02	0	0.06	0.17		
3	0.15	1.43	0.1	0	0.18	0.77		
4	0.2	1.85	0.25	0	0.32	1.05		
5	0.25	2.27	0.4	0.02	0.86	1.86		
6	0.3	2.69	0.5	0.02	0.98	2.01		
7	0.35	3.1	0.55	0.04	1.22	2.55		
8	0.4	3.52	0.63	0.08	1.42	3.13		
9	0.45	3.94	0.72	0.1	1.54	3.5		
10	0.5	4.35	0.8	0.1	1.77	3.86		
11	0.5	4.35	0.82	0.12	1.93	4.15		
12	0.53	4.54	0.83	0.12	2.24	4.66		
13	0.55	4.77	0.9	0.18	2.35	4.92		Crack 1
14	0.57	5.04	0.92	0.18	2.58	5.28		
15	0.57	5.04	0.95	0.18	2.79	5.78	Crack 1	
16	0.6	5.18	0.96	0.24	3.02	6.36		
17	0.6	5.18	0.98	0.28	3.32	6.94		

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18	0.63	5.63	1	0.31	3.68	7.6	Crack 2	Crack 2
19	0.65	5.81	1.05	0.31	3.98	8.2		
20	0.67	6.09	1.06	0.36	4.36	8.82		
21	0.67	6.09	1.18	0.36	4.52	9.29		
22	0.71	6.79	1.29	0.4	4.92	10.01		
23	0.73	6.98	1.34	0.4	5.27	10.63		
24	0.75	7.06	1.48	0.46	5.42	11.14		
25	0.77	7.49	2.02	0.48	5.71	11.79		
26	0.78	7.81	2.12	0.5	6.04	12.4		
27	0.82	8.01	2.2	0.52	6.48	13.14		
28	0.87	8.41	2.42	0.52	6.84	13.84	Crack 3	
29	0.87	8.86	2.66	0.57	7.15	14.53		
30	0.93	9.32	2.74	0.59	7.66	15.46		Crack 3
31	0.93	9.32	2.88	0.66	8.01	16.22		
32	0.95	9.56	2.96	0.74	8.5	17.32		
33	0.96	9.95	3.02	0.8	8.89	18.02	Crack 4	
34	0.99	10.14	3.11	0.88	9.36	18.92		
35	1	10.18	3.29	0.92	9.8	19.78		Crack 4
36	1.05	10.6	3.42	0.96	10.01	20.24		
37	1.08	10.9	3.57	0.98	10.42	20.98		
38	1.1	11.02	3.68	1.12	10.72	21.46	Crack 5	
39	1.1	11.02	3.72	1.46	10.96	21.93	Crack 6	
40	1.1	11.02	3.8	1.6	11	22.2		

DETAILED OBSERVATIONS OF THE BEHAVIOUR OF MODELS

After observing the failed beam-columnjoint specimens at end of experimental tests on, important observations are noted in table 4.20 These observations are picked from the main observation tables tabulated for NBCJ, FRBCJ, VRNBCJ, and IRNBCJ specimens from table 1 to table 4 The observations are focussed on first crack load, corresponding deflection of tip of the beam, location of crack and propagation of the crack till the specimens fail completely. Emphasis on whether the crack occurs in beam, column or joint portion is made. The sequence of the failure of the elements is also observed.

TABLE 5 DETAILED OBSERVATIONS OF CRACK PROPAGATION FOR VARIOUS SPECIMENS

CRACK NO	LOAD (KN)	DEFLECTION(mm)	LOCATION
		NBCJ	
1	4.35	6.62	First diagonal crack propagating into joint.
2	5.19	7.75	Another diagonal crack opposite to 1st crack in joint.
3	7.27	10.19	Vertically downward crack in beam near to 1st stirrupdeveloped.
4	7.69	13.73	Diagonal crack at centre of joint.
5	8.94	15.09	Diagonal propagation of 4th crack.
6	11.02	21.63	Diagonal crack at the base of joint.
		FRBCJ	
1	6.33	6.53	Vertical crack at beam-column junction.
2	8.01	8.62	Vertically downward crack in the beam approximately nearto 1st stirrup.
3	8.41	8.94	Vertical downward propagation of 1st crack.
4	10.14	11.98	Diagonal large crack in joint.
5	10.58	12.86	Diagonal crack opposite to crack 4 in joint.

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6	11.44	17.68	Vertical downward propagation of 1st crack till the base ofbeam.
VRNBCJ			
1	4.54	4.66	Vertical crack developed at connecting face of joint.
2	5.18	6.94	Vertical downward propagation of 1st crack.
3	8.01	13.14	Vertical crack near to 1st stirrup.
4	9.56	17.32	Diagonal crack in joint & propagation of 1st crack in upperface of joint.
5	10.9	20.98	Vertically upward propagation of 4th crack into uppercolumn.
6	11.02	21.46	Horizontal propagation of 3rd crack into upper face ofbeam. Crack propagation in column.
IRNBCJ			
1	5.81	4.74	Vertical crack just near to 1st stirrup.
2	7.06	6.99	Small diagonal crack in joint from top.
3	8.14	8.13	Vertical downward crack in beam beyond first stirrup.
4	10.81	12.71	Horizontal crack near to upper face of joint.
5	11.02	14.79	Crack parallel to bond line in beam.
6	11.44	16.33	Propagation of the crack along bond interface.

CONCLUSIONS

It is observed that for NBCJ, the first crack is diagonal crack propagating in beam-column joint area at 4.35 kN with 6.62 mm deflection under the load. Further minor cracks were developed in the joint area itself. At quite later stage a vertical crack is developed in the beam near to first stirrup from column face. This is at load of 7.27 kN with 10.19 mm tip deflection. All other cracks are developed completely in the joint area leading to final failure at 11.02 kN In all the specimens with RPC, the crack is not initiated in the joint area. In FRBCJ, first crack develops at the beam-column junction comparatively at higher load of 6.33 kN with tip deflection of 6.53 mm. The diagonal crack in joint occurs very much at later stage at a load of 10.14 kN (11.98 mm tip deflection), and the specimen fails later with the downward propagation of the first vertical crack up to the bottom of the beam a 11.85 kN. In VRNBCJ specimen, first crack develops in beam at develops at face of joint at load of 4.54 kN with 4.66 mm tip deflection. Vertical crack near stirrups occurs at 8.01 load. The diagonal crack in the joint occurs at 9.56 kN with 17.32 mm deflection at tip. Here it is observed that the crack propagates into the column from joint. Failure occurs at 11.02 kN. In IRNBCJ specimen, crack initiated vertically near the first stirrup at 5.81 kN. Small crack in joint initiates at 7.06 kN only on one face. There are no cracks formed in the joint area other than this. All the cracks appear in the beam area, until finally a crack initiates at the bond interface area at 11.02 kN which propagates and failure of specimen occurs. In all RPC specimens, there is just one diagonal crack in the joint area unlike in NBCJ where the joint area is fully cracked.

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