CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Beam-column connections are critical regions for the reinforced concrete framed structures in seismic prone areas. Proper anchorage of reinforcement is essential to enhance the performance. Innovative joint designs that can reduce congestion of reinforcement without compromising strength, stability and stiffness are desirable. ACI 352(2002) recommends additional research on use of T-headed bar in design of beam-column connections in concrete structure. The investigation of the beam-column connection longitudinal beam reinforcement bar with $90^\circ$ standard bent hooks anchorage and mechanical anchor for joint core under reversal loadings has been a research area for many years. Some of the analytical studies and experimental studies in the literature are presented below.

2.2 EXPERIMENTAL, ANALYTICAL AND SEISMIC RETROFIT BEHAVIOR OF EXTERIOR BEAM-COLUMN JOINT WITH CYCLIC LOADING

The first reported tests on exterior beam-column joints were carried out by Hanson & Connor (1967). They outlined the necessity of incorporation of a joint shear stress limit at which a brittle shear failure should be prevented. Their recommendations for the design of beam-column joints in monolithic...
reinforced concrete structures were incorporated in ACI 318-71, i.e., hoops should be always provided for unconfined joints (exterior and corner joints).

Park and Paulay (1975) recommends the detailing of joints for the earthquake resistance structures using bent-up bars, stub-beam with bent-up bars and mechanical anchorage for serving as anchorage as well as effective ties for confinement in the joint core of the exterior beam-column joints.

Morita & Fujii (1984), Kanada et al(1985) tests were carried out at the University of Kyoto with the aim of investigating the effect of stirrups in the joint and the influence of different beam bars anchorage types, and some of the following observations were made: The joints with bars bent out of the core (Type 2) had poorer behavior than the specimen with 90°hooks bent in (Type 1); the presence of stirrups increases the ultimate capacity of the joint; and specimens with anchorage shorter than the column depth exhibited a lower shear capacity. To quantify the influence of the length of such anchorages, it was proposed that the effective depth of the joints should be limited to the length of the anchorage, $l_{dh}$, instead of the depth of the column, $h_c$.

Minami & Nishimura (1985) tests were carried out at the University of Osaka to investigate the influence of the shape of beam bar anchorage, length of straight anchorage, axial load in the column and stirrups in the joint on joint shear capacity. It was concluded that axial load and stirrups in the joint have a positive effect on joint shear capacity. The length of the straight anchorage of the beam bars within the joint panel was found to have an important role which cannot be replaced by a longer bending tail.

Ueda et al (1986) the development of a computer model that can predict the loaded end deformation and anchorage length requirements for reinforcing bars extending from beams into exterior columns and subjected to
large inelastic loadings is reported. The model integrates six basic elements such as local bond stress-slip relationship, stress-strain relationship for the steel, continuity condition between steel and concrete, modification for unconfined concrete, failure criterion and equivalent embedment length criterion for a hooked bar.

The results of the model are shown to be in good agreement with the results of tests on straight and 90 degree hooked bars anchored within specimens simulating conditions for exterior column-beam connections.

Paulay (1989) suggested that, as in the case of linear element, joint shear reinforcement is necessary to sustain a diagonal compression field rather than to provide confinement to compressed concrete in joint core.

Bolong & Yuzhou (1991) the three full-scale reinforced concrete beam-column joint specimens subjected to one- and two-directional reversed loading are presented in this paper. The influences on a seismic behavior of beam-column joints with different loading systems and monolithic slabs have been analyzed. Also Chinese design code for reinforced concrete structures have been checked by test results.

Kaku & Asakusa (1991) bond and anchorage performances of longitudinal bars in reinforced concrete beam-column joints be summarized based on the investigations performed in the United States, New Zealand, and
suggested that the use of crossed inclined bars in the joint core region was one of the most effective ways to improve the seismic resistance in exterior joints.

Al-Taan & Ezzadeen (1995) developed a numerical procedure based on the FE method for the geometric and material non-linear analysis of RC members. A frame element with a composite layer system was used to model the structure. For the nonlinear solution, an incremental-iterative technique based on Newton-Raphson’s method was employed.

Tsonos et al (1995) conducted an experimental investigation to compare the response of beam-column joints subjected to seismic type loading under constant and variable axial load. A total of fourteen ductile exterior beam-column connections were tested to study various parameters (i.e., varying axial load, P-Delta effect, and joint shear stress level). A comparison of the seismic performance of specimens tested under constant axial load and other specimens with variable axial load levels indicated that axial load changes during seismic loading produces significant deterioration in the beam-column joint earthquake resistance. P-Delta effects did not significantly affect the overall joint behavior and therefore they can be ignored in detailing beam-column connections.

Kwak & Filippou (1997) introduced a FE model to study the monotonic behavior of RC beams and beam-column assemblages. In this model, concrete and reinforced bars were represented by separate material models. Another model was used between reinforcement bars and concrete to describe the behavior of the composite RC material and between these two, a bond link element was used. Improved cracking criteria derived from fracture mechanics principles were used as the basis for developing this smeared finite- element model.
Hwang & Lee (1999) this paper made proposal for determining the shear strength of exterior beam-column joints for seismic resistance. The proposed 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. The accuracy of the proposed procedure was checked by comparing calculated shear strengths with experimental data reported in previous literature, and a satisfactory correlation was found.

Hakuto et al (2000) performed tests on interior and exterior joints designed according to pre 1970s provisions. The limitation of the principle tension stress instead of the shear stress was proposed to assess the strength corresponding to the formation of the first diagonal crack in the joint panel. In this way, the influence of the axial load in the column can be realistically taken into account.

Ziyaefar & Noguchi (2000) to improve the accuracy of finite element modeling of concrete frame structures, new beam–solid transition element with developed characteristics was introduced. The refinement capability in this approach provided an accurate strain field approximation in the regions of high shear forces of beam and columns. Finite element formulation has been extended for material nonlinearity and large deformations to account for ultimate loads and secondary effects. The beam–column joints analysis results are compared with an alternative numerical approach for accuracy and efficiency.

Liu & Park (2001) tested four exterior beam-column joints with plain round bars, 90° hooks bent in and away from the joint with and without column axial load. When compared with results of similar specimen reinforced by deformed bars, (tests by Hakuto et al 2000) less shear distortion but more opening of beam bars hooks in tension and column bar buckling
were observed. Premature concrete tension cracking combined with pullout of the beam bars occurred in all the tests. Lower strength and stiffness were measured.

Ghobarah & Said (2001) tested a full-scale RC external beam-column joint. The specimen was tested under cyclic loading applied at the beam tip. The column was subjected to a axial load level of $0.2f_c \cdot A_g$. For the control specimen, T1, before the first yield of longitudinal beam steel, a diagonal shear crack was noted in the joint area forming an X-pattern. At failure, these cracks extended to the back of the column. A high rate of strength deterioration was observed at a ductility factor of 2.

Clyde et al (2000) & Pantelides et al (2002) four exterior joints with non-seismic detailing according to 1960s American standards were tested by Clyde et al, under cyclic loading and two different axial load levels (10% and 20% of $A_c \cdot f_c$). The following conclusions were made: Specimens with higher axial load level exhibited higher joint shear strength; and the energy dissipation and ductility decreased with increasing axial load. Similar results were obtained by the six tests by Pantelides et al where it was confirmed that the presence of higher axial load is beneficial in terms of the joint strength, but detrimental for displacement, ductility and energy dissipation.

Murty et al (2003) twelve cyclic tests on exterior beam-column joints were carried out to evaluate the influence of different beam-bars anchorage configurations (U-bars, ACI-318 standard 90° hook with tail extension of $12d_b$, full anchorage according to IS-456 with tail extension of $38d_b$ and static anchorage with straight anchorage of the beam bottom reinforcement). The influence of transverse reinforcement details (hair clips and closed ties) was additionally investigated. It was found that the IS full anchorage does not improve the joint performance in comparison to the ACI
standard hook, the suggested U-bar type (hair-clip bar) transverse reinforcements to be more effective.

Shyh-Jiann et al (2005) investigated the effect of joint hoops on the shear strength of exterior beam-column joint. The authors found that the major function of joint hoop is to carry shear as tension tie and to constrain the width of tension crack. They suggested that lesser amount of joint hoop with wider spacing could be used without affecting the performance of the joint.

Ayoub (2006) this paper presents a new model for nonlinear analysis of reinforced concrete beam–columns with both bond–slip and pull-out effects confirming the accuracy of the model in representing global and local parameters.

Alva et al (2007) tested four exterior beam-column joints under reversed cyclic loading. The variables were the joint transverse reinforcement and concrete compressive strength. The authors have concluded that concrete compressive strength was the major factor that governs the joint shear capacity.

Kuang & Wong (2006) and Wong & Kuang (2008) two different experimental test series on beam-column joint designed without seismic detailing (i.e., without transverse reinforcement in the core) were performed. The influence of the beam bar anchorage (Kuang & Wong 2006) and the beam-column depth ratio on the joint shear behavior were evaluated (Wong & Kuang 2008). It was shown that the form of beam anchorage significantly influenced the joint shear capacity. The need to include the effect of beam-column depth ratio in the design of the joint was also stated.
Haach et al (2008) this paper investigated the influence of the column axial load on the reinforced concrete exterior beam-column joint shear strength through numerical simulations. The numerical study is performed through the software ABAQUS®, based on Finite Element (FE) method and they are made comparison of the numerical and experimental results was presented in order to validate the simulation. The results showed that the column axial load made the exterior beam-column joints stiffer but also introduced stresses in the beam longitudinal reinforcement and also more uniform stress distribution in the joint region is obtained when the stirrup ratio is increased.

Lee & Yu (2009) proposed extensions of ACI- design methods to cover the use of mechanical anchorage (headed bars) for eccentric beam-column joints. They also reported that cyclic behavior of exterior beam-column joints can be significantly improved by attaching double mechanical device on each beam bar within the joint.

Bindhu et al (2008, 2010) in this paper four numbers of 1/3 scaled joint sub assemblage experimental test results are validated with Finite element analytical studies using ANSYS and concluded that additional cross bracing reinforcement improves the seismic performance of the exterior reinforced concrete beam-column joints under reversal cyclic loading.

Sasmal et al (2009) this paper discussed the aspects of repair and retrofitting technique adopted for a damaged reinforced concrete beam-column joint specimen under cyclic loading. The specimen designed as per Indian Standard with consideration of seismic load without adopting ductile detailing (Non-Ductile). Then, the damaged non-ductile specimen was repaired with epoxy mortar and grouted using low viscous polymer, and retrofitted using fiber reinforced plastic (FRP) wrapping in beam and column components and steel plate jacketing in joint region. The experimental results
demonstrated that a proper repair and adequate retrofitting technique strengthening can be improving the damaged regions in reinforced concrete structures.

Li & Kulkarni (2010) in their experimental test results validated a three-dimensional (3D) nonlinear finite element (FE) model analysis with influence factors like column axial load, transverse beam and beam bar anchorages ratio of the reinforced concrete (RC) wide beam-column joints.

Dahmani et al (2010) developed a three-dimensional nonlinear finite element model of reinforced concrete beam using ANSYS. The compressive crushing of concrete is facilitated by using the plasticity algorithm available with a solid element, while the concrete cracking in tension zone is accommodated by the nonlinear material model. Smeared reinforcement is used and introduced as a percentage of steel embedded in concrete.

Haach et al (2008) this paper investigates the influence of the column axial load on the exterior beam–column joint shear strength through the numerical simulations. The numerical study is performed using Finite Element Analysis (FEA) by ABAQUS® software to validate the numerical and experimental results. The results showed that the column axial load made the joint more stiff but also introduced stresses in the beam longitudinal reinforcement and more uniform stress distribution in the joint region was obtained when the stirrup ratio is increased. Additionally, some tension from the top beam longitudinal reinforcement is absorbed by the stirrups located at the upper part of the joint.

Le- Trung et al (2010) this paper presented the experimental study to strengthen the shear capacity of non-seismic joints using Carbon Fiber Reinforced Plastic (CFRP) materials. For that eight numbers of exterior RC
beam-column joint specimens including a non-seismic, seismic specimen and six retrofitted specimens with different configurations of CFRP sheets was developed and tested to find out an effective way to improve the seismic performance of the joints in terms of the lateral strength and ductility. Used the following different configurations of CFRP sheets considered were the T-shape, L-shape, X-shape and strip combinations. The research focused on the effect of using CFRP sheets for enhancing strength and increasing ductility of the non-seismic beam-column joints. The test results showed that appropriately adding CFRP composites to the non-seismic specimen significantly improved the lateral strength and well ductility of the test specimens. Especially, the X-shaped configuration of wrapping, the strips on the column and two layers of the CFRP sheets resulted in a better performance in terms of ductility and strength.

Sagbas et al (2011) in their FEA Computational analysis compared the experimental test results of seismically and non-seismically designed joint detailing for the shear deformations having a good agreement.

Mahini & Ronagh (2011) this paper presents the results of an experimental and numerical study carried out in order to evaluate the ability of CFRP sheets in preventing the plastic hinge formation at the face of the column in exterior RC joints. Seven numbers of scaled-down RC exterior joints of a typical ordinary moment resisting frame is tested under moderately monotonic/cyclic loads. Two specimens are used as control while the other five are CFRP-strengthened/repaired of different lengths and thicknesses. The results show that carbon fibre sheets can effectively relocate the plastic hinge away from the face of the column. Non-linear numerical results using ANSYS are also presented and discussed.

Asha & Sundararajan (2012) they reported that the use of with square spiral confinement in joint along with different reinforcement detailing
for anchorage of beam bars and additional inclined bars from column to beam connection can successfully move the plastic hinge away from the column face.

Masi et al (2013) this paper is focused on the analysis of test results of RC beam-column joints. Cyclic tests on full scale joint specimens having different earthquake resistant design levels was performed by Masi et al (2013), applying different values of axial force, the test results of specimens have been analyzed and compared with the results of numerical simulations based on an accurate finite element modeling using the DIANA code. Numerical simulations was used to evaluate the stress distribution in the joint panel since a function of the axial load and to quantify the beam rebar deformations and reasons for the specimens’ global failure.

Cotsovos (2013) the work presented in this is concerned with an investigation of the behavior of reinforced-concrete two-storey frames under both static (monotonic and cyclic) loading and seismic excitation in an attempt to assess the effect of cracking suffered by the beam-column joints on the overall structural response of the frames. The behavior of the structural forms investigated is established via nonlinear three-dimensional finite-element analysis.

2.3 BEHAVIOR OF EXTERIOR BEAM-COLUMN JOINT WITH MONOTONICLOADING

Monotonic testing of exterior RC beam-column joints has been carried out over the past forty years. The main aim of this testing is to evaluate the joint shear strength of subassemblies built according to different code provisions and with different reinforcement detailing. These tests usually do not provide sufficient information to evaluate seismic behavior including joint shear deformability, ductility, energy dissipation and post peak behavior.
However, tests have shown the backbone curve of the cyclic hysterics generally follows within acceptable limits.

Jirsa & Marques (1972) in these studies tests on exterior beam-column connections were performed to evaluate the behavior of standard 90° and 180° hooks conforming to ACI 318-71. Particular focus was given to three different types of confinement of the core: axial load, hoops in the core, longitudinal column bars and concrete cover. Tests with different aggregate types were also performed. The following conclusions were reached: The level of axial load does not significantly influence the behavior of the hooked anchorages; The straight embedment length between the beginning of a standard hook and the critical section at the face of the column significantly influences the capacity of the anchorage; The configuration of the column bars does not influence the capacity of the anchorage; The thickness of the concrete cover does not influence the capacity of the anchorage and the use of lightweight concrete does not influence the anchorage behavior.

Nilsson (1973) in this research work observed that the detailing of exterior joints presented more problems than for interior joints. Seven numbers of 2/3 scaled test specimens having different anchorage configurations in the joint panel and different geometric aspect ratios, \( h_v/h_c \), were carried out. No hoops in the joints panel were provided. All the specimens failed due to diagonal tension cracking. The joints with anchorage Type-1 exhibited much higher shear capacity than the ones with Type-2. In addition, it was observed that the joint shear capacity increased with decreasing ratio \( h_v/h_c \) and that the reinforcement detailing influenced the inclination of the diagonal crack.

Taylor (1974) and Taylor & Clarke (1976) twenty six 3/4 scaled exterior joints were tested in these studies. The focus of the research was to investigate the influence of beam reinforcement ratio. Usually only a few
hoops in the joints were provided (typically one or three). It was observed that for high beam flexural capacity the joint was not able to transfer the shear forces. In addition, it was recommended that the column flexural capacity should not exceed of 70% and 50% the beam flexural capacity at bottom and top joint interface, respectively. The influence of different beam reinforcement anchorage was also investigated. It was observed that for static applications anchorage Type 2 is approximately half as effective as Types 1 and 3. It was also stated that the configurations with 90°-hooks bent into and away from the joint (Types 1 and 2), are preferable than U-bars (Type 3) for seismic applications.

Hoekstra (1977) an extensive experimental program on twenty 2/3 scaled exterior joints was carried out to investigate the effect of column axial load, concrete strength, steel percentage and different configuration of hoops in the joint panel. It was observed that the concrete tensile strength has a major influence on the joint shear capacity and, to lesser extent; the column load increases the joint shear capacity. Furthermore, it was observed that for a ratio between column and beam depth of 2/3 and beam reinforcement ratio larger than 0.8%, the joint is weaker than the intersecting members. In all the tests diagonal cracking was observed in the joint core.

Scott (1992, 1996), Scott et al (1994) fifteen exterior joints were tested in these studies to evaluate the effect of different joint detailing on the shear capacity. The authors observed that the British Standard BS 8110:1985 significantly underestimates the joint shear capacity. Particular focus was given to the strain distribution in the bar anchorages, which was monitored with strain gauges. In addition, the following conclusions were attained.

- The column axial load increases the joint shear capacity; and
Overall, the joints with anchorage Types 1 and 3 performed much better than those with anchorage Type 2, as confirmed by the higher steel strain measured on anchoring length.

Parker & Bullmann (1997) based on twelve monotonic tests on exterior beam-column joints, Parker and Bullmann proposed a design model to evaluate the joint shear strength. The model provided a better estimation of the shear capacity of the joint than BS 8110:1985 and EC2 (1992). The good performance of the design model could not be validated using the tests by Scott (1992) and Taylor (1974).

Hamil (2000) carried out forty-nine monotonic tests and twenty-six cyclic tests in order to investigate the influence of the following parameters on the shear strength: Beam steel anchorage; Concrete strength; Joint ties and their positioning; Joint aspect ratio; Use of high strength and steel fiber reinforced concrete.

The following main conclusions were stated by Hamil:

- The presence of joint ties enhances the ultimate shear capacity of the joint, but it does not influence the strength at initial diagonal cracking;
- The normalized shear strength of the joint increases when fiber reinforced concrete is used; and
- Low ductility of the failure mechanism, but no shear strength decrease was observed during cyclic testing compared to the monotonic tests.
2.4 BEHAVIOR OF EXTERIOR BEAM-COLUMN JOINT WITH HEADED BAR

Chutarat & Aboutaha (2003) they are reported that the use of straight-headed bars in the exterior beam-column joint for cyclic response is very effective in relocating potential plastic hinge in the beam for the seismic design using special detailing by headed bars. Plastic hinges usually develop at the face of the column in structural moment resisting frames.

Chun et al (2007, 2009) they have tested thirty exterior beam-column joint specimens without transverse reinforcement to measure anchorage strength with respect to anchorage configuration and embedment length. The anchorage behavior of bars terminated with a head and with a 90-degree hook is investigated and compared with each other and presented.

Kang et al (2009, 2010, 2011, 2012) experimental research was performed to evaluate the applicability of headed bars with small heads in exterior beam-column joints. To examine anchorage behavior of headed bars subjected to monotonic and repeated loading 12 numbers of pullout tests was performed, with test variables such as the head size, shape, and head attaching technique. The seismic test results indicated that the joint using small-headed bars showed better seismic performance than the joint using hooked bars in terms of damage extent, joint behavior, lateral drift capacity, and energy dissipation and they can be effectively anchored in exterior beam-column joints under inelastic deformation reversals.

2.5 SUMMARY

From the literature review, the behavior of exterior beam-column joints has been widely investigated under monotonic and cyclic loading. The main influencing parameters for joints have been determined to be: Concrete
compressive strength, $f_c$; Anchorage detailing of longitudinal beam bars in the joint region; Axial load in the column; Geometric aspect ratio of the joint, $h_b/h_c$; Reinforcement ratio in beam and column; joint shear deformation; Some authors use special joint detail thereby shifting the plastic hinge away from the column face.

However, most of the authors did not fully investigate the effect of all the above parameters. This is likely to be because of the special attentions in the design standards and above all due to the difficulty in carrying out general experimental tests programmers.

Analytical study mainly strength and deformation contributions from joint shear cracking and bond-slip behavior of beam and column reinforcement bars. However, both these types of models are mostly based on experimental and phenomenological evidence. FEA offers the possibility not only to replicate experimental results but also to carry out parametric studies. This reduces the amount of experimental testing required and allows measurement of stress and strain in any portion of concrete and reinforcement of a specimen.

As per the recommended by ACI-352 using of headed bar (mechanical anchorage) in the beam-column joint are very limited based on the literature review. An attempt has been made to increase seismic performance using the mechanical anchorage for the low, moderate and high seismic prone area without losing the strength and ductility. In addition, it also reduces the reinforcement congestions in beam-column joint core.