CHAPTER 3
REVIEW OF LITERATURE

3.1 SEISMIC RESPONSE OF BUILDINGS

One of the major areas of research in the field of earthquake engineering has been the development of the method of evaluating the earthquake response of buildings under static nonlinear analysis, popularly known as the push over analysis. It was in the year **1996** that **ATC 40 (Applied Technology Council document No. 40) [01]** titled as "Seismic Evaluation and Retrofit of Concrete Buildings" was published. It emphasizes the use of available simplified nonlinear static procedures like the capacity spectrum method, the displacement coefficient method and the secant method and focuses on the capacity spectrum method (CSM) which uses the intersection of the capacity (pushover) curve and a reduced response spectrum to estimate maximum displacement. This document is a comprehensive guide for implementing the Static Non Linear analysis procedure along with the other two important documents **FEMA 273** and **274 [02]**

In the year **1996**, **Moghadam and Tso [03]** were among the early researchers who attempted to develop a simple method, yet capable, to predict seismic response of irregular buildings. They applied two static pushovers combined with a dynamic analysis of a single degree of freedom system to estimate the seismic deformation and damages of elements located at the perimeter of the building. The methodology starts with a pushover analysis of a three dimensional system from which base shear - roof centre of mass displacement relationship is obtained. Such correlation is approximated by a bilinear hysteretic curve, to account for unloading. A SDOF system is developed by means of the deflection profile, of the 3D model, when the top centre of mass displacement equals to 1% of the total height. Next, a non linear dynamic analysis of the SDOF system is performed to obtain the maximum roof top displacement Y_{max}. Another 3D pushover analysis is then carried out to determine the state of stress and deformation of the flexible edge of the building when displacement is Y_{max}. The results seems to produce comparable results with those from the dynamic analysis when Y_{max} is evaluated but when near field motions were used it failed to predict the maximum ductility demand and inter story drift at the flexible edge.

1n **1996, Kilar and Fajfar [04]** suggested another approach to tackle the pushover analysis on irregular structures. The starting point of the process is to create a pseudo 3D mathematical model which consists of assemblages of 2D macroelements, or substructures, which account for walls, frames, couple walls and walls on columns as shown in **Fig. 3.1**. These macroelements which are oriented arbitrarily in plane are assumed to resist loads only on their plane. Force-displacement relationships are developed based on the initial stiffness, strength at the assumed plastic mechanism and assumed post-yielding stiffness. Later, analysis is performed as a sequence of linear analyses, using event to event strategy. It was concluded that larger displacement and larger ductilities are required in asymmetric concrete structures in order to develop the same strength as that of its symmetric counterpart.

The pushover used a fixed load profile in the shape of an inverted triangle which does not take into account higher modes affecting the behavior of the building.

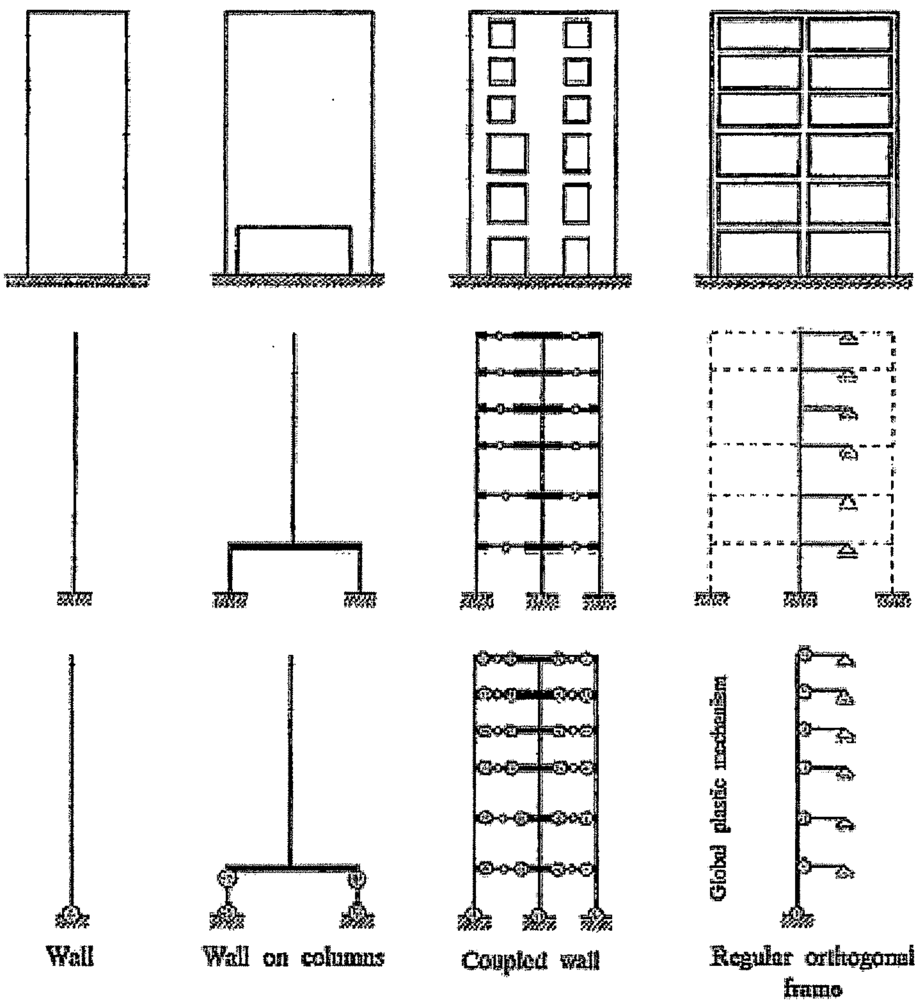

Fig. 3.1 Standard Macroelements with Mathematical Models.

Using a conventional pushover, with triangular load distribution, in **1998, Faella and Kilar [05]**, investigated the applicability of such approach on the analysis of asymmetric plan structures. They moved the load application point to fit the results from the dynamic analysis. The authors tried four possibilities, Centre of Mass (CM), CM – 0.05L, CM + 0.05L and CM + 0.15L. A single building was analyzed which was symmetric but became asymmetric by changing the position of the Centre of Mass. The results obtained were that the deflection profile both on the stiff and flexible edge could be successfully matched by shifting the point of lateral load application. In many cases, it was found that the dynamic response profile can be enveloped by shifting the equivalent static forces at the minimum and maximum eccentricities.

In the year **1998**, **Habibullah and Pyle [06]** presented the steps used in performing a pushover analysis of a simple 3D building. SAP2000, a state-of-the-art, general purpose, three-dimensional structural analysis program, was used as a tool for performing the pushover.

In **1999**, it was **Colina [07]** who showed by his work on time history analysis that when a structure is subjected to only one directional excitation, it gives very unreliable responses for a 3D structure. The displacement response is the one which is least reliable under uni-directional excitation.

In 1999, Chopra and Goel [08] pointed out some of the deficiencies of the ATC-40 procedure of pushover analysis. The report deals with development of an improved simplified analysis procedure, based on the capacity and demand diagrams, to estimate the peak deformation of inelastic SDF systems. It points out that the peak deformation of inelastic systems determined by ATC-40 procedures is inaccurate when compared against results of nonlinear response history analysis and inelastic design spectrum analysis. The approximate procedure underestimates significantly the deformation for a wide range of periods and ductility factors with errors approaching 50%, implying that the estimated deformation is about half the "exact" value. An improved capacity-demand-diagram method that uses the well-known constant-ductility design spectrum for the demand diagram has been developed and illustrated by examples. This method gives the deformation value consistent with the selected inelastic design spectrum. The improved procedures differ from ATC-40 procedures. The demand is determined by analyzing an inelastic system in the improved procedure instead of equivalent linear systems in ATC-40 procedures.

In **2000, Moghadam and Tso [09]** proposed a modified approach to account for torsional effects on irregular building. Accordingly, the target displacement was obtained by performing an elastic spectrum analysis of the building; since the top displacements of different resistant elements were different, many target displacements were needed to be computed. The lateral load distributions used in the pushover were taken from the spectrum analysis, as well, to take into account the higher order effects. With the target deformation and the load distribution fixed up, 2D pushover analyses of the selected elements were carried out. The elements were pushed until the target displacements, for each one, were achieved. Three different building configurations were used to test the scheme, i.e. uniform moment resisting frame, set-back moment resisting frame and uniform wall-frame buildings. An ensemble of 10 artificial ground motion records, with response spectrum shapes similar to the Newmark-Hall design spectrum, were developed to run the time history analyses. The authors claimed that this methodology works well in the uniform moment resistant frame system, especially in the local response parameters; however, the pushover results for the other two systems were not well correlated with the time history results. Again, the proposed methodology, although, considers a different load distribution from a triangular one, it keeps a fixed load profile during the pushover process neglecting changes in the mode shapes due to inelasticity; in addition, the bidirectional excitation in the time history analysis was not considered.

Performance-based evaluation results of exterior reinforced concrete (RC) building joints for seismic excitation were presented in the form of a report in June **2000,** by **Clyde et al [10].** RC buildings that were built in the 1960s behave in a nonductile manner and do not meet current seismic design criteria. In this report, beam-column joints of such nonductile buildings were investigated using several performance-based criteria. Four half-scale RC exterior joints were tested to investigate their behavior in a shear-critical mode. The joints were subjected to quasi-static cyclic loading, and their performance was examined in terms of lateral load capacity, drift, axial load reduction in the column at high levels of drift, joint shear strength, ductility, shear angle, residual strength, and other PEER established performance criteria. Two levels of axial compression load in the columns were investigated, and their influence on the performance of the joint was discussed. It has been observed that joint strength coefficient changes with the variation of the column compressive axial load.

In **2000, Murty and Jain [11]** studied the effect of masonary infill walls in an RC framed structure and have concluded that the beneficial effects of the masonary infill walls should definitely be taken into account especially when evaluating the earthquake response of buildings. When the effect of infill walls is neglected in the seismic analysis of RC frames, the performance of the building may be far from realistic.

In **2000, Chopra and Goel [12]** proposed a modification in the simplified non linear static analysis procedure given in ATC-40. The authors proposed two modified procedures based on Capacity-Demand diagrams which were similar to the procedure A and B given in ATC-40.

In **2000, Fajfar [13]**, proposed a simplified non linear procedure for 2D concrete structural frames. This method is also known as the N2 method where the N stands for nonlinear analysis. In this approach the structure is subjected to two pushover analysis which is symbolically mentioned as 2 in the N2 method.

In his paper on future trends in earthquake resistant design of structures in **2000, Rai [14]** mentioned that the future codes will be based on Performance Based design which predicts that pushover analysis will become a common tool for structural engineers. The acceptable risk criterion for design purposes will be prescribed in terms of performance objectives and hazard levels.

It was **Murty [15]** who pointed out in his paper in **2001**, that provision of the effect of brick infill walls must be incorporated in the revised Indian code of practice for plain and reinforced concrete. He stated that almost all RC frames built in India have masonry infills. Currently, the design practice is to neglect the presence of infills and assume the entire load to be carried by the bare frame. However, the infills contribute significantly to the strength and stiffness of the structure. Analytical studies and experiments have shown that there are large beneficial effects of considering infills in the design of the structure. The newly revised code provides no guidance to designers on how to include the same in the design. Such provisions are already available in the codes of other countries like NBC201 and Eurocode 8. If the designed structure is close to the actual one, then the structure constructed will behave as expected; else, damage will be imperative. His words proved right by the Bhuj earthquake.

In **2001, Humar et al. [16]** discussed the performance of buildings during the 2001, Bhuj Earthquake of India. They observed that most of the buildings in the epicentral region of Bhuj were either load bearing masonry or RC framed structures. One of the important observations to come out of the earthquake was that masonry infills, even when not tied to the surrounding RC frame, could save the building from collapse, provided such infills are uniformly distributed throughout the height so that abrupt changes in stiffness and strength did not occur.

By **2002, Kilar and Fajfar [17]** explored the possibility of extending the N2 method, originally formulated for planar analysis, to the analysis of irregular structures. In addition, comparisons among N2 method, the MT method (proposed by Moghadam and Tso [03]) and nonlinear dynamic analyses were carried out. The modified N2 procedure consists of two independent pushover analyses of the studied 3D structural model with lateral loading in both horizontal directions, respectively. Loading is applied at the mass centers. Displacement demand in the mass center at the top is determined for each direction separately, similar to the approach used in planar N2 analysis. Finally, the deformation quantities (displacements, story drift, rotations, ductilities, etc.) are determined by a SRSS combination of effects obtained from the pushover analyses in the two directions. The authors claimed that the extension of the N2 approach seems to be able to predict the response of a torsionally stiff multi-storey asymmetric building with a reasonable accuracy, within the limits set by the dispersion of results of dynamic analyses performed with different ground motions; however, the extreme cases of plan-wise highly irregular structures were generally not appropriate for these simplified methods.

In **2002, Penelis and Kappos [18]** aimed to develop a method that allow the modeling of the torsional response of building using 3D pushover analysis whose results do not deviate from those of time history analysis. The methodology proposes to build the mean elastic spectrum from a set of times histories previously scaled according to the PGA or spectrum intensity. With the mean elastic spectrum a dynamic response spectrum analysis was performed on the selected building, from which the translation and torque at the center of mass were calculated. Based on those two values and on an elastic static analysis of the building, the lateral force and the torque were obtained. Next, the reduction factors to convert the MDOF system to an equivalent SDOF system were calculated. Then, a 3D pushover analysis of the building, using the lateral force and torque previously calculated, was performed to obtain the force-deformation curve which was reduced by the factors already found at the last step to obtain the capacity curve of the equivalent SDOF system. Both the target displacement and torsional rotation, for the SDOF system, were calculated based on the mean inelastic acceleration-displacement response spectra, obtained for several ductility factors, and on the reduced force-deformation curve; both plot were superimposed and the desired target displacement was attained. Using the reduction factors the target and torsional rotation for the MDOF system was calculated. As examples two single-storey buildings were analyzed. Reasonable correlation between results from the time history analysis and the proposed approach could be observed in the results presented in the paper, especially for the pre-yielding stage.

In **2004, Peckley et al [19]** performed a pushover analysis on one internal plane frame of a 35 year old 10 storey RC building in Manila. By employing the fibre modeling approach, they effectively demonstrated that those buildings which were built prior to the incorporation of ductile detailing provisions, are quite deficient in resisting shear due to earthquakes. The pushover analysis was also carried out for the same building frame assuming that adequate shear and confinement reinforcement are present. The authors plotted the base shear versus the displacement graph for the existing shear deficient building and assumed adequate shear and confinement reinforcement and exhibited the effectiveness of the pushover analysis in identifying the weak links at the second floor level of an old RC building which can be retrofitted to enhance it's seismic capacity.

In **2004, Fajfar and Dolsek [20]** presented an extension to account for the effect of masonary infill walls in RC framed buildings on N2 method for seismic performance assessment. The application of the method was illustrated by a test example. Although the original N2 method was proposed for planer structures, a variant was later proposed in 2002 by Kilar and Fajfar [09] for the 3D application of the pushover analysis. The paper also proposed a modified method so as to be applicable to RC buildings with infill walls. It was concluded that the results obtained by N2 method are reasonably accurate, provided that the structure oscillates predominantly in the first mode.

In **2004, Basu and Jain [21]** gave a comprehensive account of the seismic analysis of asymmetric buildings with flexible floor diaphragms. The authors particularly focused on the torsional provisions of the codes. A superposition based analysis procedure was proposed to implement code-specified torsional provisions for buildings with flexible floor diaphragms. The proposed approach is applicable to orthogonal as well as non-orthogonal unsymmetrical buildings and accounts for all possible definitions of centre of rigidity.

In the year **2004, Das and Murty [22, 23]** studied five RC framed buildings with brick infills which were designed for the same seismic hazard equivalent to zone V of the Indian Seismic Code **IS:1893 (Part 1, 2002) [24]**. Each building was designed as per the applicable provisions given in **Eurocode 8 [25]**, Nepal Building Code **NBC 201 [26]**, Indian building code **IS: 13920 [27]** with ductile detailing and **IS: 456 [28]** without ductile detailing, and the equivalent braced frame method. The study was divided into two parts 1. Cost implications and 2. Behaviour. They concluded that the quantity of steel and concrete required in all buildings can be summarized in a material consumption chart as shown in **Fig. 3.2**. Whereas the concrete quantities required in all buildings were comparable, reinforcement steel required in the buildings designed by NBC 201 and EBF method were about half of that in the other 3 buildings.

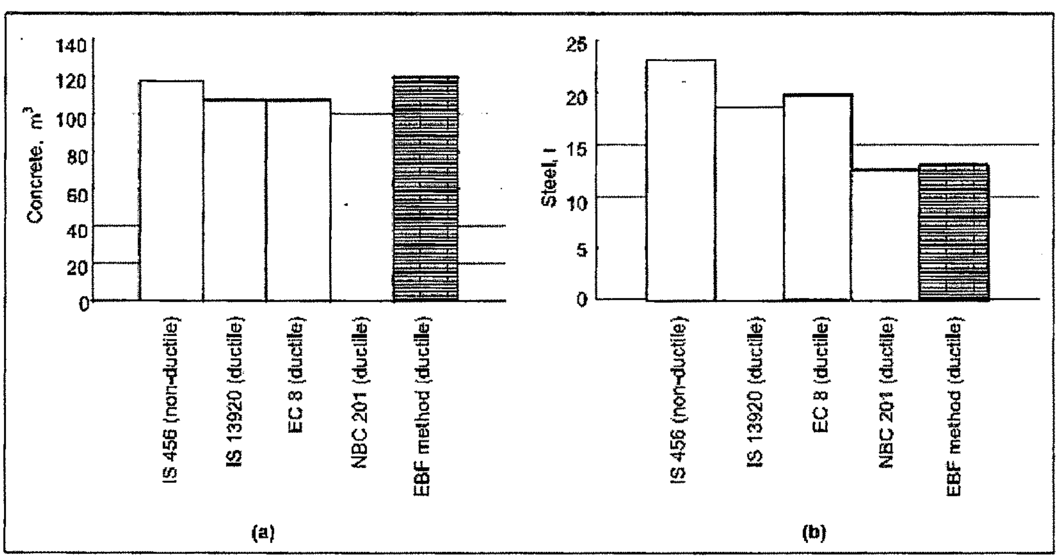

Fig. 3.2 Quantity of Concrete and Steel by various Procedures

In the other part on study of behavior of the same set of buildings, it was observed that the equivalent strut (**Fig. 3.3**) in the diagonal direction which substitutes the effect of masonary infill in a RC frame helps in resisting the earthquake forces.

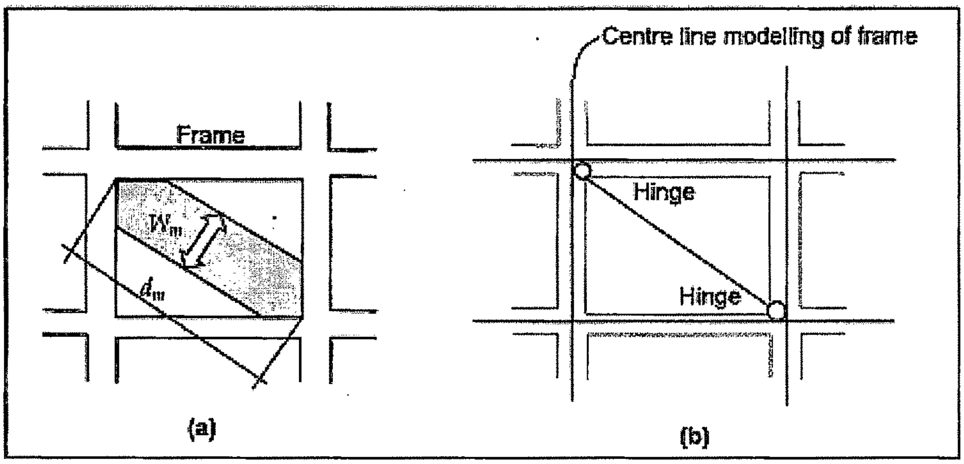

Fig. 3.3 Brick Infill Walls Idealized as Diagonal Strut

In **2006, Kaushik, Rai and Jain [29]** worked on the response of structures under the effect of masonry infilled (MI) RC frames as per the provisions in design codes of 16 countries. They observed that the behavior of MI is difficult to predict because of significant variations in material properties and because of failure modes that are brittle in nature. As a result, MI walls have often been treated as nonstructural elements in buildings and their effects are not included in the analysis and design procedure. However, experience shows that MI may have significant positive or negative effects on the global behavior of buildings and, therefore, should be addressed appropriately. The authors have commented that although all national codes mention that MI-RC frames must be treated separately, all factors associated with these type of frames are not included in any single country code. While some of the codes specify imperical formula to calculate time period, others recommend the Rayleigh formula to estimate the time period for such frames. In short, behaviour of MI-RC frames is different from normal RC frames and care should be taken at the time of seismic analysis to account for the same.

The paper by **Zaregarizi [30]** in the year **2008**, has reported the effect of brick and concrete infill walls in the seismic performance of a five storey building by push over analysis. Two techniques including shear walls and concrete infills was used for rehabilitation of a five storey reinforced concrete building with URM infill walls in Iran. The author has shown by using pushover curves, plastic hinge mechanism and interstory drift, that concrete infills have considerable strength while brick infills has lower strength. On the contrary, capability of accepting large displacement in brick infills are superior than concrete. Thus, the combination of concrete and brick infills can reduce the negative effects of any one single material infill. It is also concluded that the masonry infills can prevent collapse of buildings in moderate earthquakes. In case of shear walls, neglecting effects of existing URM infills may lead to wrong results.

The influence of vertical load in infilled RC frames has been studied and reported by **Amato et. Al. [31]** in **2008**. According to the authors, many mathematical models use equivalent strut elements to represent the infill walls in a RC frame but neglect the effect of vertical loads which influence the interaction between frame and infill giving erroneous results. The authors state that the axial deformation of the loaded columns can produce variation in the contact region between infill and surrounding frame, which in turn switches the infill behavior from a strut element to the one of a plate-shell element. The paper suggests an equivalent diagonal pin-jointed strut model which is able to represent the stiffening effect of the infill in presence of vertical loads. A numerical investigation on infilled meshes for a single storey single bay has been presented. A strong correlation between the dimensions of the equivalent diagonal strut model and a single parameter which depends on the characteristics of the system subjected to vertical load has been established.

In the year **2008, Kadid and Boumrkik [32]** evaluated the performance of framed buildings under future expected earthquakes by conducting non linear static pushover analysis. To achieve this objective, three framed buildings with 5, 8 and 12 stories respectively were analyzed. The results showed that properly designed frames perform well under seismic loads. Following are some of the conclusions drawn by them:

- The pushover analysis is a relatively simple way to explore the non linear behaviour of buildings.
- The behaviour of properly detailed RC frame building is adequate as indicated by the intersection of the demand and capacity curves and the distribution of hinges in the beams and the columns. Most of the hinges developed in the beams and few in the columns but with limited damage.
- The causes of failure of RC frame during the Boumerdes earthquake may be attributed to the quality of the materials used and also to the fact that most of buildings constructed in Algeria are of strong beam and weak column type and not to the intrinsic behaviour of framed structures.
- The results obtained in terms of demand, capacity and plastic hinges give an insight into the real behaviour of structures.

In **2008**, **Kayhani and Ashtiany [33]** have demonstrated the use of Load Dependent Ritz (LDR) vectors in modal push over analysis to calculate the dynamic response of frames. It helps in considering the spatial distribution of dynamic forces to improve the accuracy of calculated response when limited number of modes are to be considered. This method is considered to be better as compared to the eigen mode shape as higher mode effects are included in the suggested method without really computing them. Thus, the LDR vectors proves to be a better method for structures with stiffer lower stories causing a vertical irregularity in the geometry of the frames. Moreover, for regular buildings, there is no meaningful difference in using either the Ritz vector or the eigen vectors for analysis.

Thus, the above literature points to a very powerful method of evaluating the seismic performance of a framed structure i.e. using push over analysis. Hence, in the present study the performance point obtained by push over analysis is forming the basis of seismic evaluation of the RC framed structures. The various parameters under study are the base shear and roof displacement at the performance point. The study is undertaken using the commercial software ETABS and SAP2000 which gives the facility of push over analysis as per FEMA 273 and ATC 40.

3.2 SEISMIC PERFORMANCE OF SEMI RIGID JOINTS

It was as early as **1993** that the European Steel Design Education Programme **(ESDEP)** was launched. As per Lecture Note No. 14.11 **[34]**, which is available online, an account of semi-rigid joints is given. It concludes with recommendation that the connection need to be designed prior to final verification of the frame and for unbraced frames semi rigid connections are not recommended.

Back in **1994, Chan [35]** used a finite element based numerical method for non-linear vibration analysis of semi-rigidly connected members of steel frame with special features like derivation of shape function with end springs for formulation of element matrices.

Abu-Yasein and Frederick [36] in **1994** used direct stiffness matrix approach and showed that by decreasing stiffness of the joint connection the frame capacity also decreases. **Figure 3.4** shows that for frame having flexible beam-to-column connections, a small increase in connection stiffness results in a substantial increase in frame capacity for very flexible connections. It also proves that for very stiff connections extra connection stiffness results in only a small increase in frame capacity. From the same plot one can see that for very stiff joint connections (P = 1.0), all moments at the ends of the beam do not decrease as much as the stiffness of the joint connections decrease. For flexible joint connections (P < 0.5), all moments at the ends of the beam member decreases rapidly; moments at ends of beam approach zero as the stiffness approachs zero.

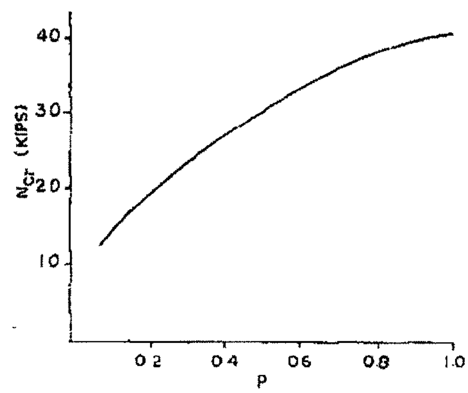

Fig. 3.4 Plot of Critical Load vs Beam-Column Joint Rigidity

Elnashai and Elghazouli [37] in their paper in **1994** studied frames with semirigid connections under earthquake loads. From the analytical as well as experimental investigations carried out by them, it was concluded that semi rigid frames exhibit ductile and stable hysteretic behavior and may be used effectively in earthquake resistant structures.

McGuire [38], in **1995** modeled 3 single span beams of same material properties simply supported at their edges with rotational springs at both the ends. It was concluded that when the mass was increased the natural frequency drops but the transition range remains the same. Therefore, it appears that the mass has no effect on the joint stiffness. Further, when the flexural stiffness is increased there is an increase in natural frequency with the transition range shifted. This phenomenon demonstrates that the flexural stiffness of the beam effects the joint stiffness.

In **1997, Lui and Lopes [39]** studied the dynamic response of semirigid frames using a computer model. The flexibilities of the connections were modeled by rotational springs with bilinear moment-rotation relationships. Geometrical nonlinearities in the form of member and frame (P-Delta) instabilities are incorporated in the model through the use of stability functions in the formulation of the frame stiffness matrix. Material nonlinearity in the form of column inelasticity was accounted for by the use of the tangent modulus concept in the formulation of the column stiffness relationship. Response characteristics of semi rigid frames under free vibration, forced vibration and earthquake excitation are studied. Response spectra were generated for frames subjected to forced vibrations and earthquake excitations. The presence of connection flexibility and P-delta effects reduced the frame stiffness, and hence increased the frames' natural periods of vibration. Semirigidity and P-delta effects were also found to affect the magnitude of base shear and the amount of energy dissipation of semirigid frames. It was concluded that the effect of semirigidity, geometric non linearity and column inelasticity increases the natural period of vibration of the frame. For a given damping ratio, for a semirigid frame to cease vibrations, the time required is longer and the number of cycles required is less than that of it's rigid counterpart. A simple formula by which natural periods of semirigid frames can be estimated was also proposed by them.

Goldey et al. [40] in **1997** developed finite element model of the whole connection and sub-models that enabled a full non-linear elasto-plastic analysis of the connection for the design of pallet rack. The moment rotation curves as shown in **Fig. 3.5** indicates that the semi-rigid connection used in pallet rack have different rotational stiffness in positive and negative rotations.

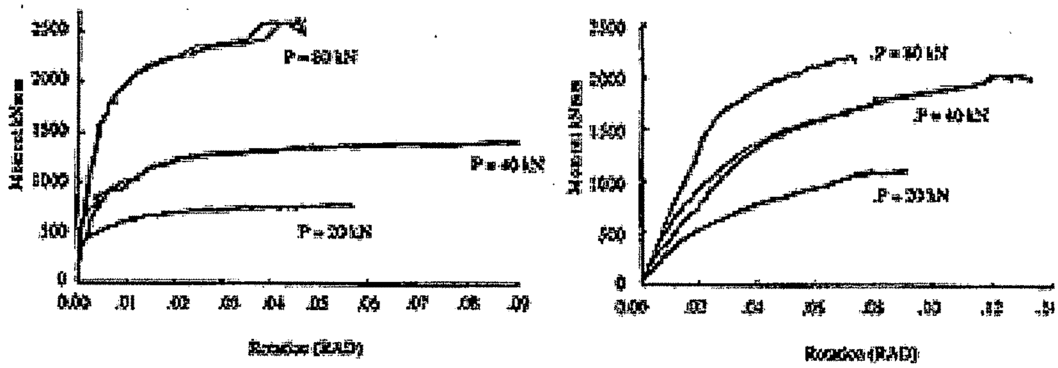

Fig. 3.5 Moment Rotation Curves from FEM Model

In **1999, Fang et al. [41]** developed a finite element procedure based on an effective numerical integration scheme for geometric and material non-linear analyses of semi-rigid composite frames. The influence of the sagging moment of the composite connection is studied along with lateral loads. The simplification in modeling the connections under sagging moment with a coarse and linear model with adequate accuracy was demonstrated.

Again in **1999, Awkar and Lui [42]** studied the response of multistory flexibly connected frames subjected to earthquake excitations using a computer model. They studied response characteristics of two multistory frames with three types of joints i.e. rigid, semi rigid and flexible. It was found that by applying Complete Quadratic Combination (CQC) rule of spectral analysis to flexibly connected frames, noticeable errors are produced for higher modes.

It was in **1999** that **Salazar and Haldar [43]** reduced the moment by using concept of T ratio in steel structures for 13 earthquake time histories for a frame model as shown in **Fig. 3.6** and found that larger reduction in T ratio causes instability and larger displacements in structure. So, T ratio must be closer to 1.

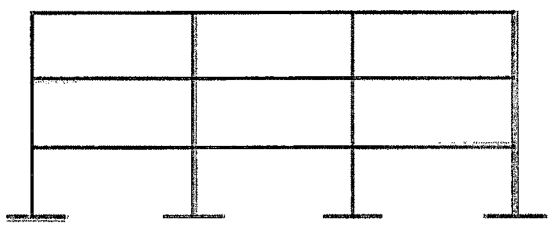

Fig. 3.6 Frame considered for T-ratio

In the year **2000, Kattner and Crisinel [44]** used the finite element method to simulate the behavior of semirigid composite joints. A two dimensional joint model was introduced which was analyzed using the existing finite element program.

Ivanyi [45] in the year **2000** performed a full scale experiment on multistory frames with semirigid connections. He has documented the issues faced in setting up a 3D experimental setup. The results and the methods of a comparative study based on second order plastic analysis and non-linear shakedown analysis are given in the paper.

Again in **2000, Tehranizadeh [46]** carried out a comprehensive forced vibration test on the half-scale models of typical Iranian four storey steel structures for identifying the dynamic behavior of semi-rigid connections known as "Khorjinee connections". Eleven mathematical models similar to the corresponding experimental models with different uncoupled torsional to lateral frequency ratio, eccentricity ratio, dimensions of plan ratio, and the connection's stiffness were studied to examine their effect on dynamic response. It was concluded that in case of braced structures, an earthquake has no considerable effect on connections. The effect of joint rigidity is significant on dynamic response of unbraced structure.

Li and Mativo [47], in **2000** presented a simplified method for estimating the maximum load of semi-rigid steel frame and concluded that this simplified method can be used in preliminary design and final check of analysis and as a check for existing building to confirm their current suitability or before any renovation for change of usage is undertaken.

It was in **2001** that **Kemp and Netherpot [48]** developed equations for rotation at the ends for double-cantilevered frames with fully rigid connection and semi rigid connection and concluded that the available inelastic rotation of the notional hinge associated with the additional moment capacity generated beyond the predicted stress-block moment at yield before failure occurs due to local buckling.

In **2001**, it was **Sekulovic and Salatic [49]**, who studied the effects of flexibility and eccentricity in the nodal connections of plane frames due to static loading. The stiffness matrix for the beam with flexible eccentric connections was developed based on the analytical solution of the second order analysis equations. It was concluded that influence of the geometric non linearity increases with load. The critical load and buckling capacity of the system significantly decrease with the increase in flexibility of joints.

In **2001, Kim and Choi [50]** developed a practical advanced analysis of semi-rigid space frames. The proposed analysis can predict accurately the combined nonlinear effects of connection, geometry and material on the behavior and strength of semi-rigid frames. They concluded that the load-displacements predicted by the proposed analysis compare well with those available from experiments. A case study was presented by them for a four storey semi rigid frame.

In **2001, Kameshki and Saka [51]** used Genetic Algorithm for non-linear planar steel frames as shown in **Fig. 3.7** and concluded that if gravity load is much larger than lateral load then semi-rigid frames are 7-8% lighter than rigid frames and if lateral force is larger than the gravity load than semi-rigid frames are around 9% heavier than the rigid frames.

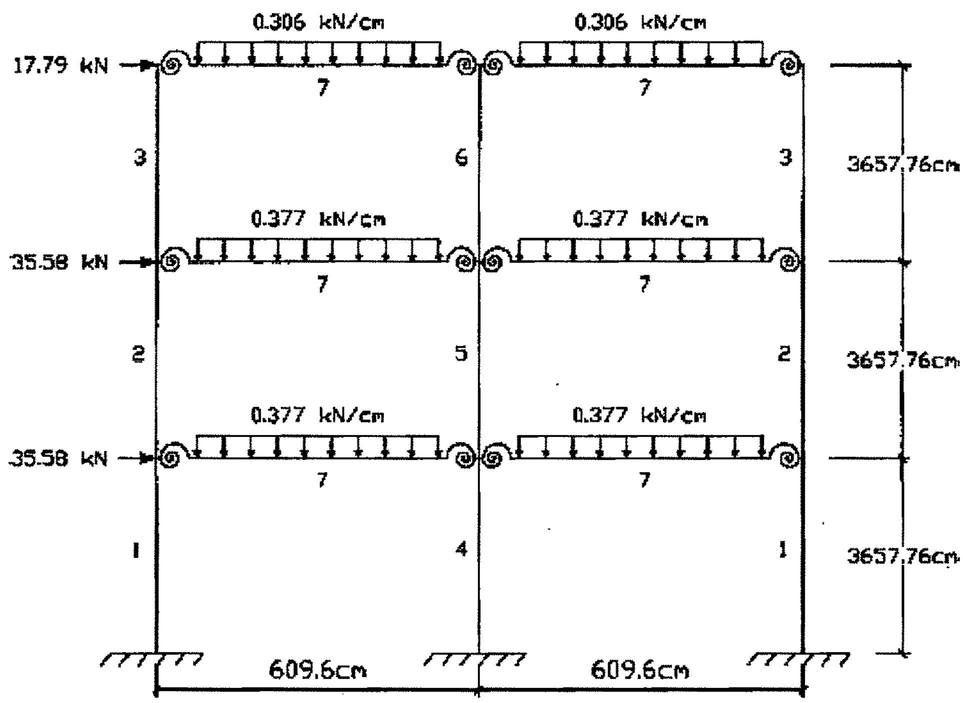

Fig. 3.7 Frame Considered with Semi Rigid Joints

Sekulovic et al. [52] in **2002**, developed equations for semi-rigid connection and performed experiments on multi-story steel frames using fully rigid connection and semi-rigid connection using top and seat double web angle. From the results, as shown in **Fig. 3.8** it was concluded that the viscous damping at connections may considerably reduce the displacement response and internal forces of the frame, particularly in the case of weak connection types. The influence of the geometric nonlinearity increases with the gravitational loads and the lateral frame deflections. It is higher in the frame with flexible connections than with rigid joints. The connections are vital structural components that are very often responsible for the behavior and safety of frame structures subjected to strong dynamic (seismic) loads. Connection design and modeling have a great importance, and therefore they recommended to use non-linear constitutive models for design and analysis.

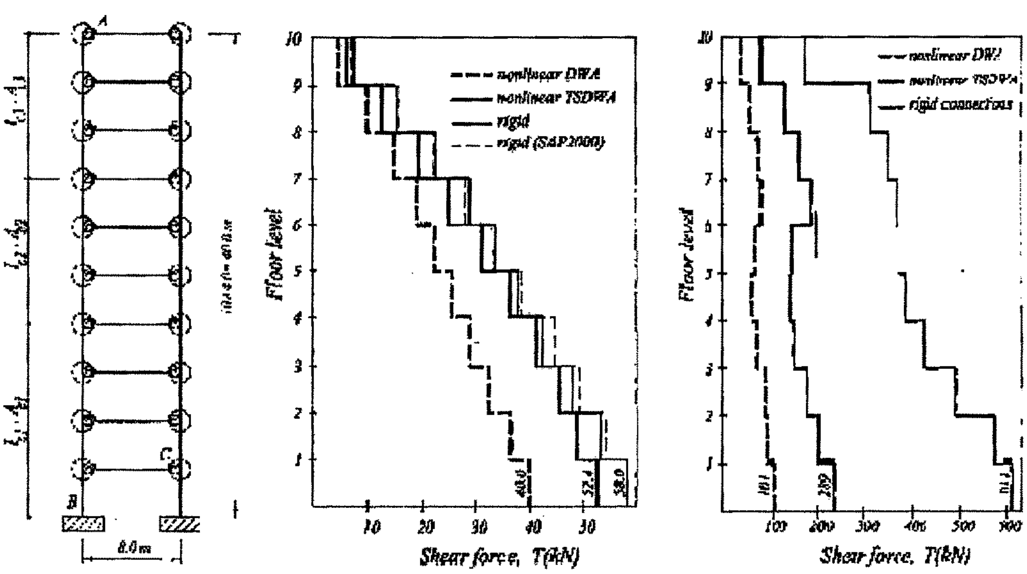

Fig. 3.8 Shear Force Envelops noted by Sekulovic et al

In **2002, Ahmad and Ahmed [53]** studied the effects of different type of semi-rigid connections in steel structures by introducing different combinations of bolts and angel sections and found that reduction of span moment ranges from 3.89 to 33%.

Akbas and Shen [54], in **2003**, concluded from an analytical study that performance of combined rigid and semi rigid frames might have high performance under a moderate intensity of earthquake and stiffness of this hybrid system is mainly contributed by rigid frames.

Using simplified formula, in **2003, Sophianopoulos [55]** introduced the joint flexibility in the boundary conditions of the L-shaped frame shown in **Fig. 3.9** for free vibration. Author found that within the elastic range and under certain combinations of parameters involved, a transition to higher vibration mode may occur. Recommendations for a consideration to the effect of joint stiffness and its specific rules on higher vibration modes are given.

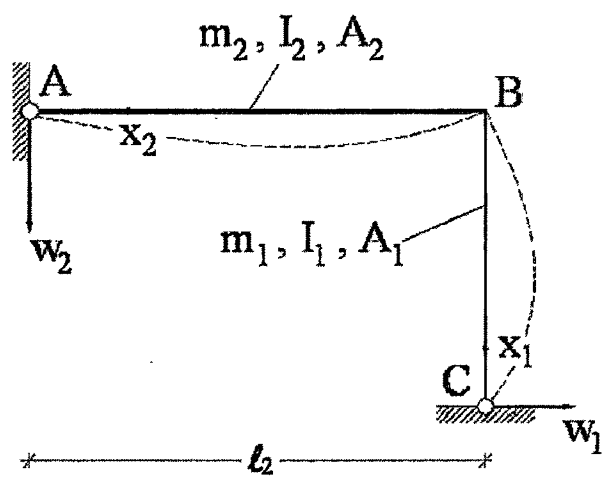

Fig. 3.9 L-shaped Frame Model

In **2003, Hadianfard and Razani [56]** studied the effects of semi-rigid behavior of connections in the reliability of steel frames. The actual behavior of beam to column connections in steel frames is seldom fully rigid or fully pinned. The true behavior of the connections is usually semi-rigid. Neglecting the real behavior of the connection in the analysis may lead to unrealistic predictions of the response and reliability of steel frames. This paper considers the effects of semi-rigid behavior of the connections in the finite element analysis and in the reliability analysis of steel frames. Assuming that the loads and the resistance of members are random variables, Monte Carlo simulation technique is used for the best estimation of the probability of failure of the frame system. Some examples are presented, which illustrate the importance of the effect of the semi-rigid behavior of the connections in the calculation of the overall reliability of the total system of the steel frames. The numerical examples indicate the importance of the assumption of semi-rigid behavior of connections in the analysis and evaluation of the probability of failure of the system of steel frames. A substantial difference has been found in the results of reliability analysis between the more realistic semi-rigid connections and the cases in which extreme assumptions of fully-rigid or fully pinned connections are used. Therefore, the more realistic semi-rigid behavior modeling of connections should be considered in the reliability analysis of steel-framed structures if more reliable results are desired.

In 2004, Langdon and Schleyer [57] proposed a generalized analytical model for examining the connection response. The model was applied to the problem of welded double angle connections, as used by the UK offshore industry. The results of an experimental investigation into failure progression was also presented, and used to generate the spring constant values. Response in two directions was examined for three different geometry configurations. The work highlights the importance of angle outstand with the hope that the proposed connection model will be incorporated into a beam-connection model capable of predicting the response of a beam with semi-rigid supports.

The study of the above papers related to the joint rigidity, shows that a lot of work has been done on identifying the role of rigidity of a joint in the overall performance of a structure. In case of seismic forces, the beam column joint stiffness is one of the key element which has attracted a number of researchers. The present study aims to study the effect of joint rigidity on the seismic performance of RC framed structures. The variation in joint rigidity is used to define some special types of frames called rigid frames, semi rigid frames and a combination of both resulting in a hybrid frame. The seismic performance is studied for all these types of frames by using the push over analysis technique.

3.3 BEHAVIOUR OF BEAM COLUMN JOINTS

In **1978, Paulay et al. [58]** examined the behavior of interior beam column joint in reinforced concrete frame in detail. The existence of two shear resisting mechanisms, one involving joint shear reinforcement and the other a linear concrete strut was postulated and the effects of reversed cyclic loading on these mechanisms, in both the elastic and inelastic range of response were discussed. They concluded that the diameter of beam bars passing through joint cores should not be excessive if slip of bars is to be avoided. In design, slip can be avoided by limiting the beam bar diameter to a certain proportion of the column depth or limiting the average bond stress on the beam bars.

In **1991, Taucer et al. [59]** proposed a reliable and computationally efficient beam-column finite element model for the analysis of RC members under cyclic loading conditions that induce biaxial bending and axial force. Correlation studies between the experimental response of several RC elements and the analytical results showed the ability of the proposed model to describe the hysteretic behavior of RC members.

In **1995, Stone et al. [60]** reported the test results of 10 hybrid precast concrete beam-to-column connections conducted on one third scale models at National Institute of Standards and Technology (NIST). The hybrid connection consisted of mild steel which was used to dissipate energy and post-tensioning (PT) steel which was used to provide the required shear resistance. It was concluded that the hybrid system is self-centering and displays essentially no residual drift. Moreover, this system can undergo load cycles to 6% drift while maintaining 55% of it's maximum strength.

Malaska [61], in **2000,** observed that the flooring system with it's connection to the supporting column significantly influences the performance of the joint. A slim floor beam connected to a tubular steel column section filled with concrete was designed using the semi-continuous concept. A mathematical model for predicting the moment-rotation characteristics of the joint response was formulated based on the geometrical and mechanical joint properties and findings from the empirical study. In the model formulation the basic mechanism of force transfer within the components of a composite connection was applied. Derived from the model and validated by the experimental results simple and robust methods that can be used by the designers were proposed.

In **2003, Rahman et al. [62]** developed a viable 3D nonlinear FE model to study the response and to predict and validate the experimental results for a 1/3 scale model of a prototype precast concrete building subjected to cyclic inelastic loads. The beam-column connection was constructed by post-tensioning the beams to the columns using high strength post-tensioned strands designed to remain in the elastic range, which gives the joint its strength to act as a restoring force. The mild steel bars served as an energy dissipater by yielding in tension and compression under cyclic loading and thus function inelastically. The model consisted of a total of 29,084 solid elements. Four types of elements were used including solid elements, contact elements, and pre-tensioning elements. Transient analysis was carried out to determine the connection response when subjected to cyclic inelastic loads simulating earthquakes ground excitation. Post-tensioning force, concentrated loads, and the inelastic loading history were applied. The results from the finite element model predicted the yielding of the mild steel bars, determined opening magnitude in the gap at the joint, monitored the forces in the PT strands, and displayed cracking contours and locations in concrete. The hysteresis plots were also obtained from the FE model. Successful modeling of this connection using 3D FE provided a practical alternative solution to optimize the joints' material and geometry for an optimum energy absorption and minimum damage in such structures.

In **2006, Rahman et al. [63]** stated that the connections between precast concrete components play an important role in determining the success of precast concrete framed structures. In particular, the connection between beam-to-column was assessed by conducting experimental tests which comprised a total of four specimens, which were limited to simple beam-to-column connections in precast concrete frames. The behaviour of load-displacement relationships, moment-rotation relationships and types of failure in connections were also investigated. Moreover, the development of safe, economical, simple and ductile precast beam-to-column connections conforming to building code requirements was proposed. It was concluded that a simple beam to column connections with single dowel and grouted should be considered as pinned connection and lateral stability should be achieved by a bracing system in case of precast concrete construction.

In 2006, Tazeen and Islam [64] proposed a mathematical model for analyzing multistoried building frames incorporating semi-rigid beam-column connections. The effect of the semi rigid joint on the internal distribution of forces, lateral drift, joint rotation, etc. was studied. It was concluded that plate thickness has significant influence on the moment carrying capacity of connection and in controlling sway of the frame. Incorporation of the stiffener in a connection has a significant impact on moment carrying capacity and controlling sway. Thus, increasing stiffener in number and size, the moment and sway can be controlled within acceptable limits.

In **2008, Wijanto and Andriono [65]** have reported that the special connection details are required to ensure full continuity and monolithic action in case of precast/prestressed concrete building systems which is becoming popular throughout the world and particularly in Indonesia. The latest development of research works of the equivalent monolithic systems and their applications in some building projects to ensure safety, economy and workability of the most suitable joint system has been presented. The paper discusses some of the recommended connection systems in light of fulfilling the seismic design requirements.

The above available research papers clearly indicates that the beam column joint must be properly modeled to capture the seismic response in case of framed structures.

3.4 POST TENSIONED SLABS AND BEAMS

The book published in **1995** by **Khan and Williams** titled **Post Tension Concrete Floors [66]** deals with the design of concrete building structures incorporating post-tensioned floors. It gives a detailed, non-mathematical account of the principles of pre-stressing, the materials and equipment used, and the planning of buildings incorporating post-tensioned floor. Post-tensioning is the most versatile form of pre-stressing, a technique which enables engineers to make the most effective use of the material properties of concrete, and so to design structural elements which are strong, slender and efficient. Design in post-tensioned concrete is not difficult and, if done properly, can contribute significantly to the economy and the aesthetic qualities of a building. As a result, post-tensioned floors have found widespread use in office buildings and car park structures, and are also frequently employed in warehouses and public buildings. However, in spite of this, most pre-stressed concrete texts have paid comparatively little attention to floors, concentrating instead on beam elements.

In **2004**, **Degertekin and Hayalioglu [67]** presented an analysis and design method for steel frames with semi-rigid connections and semi-rigid column bases. The analysis takes into account both the non-linear behavior of beam-to-column connections and P-Δ effects of beam-column members. The Frye and Morris polynomial model is used for modeling of semi-rigid connections. The members are designed according to the specifications of American Institute of Steel Construction (AISC) Allowable Stress Design (ASD). The design process is interactive, and gives choices to the designer, to change member cross-sections and connection parameters for economical and practical reasons, interacting with computer. Two design examples with various type of connections are presented to demonstrate the efficiency of the method. The semi-rigid connection modeling yields more economical solutions than the rigid connection modeling. The semi-rigid column base modeling also results in lighter frames. It is also shown that changes in the stiffness of the connections may result in economical solution and alteration in the sways.

In **2005**, **Pampanin [68]** observed that in the last decade, major advances have taken place in seismic engineering with refinement of performance based seismic design philosophy and definition of corresponding compliance criteria with an aim to provide a modern society with high seismic performance structures, able to sustain a design level earthquake with limited or negligible damage, with cost effective seismic resisting systems, based on adequate combination of traditional materials and available technology. The paper gives an overview of recent developments and on-going research on precast concrete buildings with jointed ductile connections, relying on the use of unbonded post tensioned tendons with self centering capabilities. Examples of existing on site application based on a recently developed cable-stayed and suspended solution for frame systems are provided as further confirmation of the easy constructability and speed of construction. Two Brooklyn systems were adopted for effective seismic resistance i.e. a) cable stayed system and b) suspended system.

In the year **2006, Boonyapinyo et al. [69]** carried out the seismic evaluation of post-tensioned concrete slab-column frame buildings designed for gravity and wind loads only. Numerical examples of 9 and 30-storey post-tension flat-plate buildings were included in the study. The results showed that in general post-tensioned concrete slab-column frame buildings without shear wall possess relatively low lateral stiffness, low lateral strength capacity, and poor inelastic response characteristics. The evaluation also indicated that the slab-column frame combined with the shear wall system and drop panel can increase the strength and stiffness significantly.

In **2006, Ahuja and Ahuja [70]** suggested that the design and construction of PT flat slabs requires significant improvement in India. Indian Codes of practice also need to be upgraded keeping in line with the state-of-the-art, some of which have been highlighted in the paper. A design methodology for PT flat slab design has been proposed for the Indian environment based on current state of practice. They also emphasized that punching shear failure should be avoided at all costs and measures should be built in to prevent progressive collapse. Also, design of PT flat slabs should be brought into the ambit of the structural design consultant and not stay with the contractor.

Some of the main points highlighted in the paper are as follows:

1. An independent lateral force resisting system (such as shear walls) should be provided for PT flat slab structures. For low seismic areas only, column and flat slabs, when designed as per rules of "Intermediate Frames", may be used to resist seismic forces—though the authors do not recommend this option.
2. A design methodology has been proposed that requires different levels of response reduction for various elements depending on conformance with detailing and consequently their level of ductility.
3. Minimum bottom steel should be provided in slab-column connection to prevent sudden collapse.
4. Separation between shear resisting elements and PT slab should be ensured prior to PT operation so as to avoid loss of stress in the shear resisting elements.
5. Some PT tendons should run through the column cage in both directions for better seismic performance.
6. It is important to check long term cracked deflections in PT flat slab to avoid functional failures (service limit state).

In **2007**, **Ozden and Ertas [71]** reported results of an experimental work on post tensioned precast concrete beam-column joint. This paper presents the results of tests performed on PT, precast concrete moment-resisting, beam-column connections containing different mild steel reinforcement contents. Five hybrid connections were tested under displacement-controlled reversed cyclic loading. The main variable was the mild steel's percentage of contribution to the flexural capacity of the connection, ranging from 0% to 65% of the connection's moment capacity. Each hybrid connection was compared with the test result of the reference monolithic subassembly in terms of connection strength, stiffness degradation, energy dissipation and permanent displacement. The objective was to determine the effect of mild steel reinforcement content on the behavior and performance of post-tensioned, precast concrete hybrid connections. The response of post-tensioned, precast concrete hybrid connections approached that of the monolithic subassembly as the mild steel reinforcement content increased. Connection capacities were well predicted by the joint gap-opening approach. The design assumptions of hybrid connections were found to best satisfy with a 30% mild steel reinforcement contribution.

In the year **2008, Prawatwong, Tandian** and **Warnitchai [72]** presented the findings on the seismic performance of two three-fifth scale post-tensioned (PT) interior slab-column connection models with and without drop panels. A conventional displacement controlled cyclic loading routine with monotonically increasing drift levels until failure was adopted to investigate the seismic performance of the models. The experimental results presented by the authors indicate that the models behaved like a linear elastic system with low energy dissipation without pinching in hysteretic loops. The model with drop panel showed considerably more drift capacity and ductility than the one without drop panel.

Thus, the above literature related to post tensioned slabs and beams gives an indication that there is a strong need to evaluate the seismic performance of PT structures especially in the absence of conventional frames or shear walls. The study undertaken in the present work focuses on the most sensitive issue of the performance of RC framed structures under seismic forces with PT beams and a combination of PT and conventional beams.

3.5 OUTCOME OF THE LITERATURE SURVEY

The literature survey carried out in the present work clearly indicates that the pushover analysis is one of the powerful tools for predicting the performance of a building under seismic forces. It is also evident that the post tensioned concrete structures are gaining popularity now a days. The seismic performance of PT buildings has always been an area of interest for structural engineers. Hence, it will be worthwhile to take up a study of RC framed structures having PT beams in combination with normal RC beams and subject them to pushover analysis. The joint rigidity is again one area of interest as the literature available always points at the seismic sensitivity of a building frame subjected to earthquake forces. The study of RC frames having varying degree of joint rigidity from pinned to fixed is proposed and the performance of the same under pushover analysis is one of the areas of interest. Moreover, it has become evident from the literature that changing the rigidity of the beam column joint will definitely affect the performance of a structure. Based on these facts, the numerical model development and analysis under pushover analysis is planned in the present work.