CHAPTER - I

INTRODUCTION

1.1 GENERAL

The task of designing multistoreyed frames to resist lateral loads such as wind forces and earthquake forces has come under close scrutiny during recent times. In the current design practice the floor slabs are assumed to be perfectly rigid in their own planes. There are many empirical formulae defined by different codes of practice as indicated in the references 2, 7, 9 and 14 to arrive at the effective width of slab actively taking part in resisting the vertical loads acting in the direction of gravity along with the beam. These empirical formulae do not represent the actual condition while resisting lateral loads. The actual extent of participation of the slab while resisting lateral loads requires careful consideration.

A study of the recommendations of different codes, adopted in various countries reveals that there is no separate provision for computing the effective width of the slab applicable to T beams while resisting external lateral loads acting normal to the direction of gravity. While resisting vertical loads in normal T beams the slab portion at the centre is subjected to compression whereas the slab at either end of the beam is subjected to tension. However, the ends of the beam are subjected to the same moment while it is resisting lateral loads, causing tension in the slab at one end of the beam and compression in the slab at the other end of the beam. This type of variation for the moment is not considered for the evaluation of effective width of the slab for computing the load carrying capacity.

In the seismic design of structures one of the fundamental concepts underlying the capacity design philosophy (Armstrong 1972) is that failure mechanism in a structure can be controlled by appropriately combining the member strengths. For framed structures in seismically active regions, a form of
capacity design known as "Strong Column Weak Girder" design philosophy (Park and Paulay 1987) is generally followed. According to this philosophy, the member strengths are selected so that the strength of the structure is limited to the extent of beam flexural strength. For capacity design to be successful the designer should be able to assess the member strengths, under different combinations of loads. However, where the beam is cast monolithically with slab, the beam strength cannot be reliably computed, because when the beam bends due to lateral loads, at the end which is subjected to compression, concrete in the slab contributes to additional strength and at the other end, the tension reinforcement in the slab contributes to additional strength. However, as the amount of contribution cannot be reasonably estimated, it is possible that the beams will be stronger than columns and the strong column - weak girder design may not be achieved. Hence there is a likelihood of the hinge getting formed in the column before it forms in the beam which may result in permanent sway and could jeopardize the stability of the structure. Hence there is a need to find the effective width of slab and the contribution of the slab to the strength of the beam when the structure is subjected to earthquake type lateral loads.

1.2 REVIEW OF LITERATURE

Experience from the past earthquakes has shown (Sozen 1968) that beam to column connections play a critical role in the survival of reinforced concrete moment resisting frame buildings. Vitelmo V. Bertero and George McClure (1964) conducted tests on model frames with static reverse cyclic loading to assess the bond strength around the critical section and to study stiffness variation of frames under repeated alternating over load cycles. Recognising the importance of the behaviour of the connections, Hanson and Conner (1967) conducted tests on reinforced concrete beam to column connections as early as in 1960 which has been used extensively for later studies. The ACI-ASCE committee 352 (1976) has developed recommendation for the design of beam to column connections subjected to an earthquake type of loading. These recommendations are made for the determination of joint size and for the selection and placement
of longitudinal and transverse reinforcements to satisfy the strength and ductility requirements related to the function of the joints. Among them, it is mentioned clearly, that for a framed structure with a monolithically cast slab at the joint, the effect of slab may be ignored in the design of the joint.

The studies by Khan (1971) on the elastic behaviour in a slab-frame system to investigate composite action between beam and slab conclude that there is an overall reduction of the slab deflections due to full integral beam-slab action. For lateral loading the column moments due to full integral beam-slab action are higher than the corresponding moment for bare frames by as much as 6% to 10%. An attempt was made to arrive at the effective width of slab integrally acting with the beam.

Masayoshi Nakashima et al. (1982) have conducted experiments on scale models of a portion of the floor system to examine the inplane behaviour of reinforced concrete beam supported slabs as diaphragms in building structures and their response to seismic forces. The inplane strength of the slab panel is found to be controlled by the development of a major crack parallel to the loading and along the boundaries between the column and middle strips. It is found that cyclic loading has decreased the ultimate load carrying capacity of the system by 15% to 25% and the presence of gravity load has reduced the ultimate inplane resistance by about 15%. The inplane stiffness continuously decreased as the load increased. The panels monotonically loaded without vertical load showed an essentially plastic behaviour after reaching the ultimate load.

Vijaya Rangan and Hall (1983) studied the moment and shear transfer between the slab and edge column in actual building frames. The study was conducted for uniformly applied vertical loads only, the approach used being the beam analogy method for analysis in which the slab was idealised as beams running into the columns in two directions and the strength of the connection was determined by summing up the flexural, torsional and shear strengths of these equivalent beams. The conclusions of this study are that the beneficial effect of the
restraint offered by the floor slabs against the longitudinal expansion of the 
spandrel strip enhances the torsional strength and thereby contributes to the 
stiffness of the assembly. It has also been concluded that any tests in which the 
spandrel is free to expand will result in an unrealistically low value for the 
punching shear strength.

Denby G. Morison et al. (1983) tested the response of the interior 
reinforced concrete slab column connection in a laterally loaded structure by 
subjecting it to both static and dynamic loading. The study dealt with some 
experimental variables and included the effect of percentage of reinforcement in 
the slab. The reinforcement layout was isotropic. Dynamically tested specimens 
provided data on the strength, stiffness and energy dissipation characteristics of 
laterally loaded structures. In both statically and dynamically loaded specimens the 
higher the slab reinforcement percentage, the lower was the ratio of the moment 
developed by the slab to the full yield moment capacity of the slab with respect 
to statically determined strength. The effective slab width ranged from 100% 
(at $\rho = 0.0065$) to 60% (at $\rho = 0.013$) of the full width of the slab where $\rho$ is the 
reinforcement percentage. It was concluded that the analytical model indicated 
that within connections rotations in the range of practical interest (less than 0.03), 
the strength of the tested connections was primarily a function of the stiffness of 
the slab and would therefore be sensitive to all parameters influencing cracking 
such as concrete tensile strength, time - and temperature - dependant effects and 
previous or simultaneous loading in different directions.

Ehsani and Wight (1985) tested six exterior beam to column sub-
assemblages with and without transverse beams and slab and compared their 
behaviour. The parameters investigated included the flexural strength ratio 
(defined as the sum of the flexural capacities of the columns to that of the beams), 
the percentage of transverse reinforcement used within the joint and the shear 
stress in the joint. In the case of the specimen where flexural strength ratio is 1 or 
less, hinge is formed in the column. The flexural strength ratio is reduced 
significantly due to the contribution of the slab longitudinal reinforcement. It is
recommended that, to ensure flexural hinging in the beam the flexural strength ratio should be not less than 1.2. Furthermore, when calculating flexural strength ratio, the slab longitudinal steel in a region of at least equal to the width of the beam on each side of the main beam must be considered effective. However, it is mentioned that the effective width of slab in tension is not well defined and it is recommended that a more detailed study of the problem has to be made. It is found that the transverse beams are subjected to a combination of bending and torsional loading and the confinement of a joint in the specimen with transverse beams and slab improved significantly over a similar specimen without transverse beams or slab.

Durrani and Zerbe (1987) tested six exterior beam to column sub-assemblages, one without transverse beam, one with transverse beam and four with transverse beam and slab. As the columns were designed to be stronger than the beams, the flexural hinges formed in the beams in all specimens. It was found that the specimen with slab showed a higher strength than the specimen without slab in both the gravity loading and negative loading directions. The strength increase is smaller in positive loading direction than the strength increase in the negative loading direction for simulating the lateral cyclic loading. The stiffness of the specimen with slab is 60-70% higher than the specimen without the slab. It is also found that the loss of stiffness in specimens with a slab is gradual and is not affected significantly by different slab widths. Also the specimens with a slab dissipated approximately 40% more energy than the specimen without the slab. It is recommended that the reinforcement in certain width of slab is found to be most effective in resisting bending of the main beams and connections, when transverse beams reached their torsional cracking strength. This width can be taken equal to the column width plus twice the depth of transverse beam. It is also found that the transverse beams are effective in confining the joint before experiencing torsional cracks and once the transverse beams reached their torsional strength their ability to confine the joint diminished.
Pantazopoulou et al. (1988) proposed a simple analytical model to assess the participation of slabs in the flexural behaviour of beams (with the slab in tension) at beam-column connections. In the model, the slab was assumed to act as a membrane element attached between the longitudinal beam and rigid transverse beams. According to the model, slab strains vary in the transverse direction according to a simple formulation. Based on the computed distribution of slab strains, expressions for effective slab widths were derived. These are suitable for conventional elastic or elastoplastic analysis made with the assumption that plane sections remain plane. Parameters of behaviour computed using the analytical model correlated well with measured values. Based on the experimental data, the slab was found to contribute significantly to the negative moment of resistance of beams. It is recommended that the effective slab width on either side of the beam are taken in the order of 1.5 times of the beam depth for elastic analysis upto yielding, increasing to approximately three times of the beam depth for computing post-yield deformations expected during severe earthquake loading.

Ammerman and Catherine (1989) studied the behaviour of connection in R.C. beam column slab sub-assemblages subjected to lateral loads. It was found that when the slab was in tension, the tensile strains measured in the longitudinal slab bars decreased with the distance from the column face, in the slab. Some of the factors that affect the effective width of slab, which acts as a flange to longitudinal beam, are; the torsional stiffness of the transverse beam, shear deformation of the slab, and the rigid body rotation of the slab. The ultimate capacity of a monolithic longitudinal beam/slab element may approach that of a T-beam with the entire slab width participating as an effective flange of the beam. It is suggested that the possibility of a full slab width participation should atleast be considered in designing structures which may undergo earthquake damage especially in the case of structures with torsionally stiff transverse members.

Zerbe and Durrani (1989) studied the behaviour of beam - column connections under earthquake type loading by testing indeterminate frame sub-assemblies. The specimen chosen for testing, was a two bay substitute frame with
beams and columns alone. Any restriction to the elongation of main beams and the accompanying axial compression were observed to affect the response of connections. It was reported that it increased the joint shear in both interior and exterior connection and reduced the column to beam flexural strength ratio. The energy dissipation was reported to have not been affected. But the lateral load resistance was reported to have increased significantly. A procedure to account for the presence of axial compression in the main beams in the design of beam-to-column connections was presented based on the observed mechanism of lateral load resistance and the observed behaviour of connections.

Pantazopoulou and Moehle (1990) proposed, an equivalent three dimensional frame - truss structures for analytical model of a reinforced concrete beam-column connection with slab connected monolithically to the supporting beams. The model incorporates elements to account for flexural and torsional action of transverse beams and membrane action of the slab that monolithically connects the longitudinal and transverse beams. The model is best suited for exterior connections subjected to negative moment (slab in tension), where the action of slab in stiffening the longitudinal beam is limited by deformations of the transverse beam. The proposed analytical model is used in a discretised form for analysing the frame with an existing computer program capable of accounting non-linear behaviour. Experimentally observed behaviour of an exterior connection tested in the laboratory was studied using the above mathematical model. Notably, the computed results closely match measured stiffness, strengths and distribution of strains in the slab perpendicular to the longitudinal beam. Therefore it was recommended that the in-plane flexural and torsional deformations of the transverse beam were observed to reduce the contribution of slab to the flexural action of the beam.

Shahrooz and Moehle (1990) from experiments conducted on a quarter scale model of a moment - resisting reinforced concrete frame, evaluated the seismic performance of R.C. frames. The model was subjected to a series of uniaxial horizontal base motions resulting in progressively increasing response
levels. The contribution of the floor slab to the negative moment strength was considered as one of the significant sources of over strength. The floor slab effectively doubled the beam negative moment strength. Consequently the shear force acting on the beams was increased by 55% over the design shear force. It was felt that an estimate of the floor slab contribution is indispensable to model beam flexural behaviour of T beam accurately, and thereby ensures safe beam and column design to resist earthquake forces. It was suggested that the effective flange width acting on each side of a beam was approximately 1.5 times the beam depth for interior beam column connections and the beam depth for exterior beam column connection. The contribution of the slab had approximately doubled the beam flexural strength when compared with the frame without slab.

Fariborz Barzegar et al. (1991) conducted three-dimensional elastic finite element analysis of isolated edge connections in multistoreyed structures subjected to lateral loads. The floor slabs and columns were simulated using 20-noded solid isoparametric elements. The parameters studied were the slab aspect ratio (transverse span to longitudinal span of the slab), and the square column dimension within practical ranges. The transfer mechanism of unbalanced moments from the columns to the slabs was investigated using the three dimensional stress distribution at the column - slab interfaces. Based on the results of three dimensional finite element analyses, a simple one dimensional beam model was developed to evaluate the slab effective width of edge connections for lateral load analysis.

Stavroula Pantazopoulou and John Bonacci (1992) investigated the mechanics of beam - column joints in laterally loaded frame structures. Formulations presented established the compatibility of strains and the equilibrium of stress. Here the slab was not considered. Factors known to affect the behaviour of connections including the effect of lateral restraint as well as the reduction of concrete strength associated with diagonal tensile strain were considered. The role of stirrups and axial loads (on beams and columns) on the behaviour of joint were illustrated clearly.
The investigations carried out by various authors and the parameters investigated by them are summarised and presented in Table 1.1.

1.3 CRITICAL COMMENTS ON THE LITERATURE REVIEW

The above studies reveal that the investigations relating to the contribution of slab reinforcement for both positive and negative flexural capacities of beam, in the beam column sub-assemblages, are important for correctly modeling its structural behaviour. The studies give some quantitative information on the part played by the slab in resisting the lateral loads of a frame. They are not conclusive. However, they are limited to individual elements in which the elements are free to elongate when subjected to large deformation reversals. In a real situation the beams are partially restrained against such elongations. Any restriction to the elongation of the main beams, and accompanying axial compression will affect the response of the frame. It alters the beam to column flexural strength ratio and affects the lateral load resistance significantly. The loss of stiffness in the indeterminate assembly is likely to be gradual, compared to that observed in individual connection assemblies. In the tests on individual assemblages, slabs are free to elongate which is not so in the actual condition. The prevention of rotation of the slabs imparts torsional moments on the transverse beams. The transverse beams in the sub-assemblages are free to rotate which is not so in the actual conditions.

1.4 SCOPE OF INVESTIGATION

The following investigations are proposed in the present study.

1.4.1 Parametric Study on the Influence of Slab in Plane Frames

Two analyses of a seven storey single bay plane frame subjected to lateral loads are carried out by considering the beam section as specified in ACI-ASCE recommendations [1] by ignoring the presence of flange and by considering
Table 1.1  Summary of Literature Survey

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<th>Sl.No.</th>
<th>Studies Relating to</th>
<th>Name of Researchers</th>
<th>Ref No. in the Thesis</th>
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<tbody>
<tr>
<td>1.</td>
<td>Single bay frame subjected to lateral load without slab (E)</td>
<td>Viterlmo V.Bertero and George Meclure (1964)</td>
<td>[25]</td>
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<td></td>
<td></td>
<td>Denby G.Morrison, IkuoHirasur, and Mete A.Sozen (1983)</td>
<td>[8]</td>
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<td>Ahmad J.Durrani and Hikmat E.Zerbe (1987)</td>
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<td>Olga Velez Ammerman and Catherine Wolfgram French (1989)</td>
<td>[17]</td>
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<td>Rangan B.J. (1990)</td>
<td>[21]</td>
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<td>4.</td>
<td>Experimental Studies on Frame Models (E)</td>
<td>Bahram M.Shabrooz and Jack P.Mochle</td>
<td>[5]</td>
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<td>Pantazopoulou S.J., Mochle J.P. and Shabrooz B.M. (1988)</td>
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<td>Stavroufla Pantazopoulou and John Bonacci (1992)</td>
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E - Experimental Work  A - Analytical Work
the flange as per IS:456-1978 [14] recommended for gravity loads in the absence of specific recommendations for lateral loads. These analyses are repeated for different spans of beams keeping the height of columns as constant to assess how sensitive the variations in moments between beam and column at various joints are, when the ratio between the span of beam to column height varies.

Aim of these analyses, is to study how the moments and shears are shared by the columns and beams when the beam is considered as rectangular or as 'T' section.

1.4.2 Testing of element Models idealised as 2D models

Keeping in mind, the important parameters which affect the performance of an indeterminate subassemblages which consist of the columns, longitudinal beam, transverse beam and the floor slab for one storey height (a typical substitute floor system) the following test programme has been undertaken.

Element model tests representing the typical beam element generally consisting of a beam proper and a slab which is referred to as a T beam have been conducted. Though the stiffness of the beam could be reasonably predicted, when it is cast monolithic with the slabs the variation of stiffness under lateral load on frame causes degradation of stiffness and the contribution of the slab is not well known or documented. To investigate this aspect beam elements with and without slabs are tested with the same type of load as the beam element would experience during lateral loading on a plane frame. The stiffness obtained in this investigation is intended for use in a two dimensional analysis for realistically representing the influence of slab. Therefore this model is termed in this thesis as 2D model.

The aim of this investigation is to assess the effect of slab portion along the length of the beam that takes part in the contribution of strength and stiffness of the beam.
1.4.3 Testing of 3D Single Bay substitute Frame Floor system models

In the light of observations made based on the literature survey regarding the drawbacks of subassemblies allowing free rotation and expansion of slab, the second series of tests are proposed on models to investigate the behaviour of the real three dimensional substitute frame floor system subjected to lateral load. The tests on these models in this thesis is referred to as 3D model tests. The behaviour of the floor system is also investigated through a finite element 3D analysis incorporating both the beam and the slab elements.

The aim of this investigation is to assess the contribution from the slab with longitudinal and transverse beams to the stiffness and strength of frame and to validate the theoretical analyses.