

# Behaviour of High Performance Fibre Reinforced Concrete Beam Column Joints

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**Abstract:** *Beam- column joints have been recognized as critical elements in the seismic design of reinforced concrete frames. Numerous studies were conducted in the past to study behavior of beam-column joints with normal concrete. ACI-ASCE committee 352 makes recommendations on the design aspects of different types of beam-column joints, calculations of shear strength, and on reinforcement details to be provided. These recommendations are however not intended for fiber reinforced concrete. This study investigates the flexural behaviour of beam-column junction with steel fibres. Beam – column joint of a multi-storied building has been selected, dimensional analysis was carried out and corner beam – column joint was modeled on 1:4 scale. Control specimens were also cast simultaneously to investigate structural characteristics of concrete under compression, tension and flexural conditions. Ten specimens of beam – column junction were cast, using high performance fibre reinforced concrete (HPFRC), with fibre contents varying from 0, 6, 8, 10, and 12 percent by volume. These were tested under loading frame to study the load deformation behaviour, failure pattern and other ductility associated parameters. The typical results illustrate that compressive, tensile and flexural strength values are increased by 78, 144 and 646 percent when compared with their companion specimens of High performance concrete (HPC). Ductility associated parameters also increased significantly, and slurry infiltrated concrete (SIFCON) based HPFRC undergoes small deformation without developing wider cracks. Further, SIFCON based beam column joints impart dimensional stability and integrity to the joints.*

**Keywords:** *SIFCON, dimensional stability, ductility associated parameters, EARS.*

## 1. Introduction

Joint shear failure has been observed in many RC structures subjected to severe earthquake loadings. Inadequate transverse reinforcement in the joints, in a weak column/strong beam, is considered as the main reasons for such failure observed during recent earthquakes. Under seismic excitations, beam- column joint region is subjected to high horizontal & vertical forces whose magnitudes are much higher than those within the adjacent beams & columns. Conventional concrete loses its tensile resistance after the formation of multiple cracks. However, fibrous reinforced concrete can sustain a portion of its resistance following cracking to resist more cycles of loading. Beam-column & Beam-column and slab structural systems have a crucial role in the structural integrity of building and as such they have to be provided adequate strength & stiffness to sustain the load transmitted from either beam or column. For adequate ductility of beam-column junction, use of closely spaced hoops as transverse reinforcement was recommended in the ACI-ASCE committee 352 report (ACI 2002). However, due to congestion of reinforcement, casting of beam- column joints becomes difficult and leads to honeycombing in concrete at these joints (Kumar et al. 1991).

High Performance implies an optimized combination of structural properties such as strength, toughness, energy absorption, stiffness, durability, multiple cracking and corrosion resistance, taking into account the final cost of the material and above all, the produce manufactured. HPFRC composites are defined by an ultimate strength higher than their first cracking strength and the formation of multiple cracking during inelastic

deformation process. Generally speaking “High Performance” is meant to distinguish the structural material from the conventional one, as well as to optimize a combination of properties in terms of final application in real civil engineering structures, Fig. 1. High Performance Concrete can be designed to give optimized performance characteristics for a given set of usage and chemical admixtures like Silica fume and Superplasticizer enhance the strength, durability and workability qualities to a very high extent. High Performance Concrete can be designed to give optimized performance characteristics for a given set of load, usage and exposure conditions consistent with the requirements of cost, service life and durability.

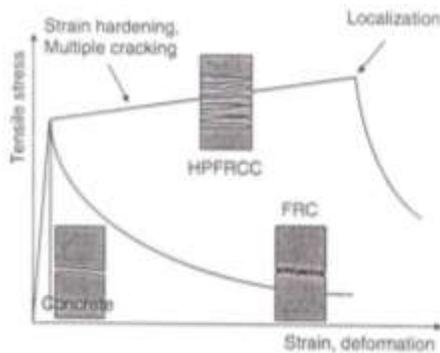


Fig. 1: Stress-Strain Behaviour of Cementitious Matrices

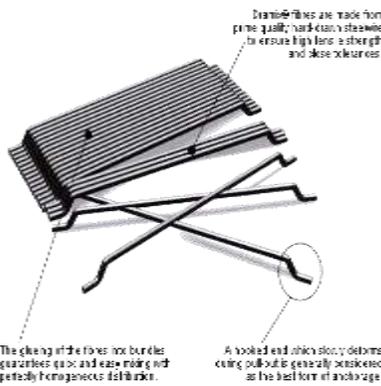


Fig. 2: Typical View of Steel Fibre

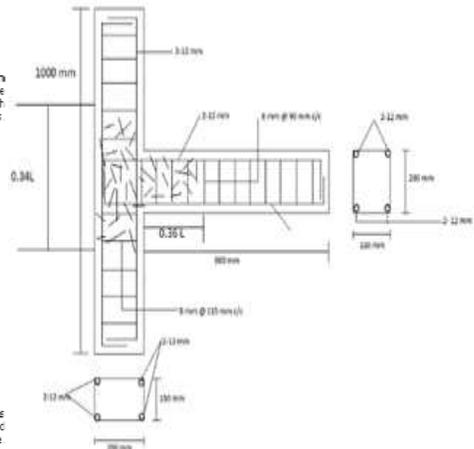


Fig. 3: Position of Steel Fibre in of Typical Beam-Column Specimen

The main objectives of present investigation are to develop HPFRCC of higher strength and to investigate its structural properties , to study structural performance of beam-column junctions by utilizing HPFRCC , to compare experimental results of present investigations with those obtained by other investigators , and finally to optimize fiber content in HPFRCC used in structural systems.

## 2. Review of Published Literature

Several investigators studied flexural behaviour of HPFRCC beam column joints with and without fibres. Some researchers also studied influence of addition of fibres in normal and HPFRCC. Kumar V et al (1) studied effect of column axial loads, grades of concrete in beam and column, transverse reinforcement of beam and ties of column on the performance of joints. It was found that the efficiency of joint increases with the increase in axial load on column for the same grade of concrete in beam and column and for richer grade of concrete in column. Jiuru et al (2) studied effect of fibers on the beam-column joints and developed equations for predicting shear strength of joints for normal strength concrete. Singh and Kaushik (3) investigated behaviour of fibre reinforced concrete corners under opening bending moments. The investigations indicated that because of low fibre volume percentage, there is only a noticeable gain in efficiency with increase in fibre volume fraction upto a certain limit beyond which there is a drop in mix workability and joint efficiency. Thirugnanan, et al (4) investigated experimentally effect of using SIFCON in the hinging zones of multistoried frames subjected to cyclic loading. It was concluded that the use of SIFCON in the hinging zones increases first crack loads and ductility by 40 & 100 percent, respectively. The energy absorption capacity was also increased by 50 percent by adopting SIFCON in the selected fuse locations of R.C. structures. Bayasi and Gevman (5) also experimentally proved the confinement effects of fibers in the joint region, and a reduction in the lateral reinforcement by the use of fiber concrete. Bakir (6) conducted extensive research on parameters that influence behavior of cyclically loaded joints derived equations for calculating shear strength of the joints. Ganesan et al (7) described the experimental results of ten steel fiber reinforced high performance concrete (SFRHPC) exterior beam-column joints under cyclic loading. Test results indicated that the provision of SFRHPC in beam column joints enhances

strength, ductility and stiffness, and is one of the possible alternative solutions for reducing the congestion of transverse reinforcement in beam-column joints.

Elnono et al (8), Opara et al (9) and Kim et al(10) also studied corner connections subjected to opening bending moments. It was found that in all the RC specimens, the joints failed before reaching the capacity of the connecting members. There was significant difference in the different joint's efficiency due to the variety of reinforcement details. Based on the comparison of observed responses, it was found that the addition of 1.5percent steel fibers was effective in reducing amount of steel rebars in the beam-column joints of railway bridges.

The critical review of published literature illustrated that most of the studies are limited to normal strength concrete and research in the area of high performance concrete beam-column joint is limited. Most of the investigators have used SFRC in the beam-column junctions and fibre volume content was restricted to 2% by volume. . The mechanism for improved tensile strain capacity of discontinuous fibre composites is also yet not well understood. Since, beam-column junctions are vulnerable locations which are subjected to high horizontal and vertical forces, HPC has been developed to investigate behavior of beam-column junctions.

### 3. Experimental Investigation

In order to study flexural behaviour of high performance fibre reinforced composite frame, a beam – column joint of a multi-storied building has been selected, dimensional analysis carried out and corner beam – column modeled on 1:4 scale. The dimensional analysis gives the dimension of the junction 1000 × 200 × 150 mm for columns and 800 × 200 × 150 mm for beams. High performance concrete was designed as per the procedure laid down in ACI committee report to achieve the compressive strength of the order of M-60. Mix 1 ,Table 1, corresponding to C : SF : FA : CA : SP and w/c ratio 0.35 provided compressive strength corresponding to 69 MPa at 28 days and was considered in the present investigation as controlled mix. Ordinary Portland Cement (43 grade) conforming to IS: 8112 was used. Silica fume obtained from Orkla India (Pvt) Ltd (Brand name: Elkem Microsilica 920-D), Navi Mumbai was used. Super plasticizer STRUCTURO 100(M) (Fosroc chemicals) was used as admixture. Structuro 100(M) combines the properties of water reduction and workability retention. Locally available natural river sand with fineness modulus 2.6 conforming to Zone II of IS 383 was used as the fine aggregate. Crushed stone aggregates with fineness modulus 6.52 conforming to IS: 383 was used as coarse aggregate. Crimped cylindrical steel fibres of 30 mm length, 0.50mm diameter with aspect ratio of 60 were added in different proportions of 0, 6, 8, 10 and 12 percent by volume of concrete mass, Fig 2.

TABLE 1: Composition of HPC and HPFRC Mix

Mix No.	Cement(C) (kg/m <sup>3</sup> )	Silica Fume (SF) (kg/m <sup>3</sup> )	Fine Aggregate (FA) (kg/m <sup>3</sup> )	Coarse Aggregate (CA) (kg/m <sup>3</sup> )	Superplasticizer (SP) (L/m <sup>3</sup> )	Steel Fibre (%)	Steel Fibre (kg/m <sup>3</sup> )	Water (L/m <sup>3</sup> )	w/c ratio
1	430	43	658	1048	10.78	0	0	162	0.35
2	430	43	658	1048	10.78	6	144	162	0.35
3	430	43	658	1048	10.78	8	192	162	0.35
4	430	43	658	1048	10.78	10	240	162	0.35
5	430	43	658	1048	10.78	12	288	162	0.35

The composition of design mix of high performance concrete was work out by the ACI method. Typical range of HPC mix composition is tabulated in Table 2.

TABLE 2: Typical Range of HPC Mix Composition

Constituent	Typical range by mass (kg/m <sup>3</sup> )
Powder	400-750
Water	150-210
Coarse aggregate	750-1000
Fine aggregate	48-55% of total aggregate weight

Cubes , cylinders and prisms of size 150 x 150 x 150 mm , 300 x 150 mm and 100 x 100 x 500 mm were cast and tested to obtain compressive, split tensile strength and flexural strength at ages 28 days.

### 3.1 Beam-Column Frame System Specimens

In order to have proper control over the mix design, the samples were cast in concrete lab as per general precautions listed in IS- 456:2002. Guidelines for specifying, mixing, placing, and finishing steel fibre were followed in construction. After 28 days of proper curing, specimens were allowed to become dry before testing. The beam-column specimens were cured by dry curing method, Fig. 3. Concrete cubes, cylinders and prisms were tested as per standard procedure laid in codes. Table 3 illustrates compressive, split tensile and flexural strength values for these concrete specimens.

TABLE 3: Test results of control specimens in Comp, Tensile and Flexure

Mix Designation	Compressive strength (MPa) $\sigma_c$	Split Tensile Strength (MPa) $\sigma_t$	Flexural Strength (MPa) $\sigma_f$
HPC	69	4.1	5.7
HPC-6SF	111	7.7	31.0
HPC-8SF	115	8.1	34.4
HPC-10SF	121	9.2	39.0
HPC-12SF	123	10.0	42.5

Beam column joint specimens were tested on a special steel girder frame having a load carrying capacity of 600kN capacity. A constant load was applied under the beam through the hydraulic jack of capacity of 100 kN. The increment of loading was taken as 10 kN and cracks induced in the specimens were marked .

## 4. Analysis of Results and Discussion

Ten nos. specimens of beam column joint, cast as per the procedure discussed earlier were tested under 600kN capacity loading frame under monotonically increasing load. These specimens have been designated as HPC, HPC-6SF, HPC-8SF, HPC-10SF, HPC-12SF, which were cast corresponding to fibre content 0, 6, 8, 10 and 12 percent by volume respectively. Control specimens cast corresponding to these fibre contents were also tested to investigate compressive, tensile and flexural strength at 28 days. Table 4 illustrates compressive, tensile and flexural strength of HPC based SIFCON specimens. It can be seen that the compressive strength ( $\sigma_c$ ) increases significantly by increasing the fibre content from 6 to 10percent. However, the enhancement is very small for the fibre content from 10 to 12%. Split tensile strength and flexural strength however were increased from 4.1 to 10MPa and 5.7 to 42.5MPa when fibre content was increased from 0 to 12 percent. A fibre content corresponding to 10% by volume is considered as optimum for practical consideration. It has been noted that the value of  $\sigma_c / \sigma_t$  decreases from 16.83 to 12.3,  $\sigma_c / \sigma_f$  decreases from 12.1 to 2.9 and  $\sigma_t / \sigma_f$  decreases from 0.73 to 0.23. It is seen that SIFCON composites differ from conventional FRC in the sense that matrix consists of very fine particles from behavioural view point. The matrix plays role not only of transforming the forces between fibers by shear but also keep the fibres interlocked. In case of HPFRC since concrete is dense even at

the micro structure level, tensile strain is much higher than that of the conventional FRC. This in turn, improve cracking behaviour, ductility and energy absorption capacity of the composites.

TABLE 4: Strength Characteristics of HPC SIFCON

Mix Designation	Compressive strength ( $\sigma_c$ ) (MPa)	Split Tensile Strength ( $\sigma_t$ ) (MPa)	Flexural Strength ( $\sigma_f$ ) (MPa)	$\sigma_c/\sigma_t$	$\sigma_c/\sigma_f$	$\sigma_t/\sigma_f$
HPC	69	4.1	5.7	16.83	12.10	0.72
HPC-6SF	111	7.7	31.0	14.42	3.60	0.25
HPC-8SF	115	8.1	34.4	14.20	3.34	0.23
HPC-10SF	121	9.2	39.0	13.15	3.10	0.23
HPC-12SF	123	10.0	42.5	12.30	2.90	0.23

#### 4.1 Beam- Column Joint: Load Deflection Behaviour

A typical load deflection behaviour for beam – column joint corresponding to 0, 6, 8, 10 and 12 percent fibre content is shown in Fig 4 to 7. The typical results corresponding to first crack load and ultimate load are tabulated in Table 5.

TABLE 5: Parametric Properties of HPC & HPC-SF Beam-Column Joints

Specimen No.	HPC	HPC-6SF	HPC-8SF	HPC-10SF	HPC-12SF
Fibre Content by volume ( $V_f$ )	0	6	8	10	12
Compressive Strength ( $\sigma_c$ ) Mpa	69	111	115	121	123
First Crack Load ( $P_{cr}$ ) kN	10.85	50.30	66.30	80.50	91.50
Ultimate load ( $P_u$ ) kN	26.80	125.50	153.80	177.00	178.00
Deflection at First Crack Load $\delta_{cr}$ (mm)	0.50	2.58	3.30	3.90	4.57
Deflection at ultimate load $\delta_u$ (mm)	1.35	6.53	7.82	8.92	8.96
Increase w.r.t. HPC for					
$P_{cr}$	-	5.00	6.60	8.00	9.10
$P_u$	-	4.80	5.54	6.22	6.85

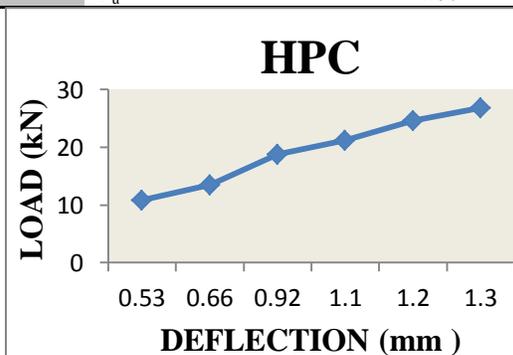


Fig 4: Load Deflection Curve for HPC Beam Column Joint (V<sub>f</sub>=0%)

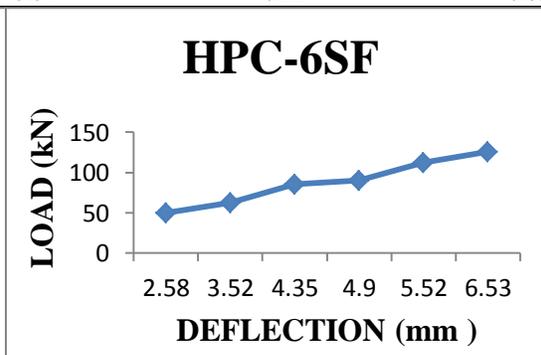


Fig.5: Load Deflection Curve for HPC Beam Column Joint (V<sub>f</sub>=6%)

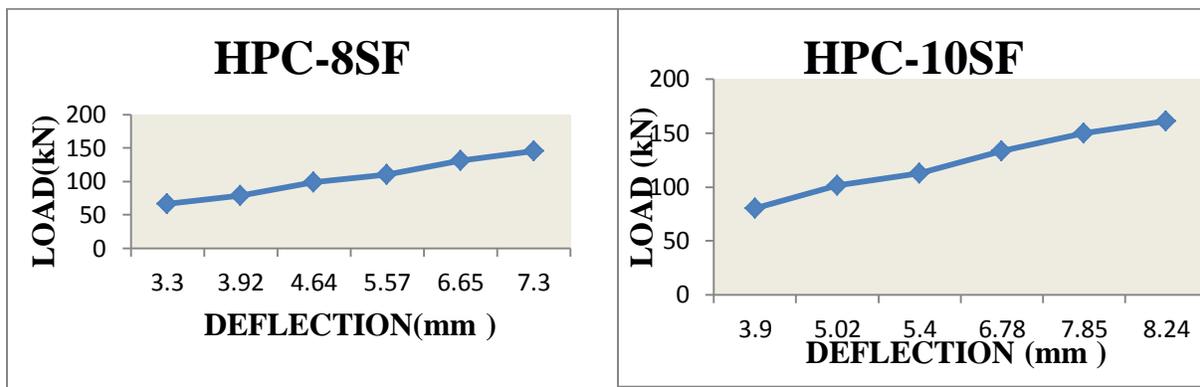


Fig 6: Load Deflection Curve for HPC Beam Column Fig 7: Load Deflection Curve for HPC Beam Column Joint ( $V_f = 8\%$ ) ( $V_f = 10\%$ )

It has been observed that the deflection values are increased by 5, 6.6, 8.0 and 9.1 times at first crack load then correspond the value of HPC. The values are however obtained as 4.8, 5.54, 6.22, and 6.85 times at ultimate load for  $V_f = 6, 8, 10, 12\%$  respectively. It can be inferred that HPC utilizing the fibre content upto 10% increases load carrying capacity of the joint significantly. The enhancement however is not significant when fibre content is increased to 12% as the load is increased from 161kN to 178 kN only. The fibre vol. fraction corresponding to 10% by volume is therefore considered as optimum value. The area under the load deflection curve represents the energy absorption capacity of the specimen. The results also illustrated an increase of 564% in deflection at ultimate load for the specimen with 12% fibre content as compared to HPC.

#### 4.2 Failure Mechanism

The failure pattern of beam column junctions corresponding to various fibre contents is shown in Fig 9, respectively. Multiple fine cracks were observed at these locations when fibre content was increased from 0 to 12%. It has also been observed that failure pattern for plain matrix and SIFCON based joint for different series was different in the sense that unlike plain matrix, joint which failed due to development of few minor cracks, failure in SIFCON joint showed multiple and density packed cracking. It was seen that first crack load and ultimate load increase tremendously. The crack pattern further illustrated that crack propagated diagonally from corner towards the opposite surface of the columns illustrating that the joint failure is primarily because of diagonal shear at the junction. Formation of plastic hinge in column has to be prevented as it affects its entire structure. Further observation of crack pattern revealed decrease in spacing of cracks, from the specimen corresponding the  $V_f = 0$  to 12%. This justified the fact that SIFCON is quite effective in inelastic range of load deflection behavior. The diagonal crack further illustrated the significance of bending stresses which plays a vital role at the fixed corner joint. The failure was found to be accompanied by dissipation of large amount of dissipation energy as the area under the curve corresponding to 10% fibre Content was maximum illustrating high ductility. Ductility associated parameters were also studied but these form in the scope subsequent research papers.



Fig. 9: Failure Pattern of HPC-8SF & HPC-10SF

The values of compression strength, first crack load, ultimate load and deflection at peak load of present study are compared with those obtained by N. Ganesen et al. for SFRC based HPC beam column joint subjected to cyclic loading. It has been observed that the values corresponding to SIFCON based beam column joint are remarkably high in comparison to those corresponding to SFRC based beam column joint. This illustrates that SIFCON based beam column joint undergo very small deflection at ultimate load which is found to be 0.176 times the corresponding values in case of SFRC with  $V_f = 1\%$ . Multiple fine cracks are found to develop in almost all specimens which indicates that steel fibres impart high ductility to beam column joint, which is one of the essential properties for beam column joint in case of earthquake resistant structures (EARS). It was also observed during the testing that the addition of fibre improves dimensional stability and integrity of the joints. The spacing of the ties in column can therefore be increased at beam column joint to avoid congestion of steel reinforcement.

The flexural toughness/energy absorption capacity of SIFCON based beam column joint being of very high order, joint constructed with SIFCON would benefit greatly to provide safe and cost effective alternatives due to reduce dead load which is a primary requirement of earthquake resistant structures (EARS). Structures of strategic importance and industrial structures of high strength demand can also be considered as potential applications. Further, if designed and constructed properly SIFCON based beam column junction can be very economical solution due to reduce weight of structures.

## 5. Conclusions

- 1 The compressive, split tensile and flexural strength values in SIFCON based materials was increased by 78, 144 and 646 %, when compared with their companion specimens of HPC.
- 2 The deflection at first crack load and ultimate load have been observed as 9.1 and 6.8 times the corresponding values of companion specimen corresponds to HPC.
- 3 Ductility associated parameters like ductility index, flexural toughness, toughness factor and toughness index increases significantly in SIFCON based beam column joints.
- 4 High performance concrete SIFCON joints undergoes small displacement without developing wider cracks when compared to HPC joint. The failure is characterized by multiple closely spaced finer cracks. This indicates that SIFCON based joints impart very high ductility which is one of the essential property for beam column joint.
- 5 SIFCON based beam column joints would impart dimensional stability and integrity of the joints.

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