



Seismic Behavior of Beam–Column Joint Using Hybrid Fiber Reinforced High-Strength Concrete

A. Annadurai¹ · A. Ravichandran²

Received: 13 March 2016 / Accepted: 2 April 2018 / Published online: 19 April 2018
© Shiraz University 2018

Abstract

Experimental studies on the seismic behavior of exterior beam–column joint specimens are presented in this paper. Two types of joint detailing were taken into account for this study. Type-1 specimens were detailed as per IS: 13920-1993 and were cast with high-strength concrete of grade M60. Longitudinal reinforcements in Type-2 beam specimens were adopted at standard 90° bent anchorage as per ACI 318-2005, without hoop reinforcements within the joint core. Uniform spacing of transverse reinforcement was maintained for beam and column. These specimens were cast in two ways: using plain high-strength concrete of grade M60 and fiber reinforced high-strength concrete with steel fibers of volume fractions 0.5, 1.0, 1.5 and 2.0%. Studies were also conducted using steel and polyolefin straight fibers (hybrid fibers) with 80–20 and 60–40% combinations for each volume fraction. All the specimens were subjected to forward cyclic loading. During the tests, first crack load, ultimate load and deflections were noted. From the test results, ductility factor, energy absorption, energy dissipation and stiffness degradations were determined for all specimens. It is found that Type-2 specimens with hybrid fiber combination of 80–20% gave better performance compared to other parameters in each volume fraction. The same combination of fibers at 2.0% volume fraction yielded results comparable to the seismic—detailed plain high-strength concrete specimen in terms of strength, ductility factor, energy absorption and stiffness.

Keywords Beam–column joints · High-strength concrete · Hybrid fibers · Ductility · Stiffness

1 Introduction

Beam–column joint is one of the most critical parts of a reinforced concrete moment resisting frame. It is highly vulnerable, particularly when the frame is subjected to seismic loading (Attaalla 2004; Sudhir and Ingle 2006). Hanson and Conner first initiated the studies on the behavior of beam–column joints at the Portland cement Association Laboratories. Since then the problem has been studied by various other investigators (Shamim and Kumar 1999; Ehsani and Wight 1985), and the design approach for

beam-to-column connections has changed considerably over the past decades.

Inelastic behavior of material and detailing of reinforcement are the main factors for ductility in the beam–column joints. Seismic codes (I.S 13920 1993; ACI 352-OR 2010) recommend closely spaced transverse reinforcement at the beam–column joints in the reinforced concrete framed structures (Tsonos and Tegos 1992; Yousef and Yakimov 1995). However, it is very difficult to provide the transverse reinforcement due to the congestion created by the longitudinal reinforcement. Due to practical difficulties mentioned above, the beam–column joints of reinforced concrete structures cannot be fully detailed according to the specifications. Salient information reported in the previous research work carried out in the area of beam–column joints are reviewed and presented below.

Megget and Fenwick (2003) have studied the seismic performance of external reinforced beam–column joints. Their studies involved four different detailing of external joint zones.

✉ A. Annadurai
annadurai.civil@sathyabama.ac.in

A. Ravichandran
ravichandranprof@yahoo.com

¹ Department of Civil Engineering, Sathyabama Institute of Science and Technology, Chennai, Tamilnadu 600119, India

² Department of Civil Engineering, Christ College of Engineering and Technology, Pondicherry 605010, India

Murty et al. (2003) have conducted experimental studies of exterior reinforced concrete (RC) beam–column joints. They have attempted to evaluate the adequacy of different details of longitudinal beam bar anchorage and transverse joint reinforcement in improving the seismic performance of RC beams.

Ehsani and Wight (1985) have investigated exterior reinforced concrete beam–column connections subjected to earthquake loads. Their studies showed that in certain cases present design recommendation could be safely relaxed.

Gefken and Ramey (1989) have carried out experimental studies on the increase in spacing of hoop reinforcement by using steel fiber concrete. They found that with the use of steel fiber concrete, the joint's strength, shear capacity, energy dissipation, joint stiffness and ductility are increased and could be used in seismic zones.

Rajagopal and Prabavathy (2014) have assessed the performance of beam–column joints with different anchorage detailing. By replacing 90° standard bent with T-type, U-bar and X-cross bars and combinations have been used. They found that the combination of X-cross bar plus U bar produced less cracks and improved seismic performances.

Jiuru et al. (1992) have investigated seismic behavior and shear strength of framed joint using steel fiber reinforced concrete. This study suggested that the steel fiber reinforced concrete used in the joint core could reduce the congestion in the steel reinforcement and minimize the construction difficulties.

Filiatrault et al. (1994) have investigated and concluded from their experiment that usage of steel fibers increases the joint shear strength and can diminish the requirements for closely spaced ties. The performance of the joints depends on the volume content and aspect ratio of fibers.

Hamad et al. (2011) have studied the effect of steel fibers on bond strength of hooked bars in high-strength concrete and concluded in the analysis of the test that the steel fibers were effective in increasing the ductility and anchorage capacity of beam–column joint specimens.

Yousef and Yakimov (1995) have studied the high-strength beam–column joints under seismic loading considering variables such as percentage of transverse reinforcement in the joint, amount of crossed reinforcement and the ratio of the column to beam flexural capacity. Their studies have shown excellent joint behavior.

Ganesan and Indira (2007) have investigated the high-performance concrete with steel fibers in exterior beam–column joint subjected to forward cyclic loading. They found that load carrying capacity is increased by increasing the steel fibers content and improvement in dimensional stability and integrity of the joints are noted.

Sheel and Anu Geetha (2012) have studied the performance of beam–column joints using different composite

materials for strengthening purpose and studied the behavior of joints using glass fiber reinforced polymer and carbon fiber reinforced polymer under static and cyclic loading.

The engineering characteristics and advantages of high-strength concrete (HSC) are different from conventional concrete. HSC is used in a variety of applications in the construction industry (Song and Hwang 2004). HSC offers several advantages like more strength and durability but are accompanied by brittleness in the post-peak behavior. In order to minimize this effect and to obtain sufficient ductility of the concrete members, one approach is to add discrete and uniform distribution of steel fibers as reinforcement in HSC (Yao et al. 2003; Banthia and Gupta 2004). It has been shown in the previous studies that the idea of hybridization with two different types of fiber composite can offer better performance than mono-fibers in the properties of concrete (Ganesan et al. 2014; Alberti et al. 2014; Thirumurugan and Sivaraja 2015). Usually a combination of fibers with different materials, aspect ratio, different shapes, tensile strength and Young's modulus is used in concrete matrices to get efficient utilization of properties of both fibers.

In the present study, two types of reinforcement detailing were considered for exterior beam–column joint core. One type of specimen was detailed as per I.S.13920 (Bureau of Indian Standards 1993) and cast with high-strength concrete, and the second type of specimen's detailing was modified with reference to ACI 318 (ACI Committee 2005) for avoiding the practical difficulties at site thus representing a non-seismic detailed exterior beam–column joint specimen. These specimens were cast using high-strength concrete of grade M60 and along with steel fibers of volume fractions 0.5, 1.0, 1.5 and 2.0%. Steel and polyolefin straight fibers (hybrid fibers) were also used with 80–20 and 60–40% combinations at each volume fraction. The prepared specimens were tested by forward cyclic load, and the results were analyzed and compared.

Table 1 Property of materials used for concrete

1	Specific gravity of cement	3.15
2	Specific gravity of fine aggregate	2.4
3	Fineness modulus of fine aggregate	3.0
4	Bulk density of fine aggregate	1643 kg/m ³
5	Water absorption of fine aggregate	0.45%
6	Specific gravity of coarse aggregate	2.74
7	Fineness modulus of coarse aggregate	3.67
8	Bulk density of coarse aggregate	1589 kg/m ³
9	Water absorption of coarse aggregate	0.42%

Fig. 1 Fibers used for this experimental work. **a** Hooked end steel fiber, **b** polyolefin straight fiber

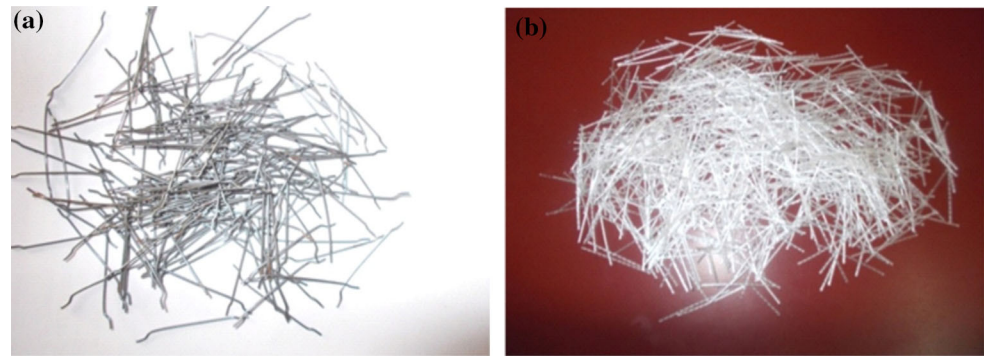


Table 2 Property of fibers

Fiber properties	Fiber details	
	Polyolefin	Steel
Length (mm)	54	35
Shape	Straight	Hooked at ends
Size/diameter (mm)	1.38 × 0.41 mm	0.6 mm
Aspect ratio	63.68	58.33
Density (kg/m ³)	920	7800
Specific gravity	0.90–0.92	7.8
Young's modulus (GPa)	10 GPa	210

Table 3 Properties of rebar

S. no.	Diameter of steel (mm)	Yield strength (N/mm ²)	Ultimate strength (N/mm ²)	Elongation (%)
1	12	548.478	628.096	16.27
2	6	488.01	640.48	1.25

Table 4 Mix proportions for concrete

Materials	Quantity (kg/m ³)
Cement	468.48
Silica fume	43.52
Fine aggregate	594.40
Coarse aggregate	1037.22
HRWR	6.40
Water	159.50

2 Research Significance

The seismic design code IS: 13920-1993 has recommended ductile detailing of beam–column joints in RC framed structures. This provision entails continuation of transverse loops around the column bars through the joint section,

transverse reinforcement for confining the concrete of beams and columns and the anchorage detailing at junctions. In practice, it is very cumbersome to follow the specification by the engineers because of various practical difficulties in placing and compacting of the concrete due to congestion of reinforcement at the junction. This study consists of investigation of the effects of steel fiber and hybrid fiber reinforced high-strength concrete in non-seismic detailed exterior beam–column joint specimens, and comparison with the seismic-detailed exterior high-strength concrete beam–column joint specimen in terms of strength and seismic behavior. The tests results showed that the hybrid fiber combinations achieved the ductile properties and reduction in transverse reinforcement leading to the feasibility of avoiding the congestion of reinforcement in the joint region.

3 Experimental Program

3.1 Materials Used

Ultratech-ordinary Portland cement of grade 53 which is used in the present study. The locally available river sand and coarse aggregate of maximum size 10 mm are used. The physical properties of the materials are presented in Table 1. The properties were used in the mix design calculations. Silica fume (D920) was used to improve the concrete properties in fresh and hardened states. High-range water reducing admixture (HRWR) (ACI.212.4R-93) Gelenium B233 was used to maintain the workability of concrete. The hooked end steel fibers and polyolefin straight fibers have been used in this study is shown in Fig. 1. Their properties are presented in Table 2. Rebar of size 12 mm as main reinforcement and 6 mm as transverse reinforcement for all types of specimens were employed in the present study. Properties of the reinforcements were determined. They are presented in Table 3.

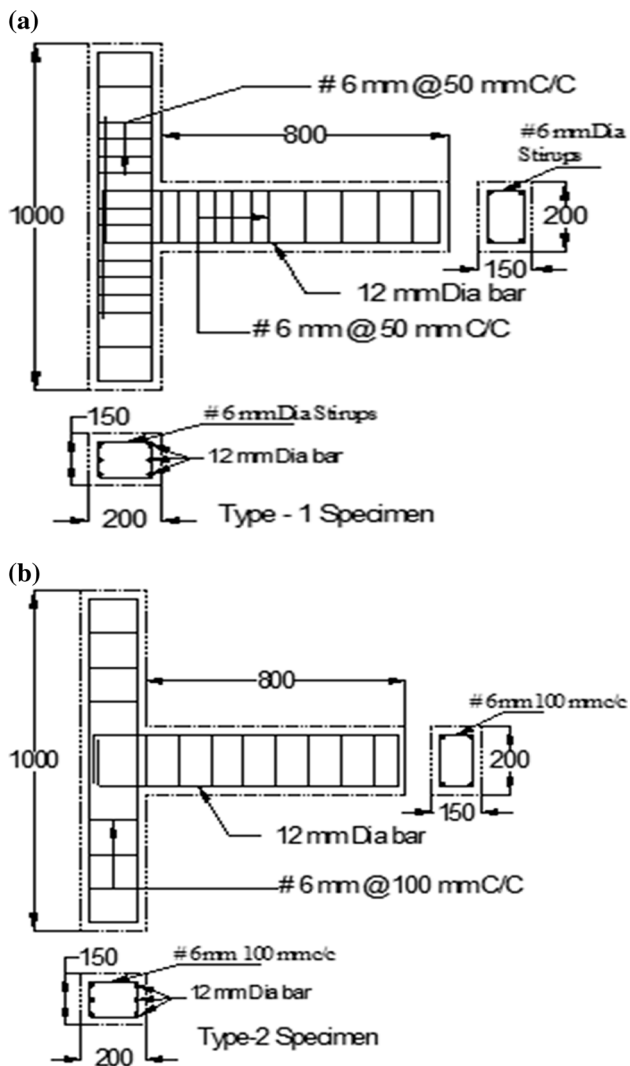


Fig. 2 a Reinforcement detailing of exterior beam–column joint (IS13920-1993), b reinforcement detailing of exterior beam–column joint (ACI 318-2005)

3.2 Mix Proportions for High-Strength Concrete

Mix proportions of high-strength concrete of grade M60 were developed by using ACI-211-4R (ACI Committee 1993) guide lines; the basic mix and various trial mixes were prepared by changing the percentage of silica fume and HRWR. The appropriate mix proportions were selected based on the cylinder compressive strength of concrete and the workability test on fresh concrete. The mix proportion of this study is shown in Table 4.

3.3 Details of Specimens and Casting Procedure

In the present investigation, two types of exterior beam–column joint specimens were taken into consideration. The dimensions of beam–column joint specimens and the

Table 5 Details of specimen names and fiber volume fractions

Sl. no.	Specimen name	Volume fractions (%)		
		Steel	Polyolefin	Total
1	HSBC1	0	0	0
2	HSBC2	0	0	0
3	HSFBC1	0.5	0	0.5
4	HYFBC1	0.4	0.1	0.5
5	HYFBC2	0.3	0.2	0.5
6	HSFBC2	1	0	1
7	HYFBC3	0.8	0.2	1
8	HYFBC4	0.6	0.4	1
9	HSFBC3	1.5	0	1.5
10	HYFBC5	1.2	0.3	1.5
11	HYFBC6	0.9	0.6	1.5
12	HSFBC4	2	0	2
13	HYFBC7	1.6	0.4	2
14	HYFBC8	1.2	0.8	2



Fig. 3 Form work arrangements and casting work



Fig. 4 Curing of specimens

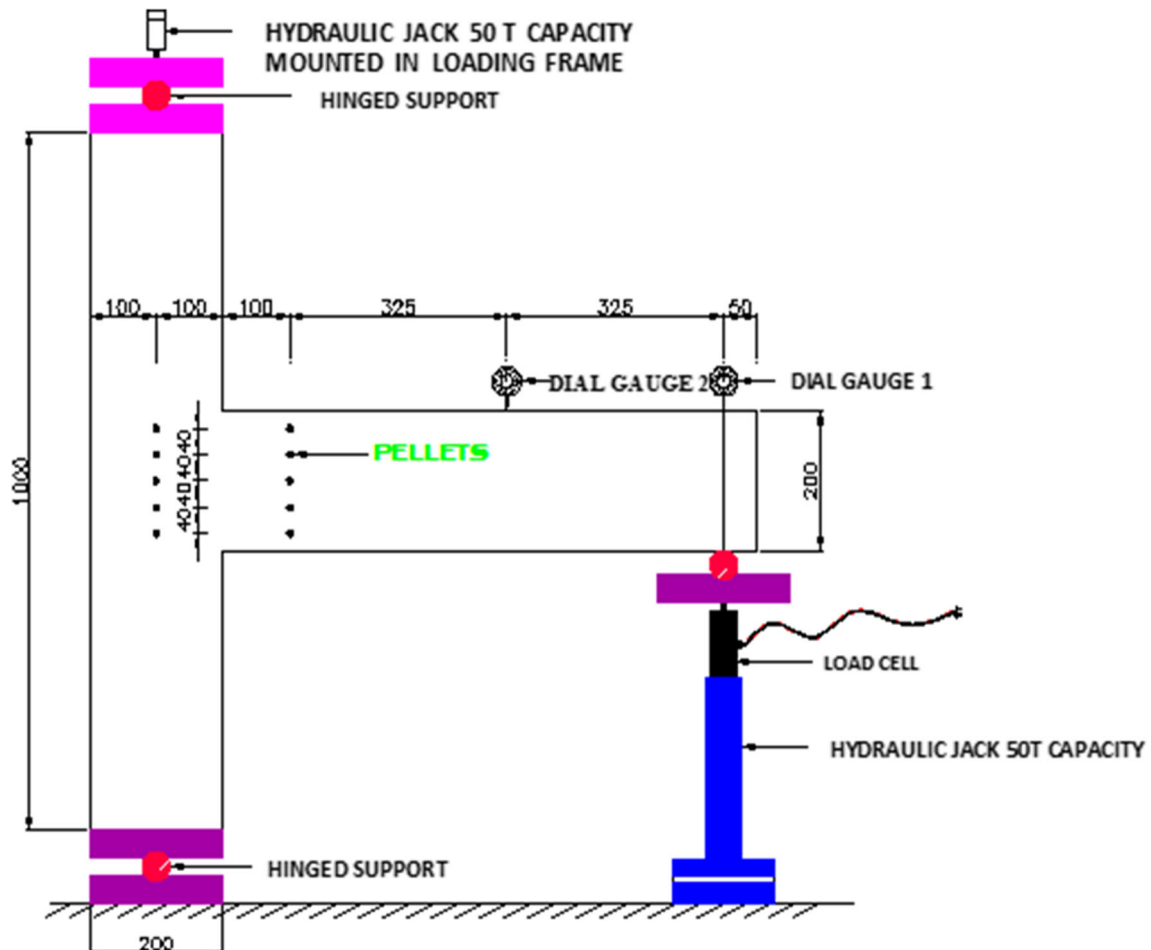


Fig. 5 Schematic diagram for experimental setup



Fig. 6 Beam-column joint specimen testing setup in loading frame

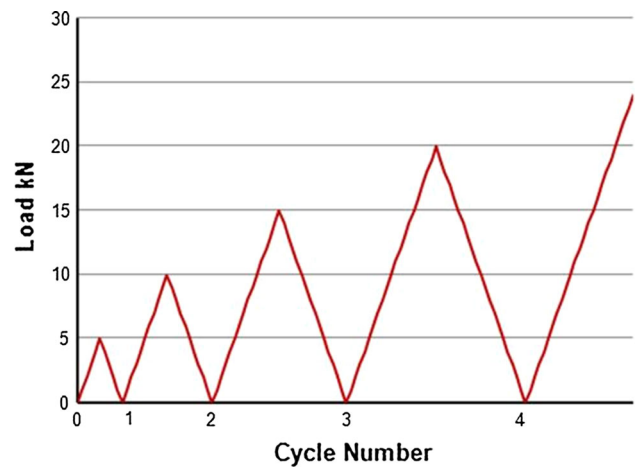


Fig. 7 Loading cycle

details of reinforcements are shown in Fig. 2a, b. Type-1 specimens were detailed as per seismic code IS: 13920-1993, and casting was done using high-strength concrete of Grade M60 (HSBC1). Longitudinal reinforcements in Type-2 beam specimens were adopted at standard

Table 6 Mechanical properties of concrete

Sl. no.	Specimen name	Compressive strength (N/mm ²)	Tensile strength (N/mm ²)
1	HSBC1	61.1	4.97
2	HSBC2	61.1	4.97
3	HSFBC1	62.5	5.08
4	HYFBC1	62	6.39
5	HYFBC2	61.5	5.54
6	HSFBC2	65	6.95
7	HYFBC3	66.1	7.13
8	HYFBC4	62.85	6.58
9	HSFBC3	67.9	7.67
10	HYFBC5	66.25	7.98
11	HYFBC6	64.2	7.25
12	HSFBC4	67.8	8.02
13	HYFBC7	67.2	9.5
14	HYFBC8	66.8	8.64

90° bent anchorage as per ACI 318 2005, without hoop reinforcements within the joint core. Uniform spacing of transverse reinforcement was maintained for beam and column. These specimens were cast by using high-strength concrete (HSBC2) and high-strength concrete with steel fibers of volume fraction 0.5, 1.0, 1.5 and 2.0%. (HSFBC1, HSFBC2, HSFBC3, HSFBC4). At each volume fraction, two specimens were cast using the same grade of concrete with hybrid fibers (steel 80%–polyolefin 20% and steel 60%–polyolefin 40% combinations, HYFBC1 to HYFBC8). The specimen names and fiber volume fractions details are given in Table 5. The formwork (mold) was made by using 12 mm thick waterproof plywood; steel cage was placed in the mold with sufficient cover, and concrete mixes were poured into the wooden molds in layers with proper compaction using needle vibrator. The details are presented in Fig. 3. For each type of beam–column joint specimen, the standard cylinder and prism specimens were cast as per ASTM Standard to study the mechanical properties of all types of concrete. After 24 h, the beam–column joint specimens were demolded and covered by gunny bags for wet curing as shown in Fig. 4.

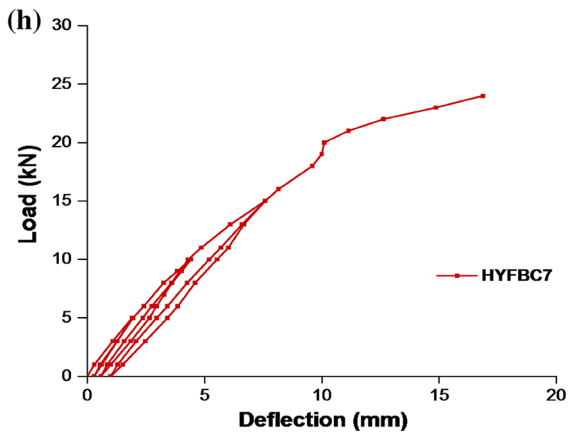
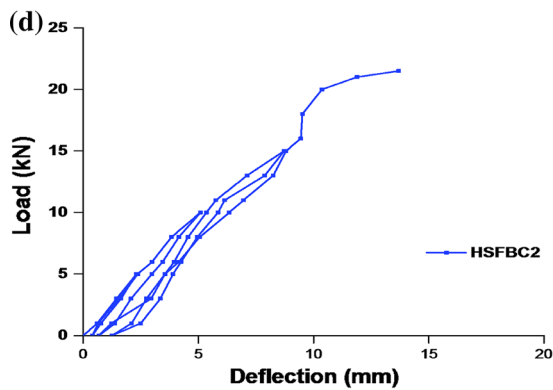
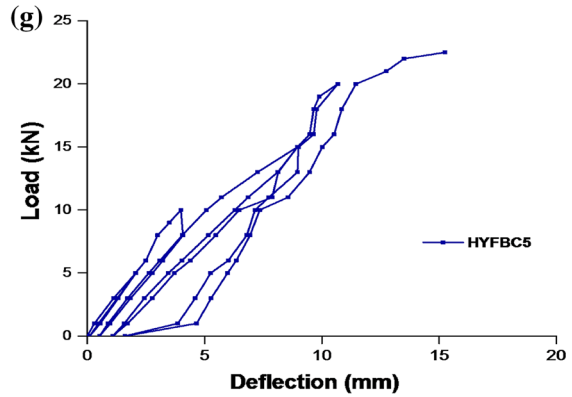
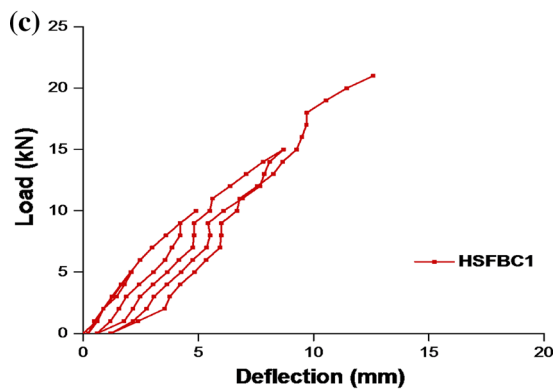
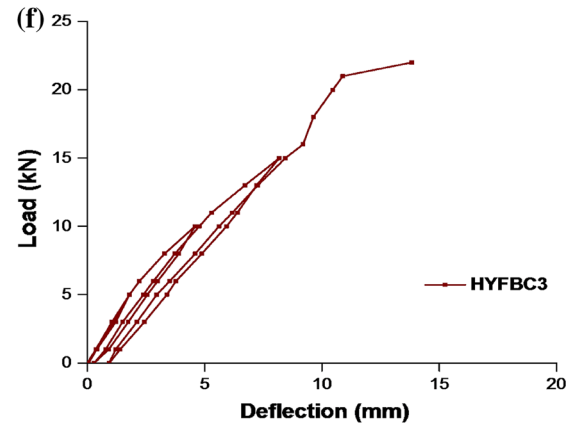
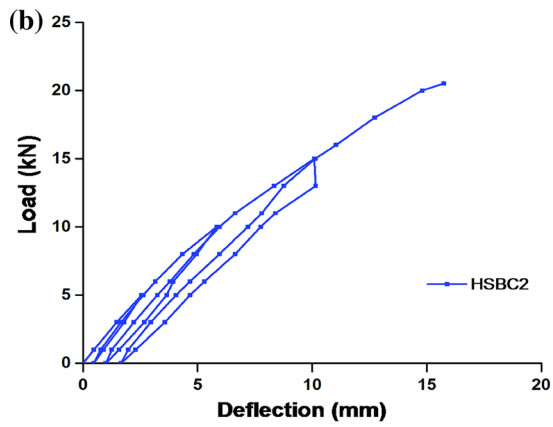
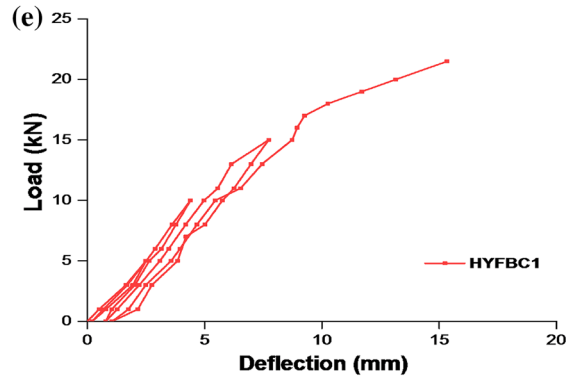
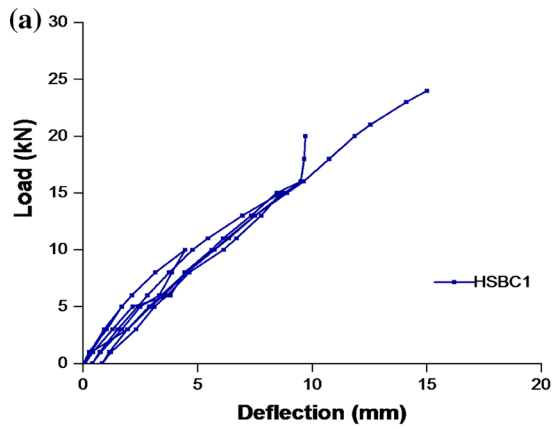
The cylinder and prism specimens were also demolded and kept in the curing tank for 28 days.

3.4 Testing of Beam–Column Joint Specimens

The specimens were tested in the 500-kN loading frame in the Structural Engineering Laboratory of Sathyabama University. The columns were positioned to simulate hinged–hinged condition, and a constant load was applied on them for keeping the specimens in a vertical position. Pellets were fixed at joint region, from top to bottom of beam–column joint core, for facilitating strain

Fig. 8 **a** Load–deflection curve (Type-1, plain HSC), **b** load–deflection curve (Type-2, plain HSC), **c** load–deflection curve (Type-2, steel fiber 0.5%), **d** load–deflection curve (Type-2, steel fiber 1%), **e** load–deflection curve (Type-2, steel fiber 0.4% + polyolefin fiber 0.1%), **f** load–deflection curve (Type-2, steel fiber 0.8% + polyolefin fiber 0.2%), **g** load–deflection curve (Type-2, steel fiber 1.2% + polyolefin fiber 0.3%), **h** load–deflection curve (Type-2, steel 1.6% + polyolefin 0.4%)

measurement using a mechanical Demec gauge. The transverse load was applied using 500-kN hydraulic jack at 50 mm from free end of the beam. The 50-kN load cell with digital indicator was used to measure the applied load accurately. Dial gauges were used at beam end, middle to measure the deflections. The strain values were measured at every interval of loading and unloading condition. The schematic diagram of the test setup is shown in Fig. 5, and the experimental test setup is shown in Fig. 6. All the specimens were subjected to forward cyclic load with reference to the previous study (Ganesan and Indira 2007; Sheela and Anu Geetha 2012). The transverse load was gradually increased with interval of 1 kN up to the first level of 5 kN load, then unloaded gradually at the same intervals and reloaded to the next increment of 5 kN load, and it was continued for each increment up to failure of the specimens. The typical change of load curve (or) loading cycle curve is shown in Fig. 7. During the test, at each and every load interval the deflections and strain reading at junction were measured. The first crack load and ultimate load were noted. The mechanical properties of high-strength concrete, fiber and hybrid fiber reinforced high-strength concrete are studied and published elsewhere (Annadurai and Ravichandran 2015). In this paper, the compressive strength and split tensile strength for all types of concrete used in the corresponding beam–column joint specimens are presented in Table 6.



4 Results and Discussion

4.1 Ultimate Load–Deflection Behavior of Specimens

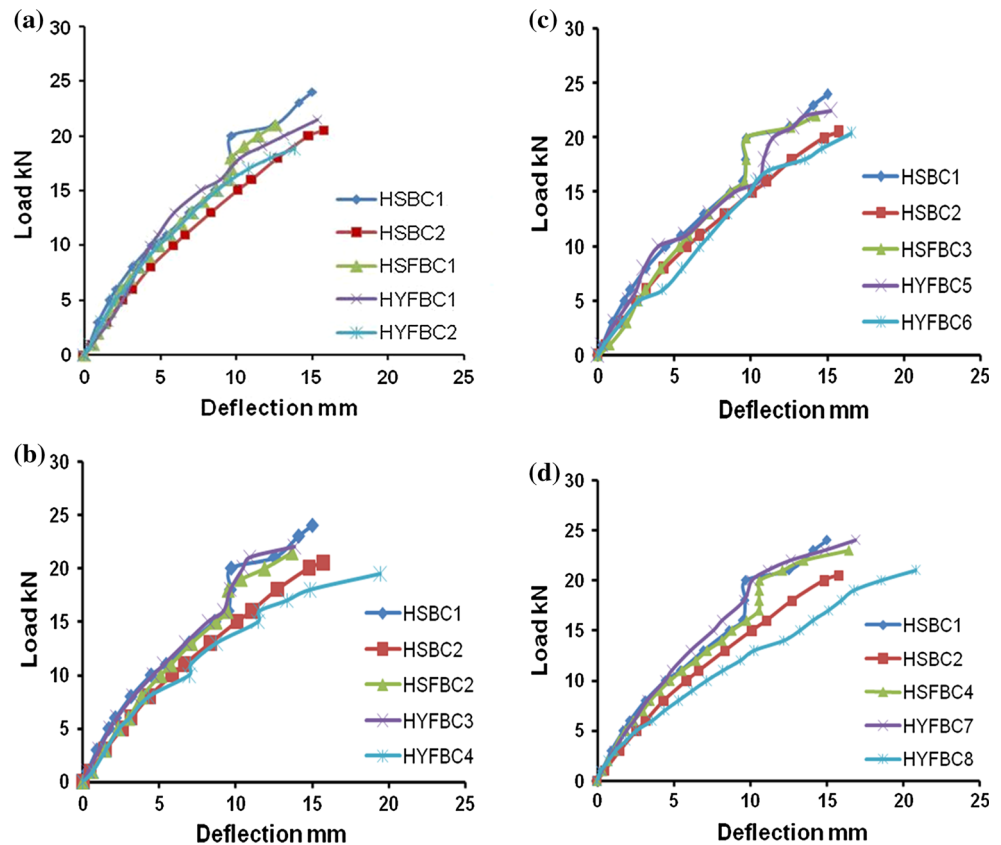
The specimens were subjected to forward cyclic load up to failure. From the test results, the cyclic load–deflection curves were plotted for all specimens and some typical curves are illustrated in Fig. 8a–h. The ascending peak load versus displacement curves of Type-1 joint and Type-2 joint specimens with high-strength concrete are compared with Type-2 joint with steel fiber and hybrid fiber reinforced high-strength concrete specimens as shown in Fig. 9a–d. It can be seen from the figures that the deflection curves of Type-2 joint specimens with steel fiber of volume fraction, 0.5–2.0%, (HSFBC1, HSFBC2, HSFBC3 and HSFBC4) and same type joint specimens with hybrid fiber (steel 80%–polyolefin 20%), (HYFBC1, HYFBC3, HYFBC5 and HYFBC7) show a similar trend as Type-1 joint specimen (HSBC1). The comparison chart of ultimate loads observed from the tests for all specimens is shown in Fig. 10. Type-1 specimen cast with plain high-strength concrete specimen (HSBC1) attained the ultimate load of 24 kN with corresponding deflection of 15.01 mm. Type-2 specimen cast with plain high-strength concrete specimen (HSBC2) attained the ultimate load of 20.5 kN, and the

deflection at peak load was 15.74 mm. It is about 85% of the ultimate load of HSBC1 specimen. Hybrid fiber reinforced high-strength concrete (HYFBC7) showed the same load carrying capacity as HSBC1, but the deflection was 16.86 mm. Steel fiber reinforced high-strength concrete specimens HSFBC1 to HSFBC4 have attained ultimate load capacities of 87.5–95.8% and hybrid fiber reinforced high-strength concrete specimens HYFBC1 to HYFBC8 capacities of value from 89.6 to 100% when compared to HSBC1. This shows that the addition of fibers in the concrete has increased the load carrying capacity.

4.2 Crack Pattern of Specimens

In all the specimens, cracks initiated at the bottom of beam–column junction during the test and the load at first crack was noted. Further increase in load after the first crack load resulted in widening of the cracks. HSBC1 specimen failed at beam–column joint face. HSBC2 specimen showed the crack formation in the beam portions and diagonal cracks at core. In the cases of fiber and hybrid fiber reinforced high-strength concrete specimens (HSFBC1 to HSFBC4 and HYFBC1 to HYFBC8), cracks were formed at beam–column joint face only. No cracks were formed in the column portion of the specimens nor were there any crack formations in the beam portion. It

Fig. 9 Comparison of peak load–deflection curves with control specimens. **a** 0.5% volume fraction, **b** 1.0% volume fraction, **c** 1.5% volume fraction, **d** 2.0% volume fraction



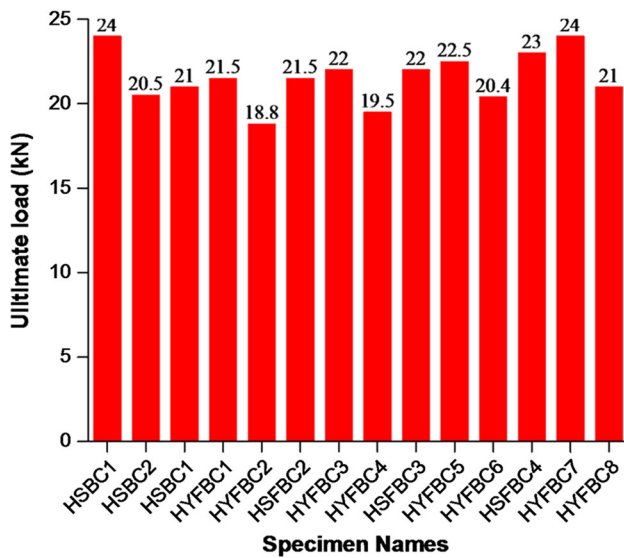


Fig. 10 Ultimate load comparisons

Table 7 Test results of first crack and ultimate loads

Specimen name	First crack load (kN)	Ultimate load, P_u (kN)
HSBC1	11	24
HSBC2	11	20.5
HSFBC1	10	21
HYFBC1	11	21.5
HYFBC2	11.5	18.8
HSFBC2	10.5	21.5
HYFBC3	11	22
HYFBC4	11.5	19.5
HSFBC3	11	22
HYFBC5	14	22.5
HYFBC6	12	20.4
HSFBC4	11.5	23
HYFBC7	15	24
HYFBC8	11	21

may be understood from the behavior that the fibers were bridging the minor cracks that were formed. The first crack load was observed at the time of testing. The first crack load and ultimate load values are presented in Table 7. Crack formations of Type-1 specimen (HSBC1), Type-2 specimens (HSBC2, HSFBC1, HSFBC4, HYFBC1, HYFBC3 HYFBC2 and HYFBC) after failure are presented in Fig. 11.

4.3 Energy Absorption Capacity and Deflection Ductility

Energy absorption capacity is called area under the load deflection curve. In this study, total energy absorption

capacity of all specimens was calculated from the ascending peak load–deflection curves. The energy absorption capacity was 208.62 kN mm for the control (HSBC1) specimen. The energy absorption capacity of hybrid fiber reinforced high-strength concrete specimens increased with an increase in fiber volume fractions. For HYBC7 specimen, energy absorption capacity was 257.96 kN mm. It is 23.65% more than the energy absorption capacity of HSBC1 specimen. Initial stiffness was calculated as ultimate load divided by the deflection at yield. Initial stiffness of hybrid fiber reinforced high-strength concrete specimen increased by 25.29% more than the control specimen (HSBC1). The energy absorption and initial stiffness values are presented in Table 8. The term ductility (Park 1988) is defined as the ability of the structure to undergo a large amount of deformations without reduction in its strength. The deflection ductility (μ) was calculated by using ascending peak load deflection curves. It is defined as the ratio between the deflections at ultimate load (δ_u) to deflection at yield load (δ_y) (Shannag et al. 2005). Type-2 specimens with hybrid fibers (HYFBC1 to HYFBC8) exhibited equal or higher value of ductility when compared with Type-1 joint specimen (HSBC1). Deflection ductility of hybrid fiber reinforced high-strength concrete specimen HYFBC7 is 10.75% more than the control specimen (HSFBC1). Deflection ductility factor was calculated for all specimens and is shown in Table 9.

4.4 Energy Dissipation of Specimens

The structures can withstand strong ground earthquake motions only if they have adequate ability to dissipate seismic energy. This energy dissipation is provided mainly by inelastic deformations in critical regions of the structural system and requires adequate ductility of the elements and their connections (Rohm et al. 2012). The energy dissipation capacity can be calculated from the area within the hysteresis loop of the load–deflection curve (Park 1988; Ganesan et al. 2014). The cumulative value of energy dissipation capacity of the beam–column joint specimen was calculated by the addition of energy dissipation capacity of the joint during each cycle. Comparisons of cumulative energy dissipated among the specimens are shown in Fig. 12. Energy dissipation capacity of Type-2 joints with hybrid fiber reinforced high-strength concrete specimen (HYFBC5) is more than the Type-1 and Type-2 specimens with plain high-strength concrete (HSBC1 and HSBC2). The energy dissipation capacity is improved by the addition of fibers and hybrid fibers in the Type-2 joints.



Fig. 11 Crack patterns of specimens after testing

Table 8 Energy absorption and initial stiffness

Specimen name	Energy absorption (kN/mm)	Initial stiffness (kN/mm)
HSBC1	208.615	2.53
HSBC2	186.78	2.03
HSFBC1	146.915	2.19
HYFBC1	204.55	2.78
HYFBC2	166.235	1.94
HSFBC2	149.025	2.28
HYFBC3	151.66	2.39
HYFBC4	256.185	1.63
HSFBC3	179.49	2.30
HYFBC5	203.7125	2.51
HYFBC6	205.35	2.0
HSFBC4	198.405	2.18
HYFBC7	257.955	3.17
HYFBC8	240.92	1.6

Table 9 Deflection and ductility factor

Specimen name	Initial yield load (kN)	Deflection at yield, δ_y (mm)	Deflection at peak load, δ_u (mm)	Deflection ductility, $\mu = \delta_u/\delta_y$
HSBC1	16	9.5	15.01	1.58
HSBC2	15	10.05	15.74	1.56
HSFBC1	16	9.59	12.59	1.313
HYFBC1	15	7.73	15.33	1.854
HYFBC2	15	9.69	13.84	1.428
HSFBC2	16	9.44	13.69	1.344
HYFBC3	16	9.19	13.82	1.504
HYFBC4	15	11.95	19.45	1.628
HSFBC3	16	9.57	14.25	1.489
HYFBC5	16	10.52	15.25	1.45
HYFBC6	15	9.98	16.56	1.65
HSFBC4	17	10.55	16.41	1.55
HYFBC7	18	9.59	16.86	1.75
HYFBC8	16	13.09	20.81	1.58

4.5 Stiffness Degradation of Specimens

The stiffness of the joints gets reduced when the beam–column joints are subjected to cyclic loading or repeated loading. In this study, the stiffness was calculated as peak load of each cycle divided by the corresponding deflection and the values were plotted as shown in Fig. 13. It shows the gradation of stiffness of all specimens. Seismic detailed specimen (Type-1) with high-strength concrete (HSBC1) shows higher stiffness values at each loading cycle compared with non-seismic detailed (Type-2) specimens with

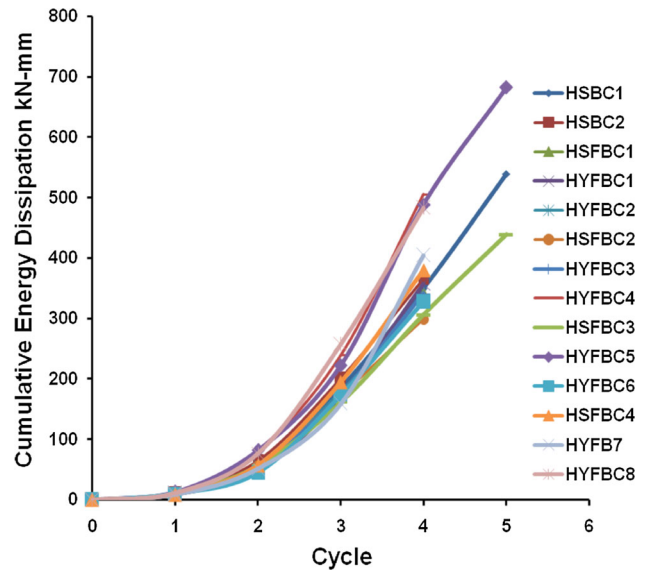


Fig. 12 Cumulative energy dissipation—load cycle curves

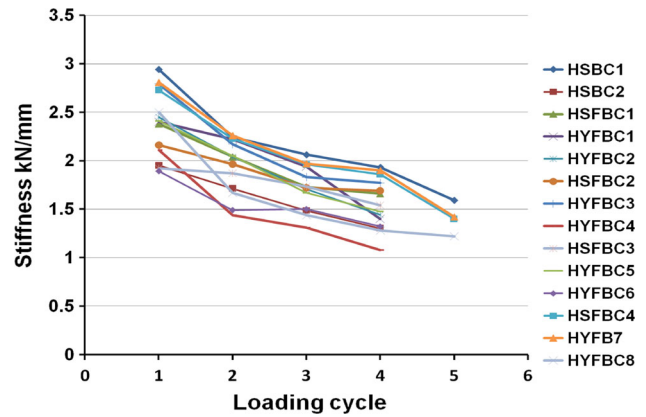


Fig. 13 Stiffness degradation chart

high-strength concrete (HSBC2), steel fiber (HBC1 to HSBC4) and hybrid fiber reinforced high-strength concrete (HYFBC1 to HYFBC8) specimens. The trend of stiffness degradation curves of hybrid fiber steel 80%–polyolefin 20% combination specimens is very similar to (HSFBC1), and the stiffness values of (HYFBC7) are much closer to HSBC1 specimen at each loading cycle.

5 Conclusions

The following conclusion can be made from the experimental results of the present study.

1. The ultimate load increased with the increase in the fiber content in non-seismic detailed specimens.
2. Hybrid specimens showed better performance than steel fiber specimens, and the specimen HYFBC7

obtained the ultimate load which had the same value as control specimen HSBSC.

3. Energy absorption capacity of non-seismic detailed specimen increased in comparison with the increase in fiber volume fraction. HYFBC7 specimen capacity was 23.65% more than the value of HSBSC1 specimen.
4. Deflection ductility also increased with an increase in fiber and hybrid fiber in non-seismic detailed specimens. HYFBC7 showed a value of 10.75% more than the value obtained from the HSBSC1 specimen.
5. Cumulative energy dissipation capacity was calculated and plotted for all the specimens. The HYFBC5 energy dissipation capacity was more compared with other specimens and HSBSC1.
6. Ductility is one of the basic parameters considered in this experimental study. Hybrid fiber reinforced high-strength concrete (steel 80%–polyolefin 20%) combination for all volume fractions, provides improved ductility, higher energy absorption and ultimate strength compared to Type-2 joints with plain high-strength concrete, steel fiber and other combination (steel 60%–polyolefin 40%) of specimens.

References

- ACI Committee. 211-4R (1993) Guide for selecting proportions for high-strength concrete with portland cement. American Concrete Institute, Farmington Hills
- ACI Committee. 212.4R-1993. (reapproved 1996) Guide for the use of high range water-reducing admixtures in concrete, pp 1–10
- ACI Committee. 318 (2005) Building code of requirements for structural concrete and commentary. American Concrete Institute, Farmington Hills
- ACI Committee. 352-R-02 (2010) Recommendations for design of beam–column connections in monolithic reinforced concrete structures. American Concrete Institute, Farmington Hills
- Alberti MG, Enfedaque A, Gálvez JC, Cánovas MF, Osorio IR (2014) Polyolefin fiber-reinforced concrete enhanced with steel-hooked fibers in low proportions. *Materials and Design* 60:57–65
- Annadurai A, Ravichandran A (2015) A strength prediction of hybrid fiber reinforced high strength concrete. *Int J Chemtech Res* 8:675–681
- Attaalla SA (2004) General analytical model for nominal shear stress of type 2 normal- and high-strength concrete beam–column joints. *ACI Struct J* 101:65–74
- Banthia N, Gupta R (2004) Hybrid fiber reinforced concrete (HYFRC): fiber synergy in high strength matrices. *Mater Struct* 37:707–716
- Ehsani MR, Wight JK (1985) Exterior reinforced concrete beam-to-column connections subjected to earthquake type loading. *ACI J* 82–43:492–497
- Filiatrault A, Ladicani K, Massicotte B (1994) Seismic performance of code-designed fiber-reinforced concrete joints. *ACI Struct J* 91:564–570
- Ganesan N, Indira PV (2007) Steel fibre reinforced high performance concrete beam–column joint subjected to cyclic loading. *ISET J Earthq Technol* 44:445–456
- Ganesan N, Indira PV, Sabeena MV (2014) Behaviour of hybrid fibre reinforced concrete beam–column joints under reverse cyclic loads. *Mater Des* 54:686–693
- Gefken PR, Ramey MR (1989) Increased joint hoop spacing in Type 2 seismic joints using fiber reinforced concrete. *ACI Struct J* 86(2):168–172
- Hamad BS, Haidar EYA, Harajli MH (2011) Effect of steel fibers on bond strength of hooked bars in high-strength concrete. *J Mater Civ Eng* 23:673–681
- IS. 13920 (1993) Indian standard code of practice for ductile detailing of reinforced concrete structures subjected to seismic forces. Bureau of Indian standards, New Delhi
- Jiuru T, Chaobin H, Kaijian Y, Yongcheng Y (1992) Seismic behavior and shear strength of framed joint using steel fiber reinforced concrete. *J Struct Eng* 118:341–358
- Megget L, Fenwick R (2003) Seismic performance of external reinforced concrete beam–column joints. *Bull N Z Soc Earthq Eng* 36:223–232
- Murty CVR, Rai DC, Bajpai KK, Jain SK (2003) Effectiveness of reinforcement details in exterior reinforced concrete beam–column joints for earthquake resistance. *ACI Struct J* 100:149–155
- Park R (1988) Ductility evaluation from laboratory and analytical testing. In: *Proceedings of the ninth world conference on earthquake engineering, Tokyo, Kyoto, Japan, vol VIII, pp 2–9*
- Rajagopal S, Prabavathy S (2014) Seismic behavior of exterior beam–column joint using mechanical anchorage under reversal loading: an experimental study. *IJST Trans Civ Eng* 38:345–358
- Rohm C, Novak B, Sasmal S, Karusala R, Srinivas V (2012) Behaviour of fibre reinforced beam–column sub-assemblages under reversed cyclic loading. *Constr Build Mater* 36:319–329
- Shamim M, Kumar V (1999) Behavior of reinforced concrete beam–column joint: a review. *J Struct Eng* 26:207–214
- Shannag MJ, Abu-Dyya N, Abu-Farsakh G (2005) Lateral load response of high performance fiber reinforced concrete beam–column joints. *Constr Build Mater* 19:500–508
- Sheela S, Anu Geetha B (2012) Studies on the performance of RC beam–column joints strengthened using different composite materials. *J Inst Eng India Ser A* 93(1):63–71
- Song PS, Hwang S (2004) Mechanical properties of high-strength steel fiber reinforced concrete. *Constr Build Mater* 18:669–673
- Sudhir K, Ingle RK (2006) Proposed codal provisions for design and detailing of beam–column joints in seismic regions. *Indian Concr J* 80:27–35
- Thirumurugan A, Sivaraja M (2015) Strength and fracture properties of hybrid fibre reinforced concrete. *IJST Trans Civ Eng* 39:93–102
- Tsonos AG, Tegos IA (1992) Seismic resistance of type 2 exterior beam–column joints reinforced with inclined bars. *ACI Struct J* 89:3–12
- Yao W, Li J, Wu K (2003) Mechanical properties of fiber-reinforced concrete at low fiber volume fraction. *Cem Concr Res* 33(27–30):4122–4151
- Yousef AM, Yakimov I (1995) High Strength concrete beam column joints under seismic loading. *IABSE reports 73/1/73/2, pp 348–354*