CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

This chapter deals with the previous research works related to the behaviour of beam column joint, experimental study on the effect of different types of fibres and their effect on the behaviour and strength of beam-column joint, axial load on column, different shapes and sizes of joint confinement reinforcement, anchorage of main reinforcement in beam-column joint etc. It deals with finite element modelling of concrete structures, particularly in ABAQUS finite element package as reported by various authors has been presented in respective sequence. The following is the order of the presentation of the literature reviewed.

- Behaviour of Exterior beam-column joints under earthquake loading
- Effects of different types of fibres
- Seismic behaviour of fibre reinforced concrete
- Effect of hybrid fibres in reinforced concrete
- Seismic behaviour of steel fibre reinforced beam-column joint
- Finite element modelling of fibre reinforced concrete
- Finite element modelling and analysis of beam-column joint using ABAQUS
- Summary of literature review
2.2 BEHAVIOUR OF EXTERIOR BEAM-COLUMN JOINTS UNDER EARTHQUAKE LOADING.

Uzmeri (1977) carried out experimental study on the behaviour of eight reinforced concrete beam-column joints subjected to slow load reversals simulating seismic loading. Variables were the quantity and size of joint reinforcement and stress strain characteristics of joint steel. He reported that the assumption of rigid beam-column joints could give invalid results. He suggested that the use of joint reinforcement with flat yield plateau might be undesirable for confinement. He recommended that joint stirrups should be extended above and below the beam steel at same spacing as in the joint for a distance of at least half the core dimension to prevent premature failure in the column just above or below the beam.

Lee et al. (1977) investigated the behaviour of six beam-column joints designed according to ACI-ASCE committee 352. The test variables were the quantity of transverse reinforcement, magnitude of axial load on the column and severity of loading. They have concluded that the cracks were formed on each specimen in their joint and beam portion and they were more numerous and severe in specimen without axial load. Their results also indicated that there was slightly higher initial stiffness in the specimen with column axial load and lower stiffness in specimen without column axial load. The shear resisting capacity was also increased by an increase in the transverse reinforcement.

Abrams (1987) conducted tests on eight small-scale joints, four medium-scale joints and six large-scale joints. Specimens were subjected to reversals of lateral force to study scale correlations for nonlinear hysteresis properties. He had concluded that stiffness deterioration was the highest for small-scale specimens as a result of weaker bond between model reinforcement and mortar. One-quarter scale specimens showed force-
deflection response similar to those of large-scale specimens. He recommended that minimum usable scale for testing of isolated reinforcement concrete components be a quarter.

Kitayama et al. (1987) reported about the ‘Earthquake resistant design criteria for reinforced concrete interior beam-column joints’. They opined that the ratio of the column width to the beam bar diameter must be limited as function of the strength of beam bars and concrete strength. They also stated that the design shear stress should be limited to prevent shear compression failure after the bond deterioration along the beam reinforcement. A minimum amount of lateral reinforcement must be placed within a joint to confine the concrete of the main strut.

Kumar et al. (1991) carried out experimental works on exterior beam-column joints. They tested twenty three specimens simulating typical exterior beam-column joints subjected to axial compression and uniaxial bending. The effects of column axial load, grades of concrete in beam and column, transverse reinforcement of beam and column on the performance of joints were studied. The steel-column shoe with a groove at the centre to hold a steel ball was fixed at each end of the column to provide a ball joint for simulating the ends are held in position. A hydraulic jack with proving ring was used to apply the load at the beam end. The lower end of the column was placed through a ball joint on a 50-T hydraulic jack. The upper end of the column was supported under the steel girder. They reported that the efficiency of joints increases with the increase in axial load on column for the same grade of concrete in beam and column and richer grade of concrete in column. However the trend was reverse when the concrete grade of beam was richer than that of the column.

Hwang and Lee (1999) proposed a method to determine the shear strengths of exterior beam-column joints for seismic resistance. The method
termed as the softened strut-and-tie model, is based on the strut-and-tie concept and derived to satisfy equilibrium, compatibility and the constitutive laws of cracked reinforced concrete. They checked the accuracy of the proposed procedure by comparing calculated shear strengths with experimental data reported in previous literature.

Kumar et al. (2002) carried out experimental study to clarify the effect of joint detailing on the seismic performance of lightly reinforced concrete frames. The parameters studied were the effect of joint rotation, column axial load, cross reinforcement in the joint and percentage of longitudinal reinforcement in the beam. About eight T-shaped beam to column joint subassemblies designed and detailed as per IS 13920-1993 were tested under cyclic loading. They found that use of cross reinforcement in the joint reduced damage in the joint but also reduced the ductility and energy dissipation capacity. The test results indicated that presence of axial load in column and allowing free joint rotation not only increased the strength and ductility but also reduced the damage in the joint region. Hence they concluded that ductility and energy dissipation capacity increased with a decrease in the percentage of longitudinal reinforcement.

Pampanin et al. (2002) carried out experiments to investigate the inherent seismic vulnerability of reinforced concrete beam-column connections designed for gravity load only. Experimental tests on six 2/3 scaled beam-column joints, with structural deficiencies, designed only for gravity load, were performed under simulated seismic loads. They reported the significant vulnerability of the joint panel zone region and the critical role of the slippage phenomena due to the use of smooth bars and of inadequate anchorage. They observed a particular “concrete wedge” brittle failure mechanism, due to the interaction of shear cracking and stress concentration at the hook anchorage location, in the exterior beam-column joint specimens.
Murty et al. (2003) reported the experimental evaluation of effectiveness of different details of longitudinal beam bar anchorage and transverse joint reinforcement in exterior beam-column joints of moment resistant frames. Twelve specimens were tested with four different arrangements for anchorage of beam longitudinal bars namely Type P, Type Q, Type R and Type S and three different arrangements of reinforcement in joint regions namely Type 1, Type 2 and Type 3. Their test results indicated that among all, the specimens with joint reinforcement Type 2 were the most effective and that they provided additional strength to the specimens beyond cracking and reduce the strength deterioration. The Type R specimens (with full anchorage of longitudinal beam bars) provide the best performance consisting the strength and ductility of specimens. They concluded that of all the joint reinforcement detailing schemes investigated, the ACI standard hook with hairclip-type transverse reinforcement was a preferred combination because of its ease of construction and overall effectiveness.

Liang and Montesinos (2004) presented results from tests of four reinforced concrete RC column-steel beam subassemblies under large displacement reversals and dynamic analyses of RCS systems under various ground motions. The test specimens were designed following a strong column-weak beam philosophy and a deformation-based capacity design method for the connections. Results from this research shows that RCS frame systems perform satisfactorily under seismic excitations. They reported that test specimens have good strength and stiffness retention capacity with excellent energy dissipation up to displacement levels of approximately 5.0% drift. The joint deformation-based capacity design procedure was effective in controlling.

Au et al. (2005) reported about a new detailing especially developed for low to medium seismicity, which involves the use of additional
diagonal bars in the joint. They conducted cyclic load test on six half scale interior beam-column subassemblies with different joint details. In their results they reported that the joints containing the newly proposed detail, with or without axial load in the column, exhibit better behaviour at the lower range of ductility factors in terms of higher load carrying capacity, greater stiffness and less strength degradation.

Rajesh Prasad et al. (2005) reported about the dynamic response of gravity- designed reinforced concrete connections. They conducted six tests on full scale specimens, which were subjected to reverse cyclic displacements applied at different speeds varying from slow quasi-static loading to high-speed dynamic loading as fast as 20 Hz. They concluded from their experiments that maximum joint shear failure occurred due to lack of transverse hoops inside the joint cores. The damage patterns and failures of the specimens showed a better correlation with the residual storey shear stiffness than with the loss of storey shear strength during the repeated cycles.

Asha and Sundararajan (2006) have presented the behaviour of external beam column joints with detailing as per IS 13920:1993 under seismic conditions. The primary variable was the type of confinement in the joint region extended from the column. They have used four types of confinement namely, square hoops, square spiral, circular hoop and circular spiral. For strain controlled testing, screw jack was used to apply displacement load at beam end. Column ends were fixed to pivot assembly. The loading programming consisted of a simple history of reverse symmetric displacement of increasing amplitudes. The test specimens were evaluated in terms of load-displacement relation, ductility, stiffness, load ratio and cracking pattern. They reported that exterior beam-column joint with square spiral in the joint region was the most effective of all the specimens tested.
Uma and Meher Prasad (2006) studied the behaviour of beam-column joint. They presented a review of the postulated theories associated with the behaviour of joints. They suggested that in seismic design, the damages in the form of plastic hinges are accepted to be formed in beams rather than in columns. They reported that the factor impacting the bond transfer within the joint appears to be well related to the level of axial load and the amount of transverse reinforcements in the joints. The functional requirement of a joint, which is the zone of intersection of beams and columns, is to enable the adjoining members to develop and sustain their ultimate capacity. The demand on this finite size element is always severe especially under seismic loading. The joints should have adequate strength and stiffness to resist the internal forces induced by the framing members. The high internal forces developed at plastic hinges cause critical bond conditions in the longitudinal reinforcing bars passing through the joint and also impose high shear demand in the joint core.

Alexandors and Tsonos (2007) conducted experiments to study the cyclic load behaviour of reinforced concrete beam-column joint of modern structures. They examined the seismic performance of four one-half exterior beam-column joints. The four sub assemblages were designed and constructed in turn, according to Eurocode 2 (E\textsubscript{1}) and Eurocode 8 (E\textsubscript{2}), according to ACI 318R.02 (A\textsubscript{1}) and according to Greek Earthquake Resistant Code. The sub assemblages were subjected to cyclic lateral load histories so as to provide the equivalent of severe earthquake damage. They reported that A\textsubscript{1} and E\textsubscript{2} beam column joint performed satisfactorily during the cyclic loading sequence to failure allowing the formation of plastic hinges in their adjacent beams. The joint E\textsubscript{1} and G\textsubscript{1} performed poorly under reverse cyclic loading. They indicated that the current design procedures could sometimes result in severe damage to the joint, despite the use of a weak girder-strong column design philosophy.
Jachong and Lafave (2008) prepared an extensive database of the reinforced concrete beam-column connection test specimens exhibiting joint failure when subjected to reverse cyclic lateral loading. They collected the data of about 341 experimental subassemblies in total from all over the world. They suggested joint shear strength and deformation models indicate that RC joint shear capacity under reverse cyclic lateral loading is mainly dependent on concrete compressive strength, beam reinforcement and joint transverse reinforcement.

2.3 EFFECTS OF DIFFERENT TYPES OF FIBRES

Soroushian and Bayasi (1991) reported the results of different types of steel fibre in concrete. The objective of their study was to compare the effects of different steel fibre types on fresh-fibre mix workability and hardened material flexural and compressive characteristics of concrete. The steel fibres considered in their study were straight-round, crimped round, rectangular, hooked-single and hooked-collated fibres with aspect ratios of about 60 and 75. A constant fibre volume of 2% was used. The fresh fibrous concrete was characterised by its slump, inverted slump-cone time and subjective workability. They presented that the inclusion of fibres decreases the workability of fresh concrete; this effect is more for fibres with higher aspect ratios. Crimped fibres result in slightly higher slump values when compared with straight and hooked fibres. They also reported that hooked fibres are more effective in enhancing the post-peak energy absorption capacity of concrete under compression and also under flexure.

Balaguru et al. (1992) reported the results of an experimental investigation on the flexural behaviour of steel fibre reinforced concrete (SRC). The variables investigated were fibre types, length and volume fraction and matrix composition. They conducted test on cylindrical and
prism specimens. Three fibre types, three fibre lengths, four fibre volume fractions and four matrix compositions were evaluated. In their results they reported that the excellent ductile behaviour can be obtained using fibre content in the range of 1.5% volume fraction. Increase in fibre content results in ductility and energy-absorption capacity. The post-peak load-deflection responses were flatter and the toughness indexes were higher. Hooked-end fibre had better results than corrugated and deformed-end steel fibres.

Yoon et al. (2002) have conducted tests on reinforced concrete beams with three steel fibre - volume fractions (0, 0.5 and 0.75%), three shear span-depth ratios (2, 3 and 4) and two concrete compressive strengths (31 and 65 MPa). They demonstrated in their results that the nominal stress at shear cracking and the ultimate shear strength increased with increasing fibre volume, decreasing shear span – depth ratio and increasing concrete compressive strength. They reported that as the fibre content increased, the failure mode changed from shear to flexure.

Sekar (2004) carried out experiments to study the feasibility of using industrial waste fibres in fibre reinforced concrete. He used three types of waste fibres, namely, lathe, wire winding and wire drawing industries. He cast 180 numbers of concrete cylinders with and without fibres and conducted tests on compression, split tension and flexure. He reported that the addition of waste fibres from lathe and wire winding industries in plain concrete increases the strength and waste fibres from wire drawing industries decreases the strength.

Perumal and Elangovan (2009) conducted experiments to study the behaviour of superplasticised steel fibre reinforced concrete using M20 grade concrete. The dosage of superplastiser was optimized as 0.8%. Workability, compressive strength, strain and Youngs modulus were found
out at 7 days and 28 days. Experimental results were compared with composite theory action of fibrous concrete and found coincide with theoretical values. They reported that the workability value and its structural strength values were found increase considerably.

2.4 SEISMIC BEHAVIOUR OF FIBRE REINFORCED CONCRETE

Mirsayah and Banthia (2002) conducted experiments to study the shear behaviour of fibre reinforced concrete using direct shear tests. Two steel fibres, one with flattened ends and circular cross section and the other with crimped geometry and a crescent cross section, were investigated at fibre volume fractions varying between 0 and 2%. Direct comparison was made with flexural toughness. They reported that for the flattened end fibre, an almost linear increase in the shear strength was noted with increase in the fibre volume fraction. The fibre with crimped geometry, shear strength approached a plateau value beyond which no increases in shear strength occurred with an increase in fibre volume fraction. They presented that plain concrete failed at a low equivalent shear strain of 0.4% and fibre reinforced concrete supported as high as 10% strain in shear.

ACI Committee 544 (1993) had published a guide for specifying, proportioning, mixing, placing and finishing steel fibre reinforced concrete. This guide describes the current technology in specifying, mixing, placing and finishing of steel fibre reinforced concrete (SFRC). The emphasis in this guide is on the differences between conventional concrete and SFRC and on how to deal with them. Guidance is provided for mixing techniques to achieve uniform mixtures, placement techniques to assure adequate compaction and finishing technology to assume satisfactory surface texture. They also tabulated sample mix proportions. ACI Committee 216 (1999) had published
a guide specifying the measurement and properties of fibre reinforced concrete.

Ashour and Wafa (1993) had investigated the inclusion of steel fibres on the flexural behaviour of high-strength concrete beam. Eight high strength concrete beams with different fibre contents and shear span-depth ratios were tested to study the influence of fibre addition on ultimate load, crack propagation, flexural stiffness and ductility. The concrete matrix compressive strength was about 80 Mpa. They suggested that the addition of steel fibres enhanced the strength, ductility and flexural stiffness of the tested beams. The post-cracking stiffness of the load-deflection curves increases due to the presence of steel fibre. The addition of steel fibres increases the length of the plastic hinges developed in the tested beams. This length was found to be proportional to the fibre content.

Adebar et al. (1997) had summarised all available previous shear tests on the fibre reinforced concrete beams without stirrups and presented the results on large-scale beam element tests. The beams were constructed with varying amounts of steel fibres (0 to 1.5 % by volume). The specimens were subjected to axial tension in addition to shear and bending. They emphasized that increasing the amount of fibres was found to reduce the crack widths and increase the shear strength. They also stated that the maximum increase in shear strength was 117 percent.

Suresh Gupta et al. (1999) reported about the usage of HPC (High Performance Concrete) in the construction industry. They reported that HPC as an optimised solution considering the economics, strength and durability required for special structures. They reported about the materials and their properties which were added to concrete to increase its strength. They also gave the mix design procedure for High Performance Concrete.
Montesinos and Wight (2000) investigated the seismic behaviour of beams after increasing hoops spacing and evaluate the potential of HPFRCC materials as a replacement of joint transverse reinforcement. They also tested a 3/4-scale exterior beam-column subassembly under large displacement reversals. The result indicated that ‘the specimen with ECC material exhibited a large number of hairline diagonal cracks with little damage at the end of the test (5.0% drift). In terms of shear distortion response, it is clear that the ECC connection exhibited excellent performance during the test, even though no transverse steel reinforcement was used in the connection region.

Kim and Parra-Montesinos (2003) proposed their experimental results of HPFRCC low-rise walls under the large displacement reversals loading. Two low-rise walls with a shear span-to depth ratio of 1.5 were constructed. One wall contained 1.5% PE fibres (by volume), while the HPFRCC in the other wall contained a 2.0% volume fraction of hooked steel fibres. To evaluate wall shear distortion capacity and contribution of fibres to shear strength, both of tested walls were designed to fail by a shear diagonal tension mechanism with limited flexural yielding. The results showed that even though the hysteretic behaviour of both wall specimens was nearly identical, the HPFRCC wall with PE fibres exhibited a larger number of cracks of smaller width and larger damage tolerance compared to the wall with hooked steel fibres.

Zerbino et al. (2006) have reported the benefits obtained from the steel fibre reinforced high strength concrete. They tested different concretes with characteristic compressive strengths up to 70 Mpa and conducted experiments to study the effects of the strength of the matrix, the type of fibre (that is low carbon and high carbon steel) and the fibre content. The behaviour under uniaxial compression was analysed using lateral and axial deformation of the specimen. The flexural tests were performed for evaluating the post-
peak behaviour and toughness. The fibre volume fractions used were 0.5% and 1% and of all the specimens tested, the specimen mixed with 1% of fibre showed maximum compressive strength and flexural toughness. They also stated that for the same fibre type and dosage, improvements in loading capacity and post-peak softening behaviour were observed for higher matrix strength.

Ganesan et al. (2007a) reported the behaviour of steel fibre reinforced high performance concrete members under flexure. They conducted the experiments in ten beam specimens to compare the behaviour of high performance concrete (HPC) and steel fibre reinforced high performance concrete (SFRHPC). HPC mix for M$_{60}$ grade was obtained based on ACI 211 method. They used 10% replacement of cement by silica fume and 20% by flyash for preparing HPC. Four volume fractions of steel fibre, namely, 0.25%, 0.5%, 0.75% and 1% were used. They reported that comparing HPC beams, with SFRHC beams additionally reinforced with 1% volume fraction of fibres, the first crack load was increased by 25% and ultimate load was found to increase by about 15%. They also stated that the energy absorption capacity and ductility factor improved considerably when fibre content was increased.

2.5 SEISMIC BEHAVIOUR OF STEEL FIBRE REINFORCED BEAM-COLUMN JOINT

The beam-column joint region is a very important area in seismic-resistant frame; especially for the exterior T joints as they carry larger shear forces compared with interior joints. During an earthquake, large lateral forces apply on the side of the building and the shear forces caused by longitudinal beam steel bar penetrate into joint core. The shear force may cause a corner to corner diagonal tension failure. Joints not designed to resist high shear, such as pre-70’s beam column joints are likely to undergo shear
failure in joints. Well confined joints show a better behaviour, but the stirrups and hoops in joint area may cause steel congestion. Considering the advantages of steel fibre reinforced concrete described earlier, such as high energy absorption capacity, improved tensile strength and damage tolerance of concrete, using steel fibres in beam column joints may be an effective method for relaxing the stirrup congestion and improving the shear capacity of joints in seismic resistance frames.

Gefken and Ramey (1987) have carried out experimental work to determine whether the increase in joint hoop spacing in conventional seismic joints could be achieved using steel fibre concrete in place of conventional concrete in the joint region. They tested ten beam-column specimens. The specimens were cast by using normal concrete and by using steel fibre reinforced concrete with fibre volume fraction of 2% in the joint region. A cyclic load was applied at the beam tip by using universal testing machine. They determined that steel fibre concrete specimens with joint hoop spacing of up to 1.7 times the spacing recommended by ACI –ASCE committee 352 for a conventional seismic joint had the same or better ductility, ultimate strength, energy dissipation capacity and joint stiffness. They finally concluded that by using steel fibre concrete, a type 1 joint (non seismic) could replace a plain type 2 joint (seismic).

Tang (1992) published results of SFRC joint tests. In their laboratory five exterior joints and 7 interior joints were constructed and tested under reverse cyclic loading. Two types of steel fibres were used in their test. The first was of rectangular cross-section with dimensions of 0.4 mm × 0.4 mm - 0.5 mm × 0.5 mm by shearing a thin low-carbon steel plate. The length of these fibres was 25-30 mm and aspect ratio was 54-62. Another was cut wire fibre manufactured by cutting round high strength steel wire which had the diameter of 0.7-0.8 mm with 50-55 mm length and aspect ratio of
66-75. A formula for determining the contribution of the shear resistance of steel fibres in the joint was given in this research.

\[ V_f = 2 \frac{1}{d_f} \rho_f A_f \]  

(2.1)

The results showed that using steel fibres can significantly increase the joint shear strength and also the shear stress corresponding to the first crack. It was also found that in exterior joint tests the problem of bar slip in the SFRC joint was significantly less than that in the RC joint; the slip reduced from 0.8 mm (RC) to 0.46 mm (SFRC). In interior joints tested, the steel fibres provided a better bond capacity and improved the bar anchorage capacity.

Andre et al. (1995) have reported the use of steel fibre reinforced concrete to increase ductility in a beam to column joints during earthquake excitation. They tested four full scale exterior beam column joints, part of a prototype building designed according to the National Building Code of Canada, under cyclic loading. They used two different types of mixes for casting the specimens. The first mix was normal concrete mix without fibre. The second mix was fibre mix consisting of 1.6% of steel fibre in the joint region. The experimental results indicated that FRC is an appealing alternative to conventional confining reinforcement to increase ductility. Steel fibre bridging across cracks in the concrete mix increase the joint shear strength and can diminish requirements for closely spaced ties. The performance of a joint is closely related to the volume content and aspect ratio of the fibres. They presented that the specimen with fibre concrete had dissipated 10% more energy than the seismically detailed specimen.

Ganesan and Indira (2000) have reported the experimental results of exterior beam-column joints that employ steel fibre reinforced concrete
(SFRC) and natural rubber latex under cyclic loading. Ten numbers of beam column joint were cast by using two different volumetric ratios of transverse reinforcement in the core of the joint and four different values of volume fraction of \( V_f \) steel fibres namely 0.5 \%,1.0\%,1.5\% and 2\% and two different values of dry rubber content of \( l_f \) 0.5\% and 1\%. Test results have indicated that latex modified SFRC with \( V_f = 1\% \) and \( l_f = 0.5 \% \) have maximum joint strength, ductility and energy absorption capacity of the joint. The specimens were tested in a universal testing machine of 300 T capacity. The specimen was mounded in a vertical position and a hydraulic jack was used to apply the load at the free end of the column.

Gebman (2001) made six 1/2-scale beam-column joints, two of those were conventional joint specimens and four steel fibres reinforced joints. The steel fibres used were of 30mm length and an aspect ratio of 60. For reducing the amount of lateral hoops in the joint, 2\% steel fibres (by volume) was added in the joint region to increase the joint hoop spacing from 10.2 cm (for two conventional joints) to 15.2 cm (for two fibre joints) and 20.3 cm (for the other two fibre joints). Residual load-bearing capacity, damage tolerance, and energy dissipation capacity were considered in this research for comparing the joint behaviour. The test results showed that the performance of specimens with steel fibres were better than other specimens. Steel fibre specimens had a significant improvement in load bearing capacity as well as the damage tolerance because of the smaller width of cracking. However, it was observed that the steel fibre joints had more cracks than the conventional joints. The energy dissipation capacity of the steel fibre specimens dramatically increased and the increase was approximately 100\% (for hoop spacing of 20.3 cm) and 300\% (for hoop spacing at 15.2 cm) compared with the conventional joints.
Thirugnanam et al. (2001) reported about the ductile behaviour of SIFCON structural members. They tested single span beam and multi-bay multi-story R.C frame with SIFCON beam-column joints to study the structural response of the frame under cyclic loading. They mixed 8% of volume of fibre with the concrete in the joint region. They reported that the use of SIFCON in the hinging zones of the R.C structure increases the first crack load by 40%, ductility by 100% and energy absorption capacity by 50%.

Bayasi and Gebman (2002) have reviewed the available literature and further reported an experimental study regarding the effect of using steel fibres in seismic beam-column connections. They noted that the addition of steel fibres to seismic joints without changing joint design to improve resistance to earthquake loading. They reported that due to the confining effect of steel fibres, lateral joint reinforcement can be reduced when using steel fibres in joints. Based on the available test data, they stated that for the steel fibre reinforcement index $V_f (l/d)$ ranging between 1.0 to 1.6, the lateral reinforcement reduction ranged between 0.3 and 1.1 % equivalent to 50 to 200 % increase of hoop spacing. They have constructed ½ - scale beam-column joints. Reinforcement ratios of the ½ - scale joint are practically equivalent to the ratios of original joint.

Gencoglu and Eren (2002) have reported the experimental results of steel fibre reinforced concrete on the behaviour of the exterior beam-column joints subjected to reverse cyclic loading. Two different ready-mixed concrete mixes of compressive strength 26 Mpa and 33 Mpa were taken for their study. Hooked steel fibre of volume fraction 1% was mixed with the concrete. They carried out tests on full-scale exterior beam-column joint assemblies subjected to displacement controlled reverse cyclic loading. The results indicated that the ductility and strength capacity could be increased by using SFRC and
decreasing the stirrups in the joint and confinement regions of the beam and column.

Montesinos (2005) conducted experiments on several high-performance fibre-reinforced cement composites (HPFRCC) materials for the use in earthquake-resistant structures including beam-column connections, low-rise walls, and coupling beams at the University of Michigan. The results emphasized on the potential of HPFRCC for the use in earthquake resistant structures. The use of HPFRCCs in beam-column connection allowed total elimination of joint transverse reinforcements while leading to outstanding damage tolerance.

Jamal et al. (2005) in an experimental investigation reported the effect of using high performance steel fibre reinforced concrete (HPFRC) in place of conventional concrete in the joint region. They compared the properties such as ultimate strength, ductility, energy dissipation capacity and joint stiffness of the reference concrete specimens with those containing different amount of hooked steel fibre. They reported that the steel fibre concrete specimens exhibited three times higher load levels, 20 times larger energy dissipation and two times slower stiffness degradation compared to the reference concrete specimens.

Montesinos et al. (2005) reported the feasibility of using high performance fibre reinforced cement composites (HPFRCC) as a means to eliminate the need for confinement reinforcement and associated construction problems in beam-column connections subjected to earthquake loading. The fibre cementitious material used in this study contained polyethylene fibres with a 1.5% volume fraction. They tested two full scale beam-column connections. They reported that the HPRCC specimen exhibited excellent strength, deformation capacity and damage tolerance. They presented that no
signs of bond deterioration in beam longitudinal bars passing through the connection were observed in the test specimens.

Liu and Cong (2006) reported about the seismic behaviour and failure modes of beam-column joint subassemblies reinforced with steel fibres. He tested six 2-D exterior beam-column joint subassemblies under simulated seismic loading. He compared the performance of steel fibre reinforced concrete with the conventional joint. He reported that the steel fiber reinforced concrete within beam-column joints can significantly enhance the shear resistance capacity of joints. Furthermore, he also reported that using steel fibre reinforcement is an effective method to reduce the lateral reinforcement in the beam plastic hinge region. He gave some preliminary suggestions for a simple but rational analytical procedure to evaluate the joint shear strength when either fibres and/or stirrups are adopted.

Ganesan (2008) has carried out a research programme to ascertain the feasibility of using SFRHPC (steel fibre reinforced high-performance concrete) in the beam-column region by using steel fibre. The volume fraction of fibre ranges from 0 to 1% with an increment of 0.25%. The specimens were tested in a UTM. The cyclic load was given with a load increment of 0.5 kN. The experimental results showed that an increase of about 20% in first crack load and 37% in ultimate load for SFRHPC specimens with 1% steel fibres. He reported that the SFRHPC joints exhibit enhanced strength, ductility and stiffness and is one of the alternative solutions for reducing the congestion of reinforcement in beam column joints. He suggested that the technique of inclusion of steel fibres in beam-column joint appears to be a useful solution in the case of joints subjected to repeated, cyclic loading or seismic loading.

Ganesan et al. (2007b) reported the experimental results of ten steel fibre reinforced high performance concrete (SFRHPC) exterior beam-column
joints under cyclic loading by using M$_{60}$ grade concrete. Volume fraction of the fibres used in this study varied from 0 to 1% with an increment of 0.25%. Joints were tested under positive cyclic loading and the results were evaluated with respect to strength, ductility and stiffness degradation. Test results indicated that the provision of SFRHPC in beam-column joints enhances the strength, ductility and stiffness, and is one of the possible alternative solutions for reducing the congestion of transverse reinforcement in beam-column joints. They also made an attempt to compare the shear strengths of beam-column joints obtained by using the models proposed by Tsonos et al. (1992) Bakir et al. (2003), Jiuru et al. (1992). As these models are meant for the joints in ordinary concrete, comparison was not found to be satisfactory. The model proposed by Jiuru et al. (1992) was modified to account for the presence of high performance concrete. The proposed model was found to compare satisfactorily with the test results.

Wang and Lee (2007) reported about the reinforced concrete (RC) structure strengthened with ultra-high steel fibre reinforced concrete (UFC). They conducted cyclic load test on interior RC beam-column joint sub-assemblages strengthened by means of joint replacement with UFC to observe their seismic performance. They also conducted experiments on mechanical properties of UFC such as compressive, flexural, rebar bonding, slant shear strengths and durability. Their test results indicated that the UFC displays excellent performance in terms of mechanical and durable behaviour. They stated that UFC-replaced joint frame behaves very well in seismic resistance and its performance was even much better than the frame strengthened with RC jacketing as normally seen in the traditional retrofit schemes.

Tamilselvi et al. (2008) carried out experiments to study the behaviour of two bay two storey reinforced concrete frames with slabs of 1/8
scale using SIFCON in the beam-column joint region and in the plastic hinge location adjacent to the joint. The specimens were subjected to lateral reverse cyclic load at the top storey. They discussed about the displacement of the top storey, stiffness, ductility and energy absorption capacity. They reported that the SIFCON specimens had more ultimate strength, more stiffness, more energy absorption capacity and less deflection.

2.6 EFFECT OF COCKTAIL FIBRE AND HYBRID FIBRE REINFORCEMENT IN CONCRETE

Lars (1996, 1997 and 1998) has studied the effect of cocktail fibre (combination of steel and synthetic fibre) mixed with the high strength concrete. He conducted some tests to observe the influence of steel fibres on the post-peak behaviour of HPC under compressive forces by casting cylindrical specimens. In the first set of tests he conducted experiments on compressive test on cylindrical specimens by using only steel fibres. From those tests he reported that the steel fibres did not improve the fracture behaviour of the HPC. He conducted several tests to study the influence of different fibre values and forms. The only use of polypropylene fibre leads to increase of material workability but did not change the fracture behaviour in the region of maximum stress. In the third phase he created a mixture of both steel fibres and polypropylene fibres. That is called “fibre cocktail” concrete. He reported that the improvement of ductility can be seen with steel fibre values of 1.5 Vol-% after adding 0.2 % of polypropylene fibres to the concrete mixture. After adding synthetic fibres to the steel fibre reinforced concrete the development of a plateau can be observed even in region of maximum stress in the stress strain curve.

Eswari and Jaganathan (2008) have studied the characteristics of hybrid fibre (i.e.,) high modulus hooked end steel fibre and low modulus straight polyolefin fibre in cement mortar. They used hybrid fibre volume
proportion varying from 0 to 2%. Their study parameters included compressive strength, split tensile strength and flexural strength evaluated for reference, steel fibre, polyolefin fibre mortar and hybrid fibre mortar. From their test results they reported that increase of fibre content increases the compressive strength, tensile strength and flexural strength appreciably.

Eswari et al. (2008) presented a study on the ductility performance of hybrid fibre reinforced concrete. They investigated influence of fibre content on the ductility performance of hybrid fibre reinforced concrete specimens having different fibre volume fractions. The parameters of their investigation included modulus of rupture, ultimate load, service load, ultimate and service load deflection, crack width, energy ductility and deflection ductility. They cast total of 27 specimens, 100 mm X 100 mm X 500 mm and were tested to study the above parameters. They used 0.0 to 2.0% volume fraction of polyolefin and steel fibres in different proportions. The ductility performance of hybrid fibre reinforced concrete specimens was compared with that of plain concrete. They reported that a hybrid fibre volume fraction of 2.0% with 30-70 Polyolefin–Steel combine significantly improves the ductility performance of reinforced concrete specimens.

Somma (2008) reported about the shear strength of fiber reinforced concrete beam-column joints under seismic loading. They have studied the experimental works done by other researchers on beam-column joints both without and with fiber reinforcements. On the basis of his studies he proposed a new formula that predicts the shear strength of fiber-reinforced concrete beam-column joints. He compared the shear strength values obtained with this formula to those derived by the experimental tests and he reported that the proposed expression gave an accurate and uniform prediction of the shear resistance, as it properly estimated the tests results.
2.7 FINITE ELEMENT MODELLING OF FIBRE REINFORCED CONCRETE

Zhang et al. (1994) have presented a reinforced concrete model for nonlinear finite element analysis. They developed smeared/layered reinforced concrete model for three dimensional finite element analyses. That model performed the nonlinear behaviours of both concrete and reinforcement steel on the supposition of compatible deformation of the two materials. The effects of concrete cracking, tension stiffening and dowel action were also considered in the new model. It was assumed that the rebars were constructed in three orthogonal directions. That makes mesh generation very convenient. It was assumed that the reinforcement steel was smeared in the concrete or layered in the element, where the number and location of the layers can be adjusted.

Shannag et al. (2007) have reported the experimental results as well as FEM analysis results of cyclic response of fibre reinforced concrete joints. They used two different concrete mixes viz normal concrete of compressive strength 27 Mpa and high performance concrete of compressive strength 75 Mpa. They used 0, 2% and 4% of brass coated steel fibre and hooked steel fibre. They prepared one third scale reinforced concrete interior beam column joint and observed that the best energy dissipation was exhibited by the specimens strengthened using hooked steel fibres. They also stated that this dissipated energy increased significantly with increase in fibre content. They used nonlinear static (pushover) procedure to model the behaviour of interior beam-column joints under lateral cyclic loading. The experimental results were found to be in good agreement with the results of the applied modelling technique and assumptions made. They reported that the static pushover analysis appears to be a viable tool for predicting the load-deflection and moment curvature responses of beam-column joints.
Bindu and Jaya (2008) reported the performance of exterior beam column joints with cross inclined bars under seismic type loading. Four exterior beam-column joints of one-third scale, designed for earthquake loads as per IS 1893:2002 and detailed as per IS 13920:1993 were cast. The difference between group 1 and group 2 specimen was that the group 2 specimens were tied with diagonal cross inclined reinforcement in the joint region at the two faces. They reported from their tests that the cross–inclined bars as confining reinforcement improve the seismic performance. They compared their test results with the analytical model developed by using finite element software package ANSYS. Only half of the system was modelled through thickness so that the symmetry condition was used. Solid 65 element was used to model the concrete and link 8 element was used to model the reinforcement. The models were analysed with monotonic loadings in the upward direction and the performance were compared. The load-displacement relations of finite element model were compared with experimental curve.

Al-Ta’an and Al-Saffar (2008) have used the finite element method to study the nonlinear behaviour of beam-column fibrous reinforced concrete joints under short–term monotonic loading. Concrete was represented by eight noded isoparametric elements and the reinforcement was represented by axial two noded bar elements embedded in the concrete elements. Strain hardening approach has been employed to model the compressive behaviour of the fibrous concrete. In tension a continuous function is used to model fibrous concrete in the pre-peak and post – peak states. Material nonlinearities due to cracking of concrete, crushing of concrete in compression, debonding and pull – out of fibres and yielding of reinforcement have been taken into account. A smeared fixed crack approach of the cracked concrete in tension is assumed. An incremental – iterative scheme based on Newton – Raphson’s method is employed for the nonlinear solution algorithm and a displacement criterion is adopted for checking the convergence of the solution. They
developed equations for compressive stress-strain relationship and tensile stress-strain relationship for fibrous concrete.

Thirugnanam et al. (2010) presented the experimental study on the behaviour of Interior RC Beam Column Joints subjected to cyclic Loading. They cast $1/5$th scale interior R.C beam-column joint designed for seismic load according to IS 1893 (Part I): 2002 and IS 13920: 1993. They compared their experimental results with FEM model analysis in ANSYS. They reported that the structural behaviour of interior beam column joint model has been similar to that of the analytically predicted one.

2.8 FINITE ELEMENT MODELLING AND ANALYSIS OF BEAM-COLUMN JOINT BY USING ABAQUS

Amiya and Tripathi (2002) reported about the effect of in-plane forces in beam-column junction. They analysed the joint by analytical method (moment distribution method), STADD.Pro (matrix method of analysis) and ABAQUS (Finite Element analysis). They concluded that present design procedure neglects the action of membrane forces, which makes the frame uneconomical and also more unsafe and undurable. Also the deformation pattern shown by conventional frame analysis doesn’t support the true deformation pattern as well as stress levels. They suggested that current design methods should be revised by including the action of membrane forces into it or else use ABAQUS and designing of the beams and columns must be done based on the results of ABAQUS, which will result in an economical and a safe design.

Danesh et al. (2008) studied about the shear strengthening of beam-column connection using GFRP using FEM. They compared the test results with the FEM results using ABAQUS finite element software. Concrete damaged plasticity model (CDP) was used for defining concrete behaviour in
plastic range. Concrete stress - strain behaviour under uniaxial compression after elastic range \(0.7f_{cc}\) should be defined in terms of stress versus elastic strain. Concrete behaviour under uniaxial tension is assumed to be linear until forming microscopic cracks at the peak stress (failure stress). Post failure behaviour should be defined in terms of stress versus cracking strain. Longitudinal and transverse reinforcement behaviour was defined as an elastic-plastic material using a bilinear curve. To introduce plasticity, kinematics hardening option was used. A truss element called T3D2 was used to model reinforcement elements. A monotonic downward load, instead of cyclic loading, was applied at the tip of the beam and the results were compared with the downward loading response envelope curves of the experimental tests.

Lin-Hai et al. (2008) presented an investigation on the fire performance of steel reinforced concrete (SRC) beam-to-column joints under fire. They carried out and described two new tests on SRC beam-to-column joints subjected to the ISO-834 standard fire. A finite element analysis (FEA) modelling was developed using ABAQUS. The comparison of results calculated using this modelling shows generally good agreement with the test results. They used FEA modelling to analyze the mechanism of the composite joints under fire.

Haach et al. (2008) reported the influence of the axial load on the behaviour of exterior beam-column joint by using ABAQUS. Concrete was modelled by the “Smeared Cracked Concrete” model. The interaction between concrete and reinforcement was modelled approximately by introducing some “tension stiffening” in the concrete modelling to simulate load transfer across cracks. Two-dimensional planar solid (continuum) elements with 2 active degrees of freedom were used to model concrete (CPS4). The longitudinal and transverse reinforcement were represented by
truss elements whose nodes were embedded in the concrete elements (T2D2). In their results they reported that the column axial load made the joint more stiff but also introduced stresses in the beam longitudinal reinforcement. A more uniform stress distribution in the region was obtained when the stirrup ratio was increased.

2.9 SUMMARY OF LITERATURE REVIEW

Results from previous studies recommend that FRC with steel fibres in 1.2 to 2.0 % volume fractions can be used for partial replacement of confinement reinforcement in beam-column joints. The compressive strength of the fibrous concrete is slightly higher than the compressive strength of plain concrete mix. The static flexural test showed that an excellent anchorage is established between the steel fibre and the cement matrix, resulting in a high ultimate flexural strength, high load carrying capacity and high ductility of the composite material. The steel fibre reinforced concrete shows a greater ability to absorb impact loading than ordinary concrete. All the experimental works on beam-column joints were done only by using steel fibre. It was reported that the ductility has been improved due to the addition of fibre cocktail or hybrid fibre (combination of steel and synthetic fibre). After adding synthetic fibres to the steel fibre in reinforced concrete it is observed that the stress strain curve became flat even in the region of maximum stress. These tests were conducted only on the cylindrical specimens. Since the literature about hybrid fibre in the beam column joint is scarcely available, an attempt was proposed to make a study on the effect of using hybrid fibre in the beam column joint on the properties: improvement of ductility, energy absorption and strength.