ESTIMATION OF EFFECTIVE SLAB STRIP WIDTH OF RC FLOOR SYSTEMS FOR PLANE FRAME IDEALIZATION

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The thesis titled "Estimation of Effective Slab Strip Width of RC Floor Systems for Plane Frame Idealization" Submitted by: Mohammad Moinul Islam, Roll No: 040004308P, Session: April/2000; has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science in Civil Engineering (Structural) on 25th February, 2007.

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Declaration

Declared that, except where specified by reference to other works are made, the studies embodied in this thesis is the result of investigation carried out by the author. Neither the thesis nor any part has been submitted to or is being submitted elsewhere for the purpose of any other degree.

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Abstract

There are two distinct methods (Direct Design Method and Equivalent Frame Method) of plane frame idealization for the analysis of RC frame buildings for vertical loads but there is a lack of well-guided code for plane frame idealization for lateral load analysis. In 2D plane frame analysis, an appropriate width of the floor panel needs to be selected, which is structurally representative of the actual 3D frame. The ratio of the width of this slab strip to the total panel width is known as effective slab strip ratio. In this work, an investigation is performed to study the effects of various parameters related to framed RC floor systems such as column dimensions, bay width, span length, slab thickness, number of floor, floor height etc, on the effective width of slab strip.

To carry out the investigation, both 2D and 3D frames with floor systems were modeled using finite elements. In 3D model, the slab is modeled using shell elements, columns are modeled using solid elements and beams are modeled using frame elements. In 2D model, both columns and beams are modeled using frame elements. Applying a set of lateral load on the 3D frame, lateral deflection was computed. Then applying the same lateral load on the 2D frame having same column properties and at the same time adjusting the moment of inertia of the beams, the deflections are matched as closely as possible. When deflections are matched, the moment of inertia of the beam of 2D model corresponds to the inertia of the structurally active part of the floor slab system of 3D model. Since slab thickness is known, the width can be calculated from the inertia. The process is a simple trial and error method. The whole process is carried out under various parametric conditions.

It has been found that some parameters like slab thickness, number of span, number of floors, floor height and column dimension along bay have no effect on the effective slab strip width for the flat plate structure. On the other hand, span length, bay width and column dimension along span have been found to have significant effects on effective slab strip ratio for the flat plate structures. Similarly, number of span, number of floor, floor height and column dimension along bay have no effect on the effective slab strip ratio for slab having column line beam. Whereas, slab thickness, span length, bay width, column dimension along span and beam depth have been found to have significant effects on effective slab strip width for slab having column line beam.

Based on the study on both flat plate structure and slab with column line beams, two empirical equations have been developed to estimate the width of structurally effective part of the slab. The accuracy of the proposed equations have been demonstrated by determining the effective width for several examples with arbitrarily chosen parameters within the applicable range and comparing the result with those obtained from FE analysis. It has been shown that the suggested equations predict the effective width with acceptable accuracy.

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Either the direct design method or the equivalent frame method may be used for plane frame idealization and analysis of two-way slab systems for gravity loads, according to ACI Code 318. However, the ACI Code provisions are not meant to apply to the analysis of buildings subject to lateral loads, such as, loads caused by wind or earthquake (Nilson et. al. 2003. Plane frame analysis, with the building assumed to consist of parallel frames each bounded laterally by the panel centerlines on either side of the column lines, has often been used in analyzing unbraced buildings for horizontal loads, as well as vertical.

The slab of the flat plate floor, in this approach, is treated just like an ordinary beam, as in a moment resisting frame and can be modeled easily in any elastic frame analysis program. Although physically no beam is not exists between the columns, for analytical purposes it is convenient to consider a certain width of slab behaving as a beam between the columns when the lateral loads are considered. The ratio of the considered certain width of the slab to the actual width of slab panel is known as effective slab strip ratio, α.There are, however, no guidelines in codes available to assist the designer in making such a decision. Because of the complexity of the moment-transfer mechanism between the slab and the column under lateral loading, the assumptions regarding the effective slab width and its stiffness have been very subjective. Simplifying assumptions are not questioned as long as they result in a safe design. However, these assumptions can give a misleading prediction of the building response. There are still significant scopes to investigate this matter in order to assist the design engineer with some definite guideline to estimate the effective slab strip ratio.

1.2 BACKGROUND

Although there are still no code provisions on effective width of slab, many researchers in the past attempted to formulate guideline on this matter. A few of those are described below.

Pecknold (1975) proposed a simple expression and different curves based on slab aspect ratios and square column size/slab length ratios for finding effective width of a typical interior panel. His analysis was based on elastic plate theory.

Fraser (1983) made a long term and extensive investigation into the structural behavior of concrete floor system. A large number of floors were analyzed by assigning various values for all the parameters, span, aspect ratio, slab thickness, beam and column dimension. In his parametric study based on finite element analysis, he proposed few empirical equations for determination of the effective beam stiffness.

Smith and Coull (1991) suggested curves of bay/span ratios for different values of column size to find out α for flat plate structures. However, it is suggested that the stiffness calculated by using this effective slab strip ratio should be reduced to 50% in the analysis due to cracking as the slab bends.

Luo et al. (1994) studied the response of flat plate buildings and made an extensive experimental investigation on plate column sub assemblages and proposed an effective slab width concept to be used for hysteretic static analysis to represent earthquake type loadings. Based on the findings of the experimental results, they proposed some constant factors to be used in their hysteretic model.

Luo and Durrani (1995) proposed an equivalent beam model for flat slab building based on experiments of 40 interior and 41 exterior connections. They determined the effective slab width using Pecknold's (1975) method and compared it with experimental results. Based on the comparison, they suggested simpler formula for effective slab strip ratio (α) in terms of the sides of the rectangular column sections and spans.

Grossman (1997) evaluated 3 methodologies for determining effective slab strip ratio (α) and introduced a factor K_d to count the stiffness degradation caused by increased loading and proposed equations for finding α.

Later Islam (2003), by means of computational finite element investigation, studied a number of parameter and panel aspect ratio to find out any appreciable effect upon effective slab strip ratio for flat plate and slab with column line beam structures. In that study columns were modeled using common frame elements and no effect of column size on α was noticed. Thus the finding of Islam (2003) contradicted with the earlier findings by other researchers.

From the discussion made above it can be said that number of researchers has addressed the problem of determining effective slab width of flat plate structures in the past.

1.3 RESEARCH SIGNIFICANCE

Now a days, powerful digital computers are available with sophisticated 3D finite element packages. Using such a software, we can easily develop a full 3D model of a flat plate (or slab) floor system, apply the loads, analyse and design reinforcement based on results of analysis. Thus the question may arise, why do we need 2D plane frame idealization? Despite the ease of modeling and analysis of full 3D structure, the necessities and importance of plane frame idealization has not yet been diminished as discussed below.

Firstly, plane frame idealization using equivalent beam approach enable us to develop an idea about the structural behaviour of flat plate floor system subjected to lateral load. By determining the equivalent beam we can develop an insight about the part of the slab that is effective as a flexural member and taking part in resisting the lateral load. This may be especially useful in construction of banded slab system where the part of the slab effective as beam may be thickened for extra strength. Alternatively, by knowing the effective width we may provide reinforcement accordingly in banded fashion. Although such procedure is possible on the basis of full 3D analysis and reading the slab (shell) stress or moments, it would be much easier for us to design reinforcement bands if we have a prior idea about effective width of the slab. This may be especially useful when bay width is large compare to span.

Secondly, equivalent beam approach is used by many researchers as a tool to model and study the behaviour of flat plate floor system. For example, Vainiunis, Popovis and Jarmolajev (2002) studied punching shear behaviour of RC flat plate floor slab to column connection based on computer modeling and analysis. In their research, they used plane frame idealization (Equivalent beam modeling) for analysis of flat plate floor system. Erberik and Elnashai (2003) made a detailed seismic vulnerability analysis of flat plate structures. They used Luo and Durrani's (1995) equivalent slab strip method to model 2D equivalent frames of flat plate floor systems. More recently Kang and Wallace (2005) studied dynamic response of flat plate system with shear reinforcement. They performed 2D plane frame idealization of flat plate system based on Pecknold's (1975) approach. The accuracy and reliability of these researches significantly depend on the accuracy in determining equivalent slab strip ratio. However due to difference in assumptions and simplifications different approaches give different value of equivalent slab strip ratio. Therefore there is still scope of further improving the methodologies for determining equivalent slab strip ratio.

Thirdly, when column line beam is present, apparently there is no straight forward way to determine the slab strip which takes into account all the structural parameters like span, column dimensions, bay width etc. ACI 318 does include a provision for determining the effective T beam section based on slab thickness or span. However it neglects the effect of other parameters mentioned above. Therefore, for column line beam structures also, further study may be carried out.

1.4 OBJECTIVES AND SCOPE

The objective of the present study is to develop a guideline to determine the effective width of the slab strip based on finite element modeling and analysis. The structures with column-supported slabs and slabs with column line beam subjected to lateral loads will be considered. To carry out the investigation, a series of multi storied flat slab structure shall be studied under different parametric conditions using 3D modeling as well as its 2D plane frame idealization. Material is assumed to be isotropic and homogeneous and it is also assumed that the loading will not cause the structure into inelastic conditions. Based on the study, an attempt shall be made to present a guideline to find effective slab strip width that is structurally effective. Study shall be carried out for regular structures.

1.5 METHODOLOGY

Three-dimensional model of the building shall be developed using typical elements – two noded frame elements with six degrees of freedom per node for beams, eight noded solid element with three degrees of freedom per node for columns and four noded rectangular shell elements for the slab. The same structure shall be modeled as two-dimensional plane frame using only frame elements (two nodes with three degrees of freedom per node). Columns of this 2D model shall have same property (cross section etc.) as those of 3D model. Considering the deflections (at top) of the 3D model as representative, the inertia of the beams of 2D model shall be adjusted so that same deflection is obtained under same set of forces. Then from adjusted moment of inertia, a reduced panel width is obtained considering the beam depth same as slab thickness. Finally, the ratio of reduced width to total panel width gives the value of effective strip ratio. The process is a simple trial and error method but very effective in finding the effective slab ratio for flat plates and slab with column line beam. The whole process is carried out under various parametric conditions within certain range.

1.6 ORGANIZATION OF THE THESIS

The thesis is organized to represent and discuss the problem and findings that come out from the studies performed. Chapter 1 introduces the study, in which an overall idea is presented before entering into the main studies and discussion as well as the work performed so far in connection with it collected from different references. Chapter 2 represents the slab system in brief. It also describes the strategy of advancement for the present project to a success as well as presents some literature review. Chapter 3 is all about the finite element modeling exclusively used in this project and it also shows some figures associated with this study for proper presentation and understandings. Chapter 4 is the heart of this project write up, which describes the computational investigation made throughout the study in details with presentation by many tables and figures followed by some definite remarks. Chapter 5 represents the development and verification of two empirical relations for both flat plate structure and slab with column line beam. The last chapter is Chapter 6, which summarizes the whole work as well as points out some further directions.

CHAPTER 2

LITERATURE REVIEW

2.1 PLANE FRAME ANALYSIS OF RC FLOOR SYSTEM

For lateral load analysis, the designer may select any method that is shown to satisfy equilibrium and geometric compatibility and to give results that are in reasonable agreement with available test data. The results of the lateral load analysis may then be combined with those from the vertical load analysis according to the ACI code 318(13.5.1). For vertical load analysis by the Equivalent Frame Method, a single floor is usually studied as a substructure with attached columns assumed fully fixed at the floors above and below. For frame analysis under horizontal load, the equivalent frame includes all floors and columns extending from the bottom to the top of the structure.

The main difficulty in equivalent frame analysis for horizontal loads lies in modeling the stiffness of the region at the beam column (or slab beam column) connections. Transfer of forces in this region involves bending, torsion, shear, and axial load and is further complicated by the effects of concrete cracking in reducing stiffness and reinforcement in increasing it (Nilson et. al., 2003). Frame moments are greatly influenced by horizontal displacements at the floors, and a conservatively low value of stiffness should be used to ensure that a reasonable estimate of drift is included in the analysis.

While a completely satisfactory basis for modeling the beam-column joint stiffness has not been developed, a method based on an equivalent beam width may be used in practice. In this method an equivalent beam width αl_2, less than the actual width l_2 is used to reduce the stiffness of the slab for purposes of analysis.

The analysis under lateral load for the column and slab system is therefore no more difficult than that for an assemblage of horizontal and vertical elements. However the designer faces a special problem when the horizontal connecting system consist a flat plate, beam slab or waffle system. This is because there is a nagging question as to what width of the slab will be effective as a connecting beam. Because parameters such as the slab span width ratio, the relative dimension of the column with respect to the longitudinal and transverse spans of the slab may have significant influence on the effective width of slab (Nilson et. al. 2003).

2.2 CONCEPT OF EFFECTIVE SLAB WIDTH

The concept of an "effective width" is usually used in the analysis of flat plate building subjected to lateral loads. Although physically no beam is exists between the columns for analytical purposes, it is convenient to consider a certain width of slab behaving as a beam between the columns when the lateral loads are considered. The effective width factor is dependent on various parameters such as column aspect ratios, distances between the columns and thickness of slab. Assuming that one can determine the effective width, the lateral resistance of the system is analytically equivalent to a rigid frame consisting of columns and equivalent beams connected to the columns.

An explanation/definition of α as given by Nilson et. al. (2003) is as follows. Fig.2.1(a) shows a plate fixed at the far edge and supported by a column of

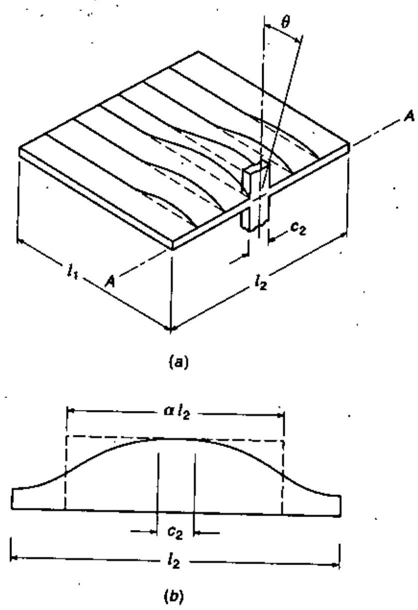


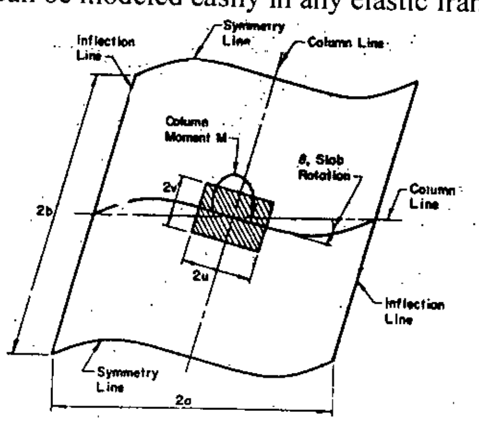
Fig: 2.1 Equivalent beam width for horizontal load analysis (Nilson et. al. 1997) width C_2 at the near side. If a rotation θ is imposed at the column the plate rotation along the axis A will vary as shown by Fig.2.1 (b), from θ at the column to smaller values away from the column. An equivalent width factor α is obtained from the requirement that the stiffness of a prismatic beam of width αl_2 must equal the stiffness of the plate of width l_2. This equality is obtained if the areas under the two rotation diagrams of Fig.2.1(b) are equal. Thus the frame analysis is based on a reduced slab (or slab beam) stiffness found using αl_2 rather than l_2.

2.3 DETERMINATION OF EFFECTIVE SLAB WIDTH

In the past, a number of researchers have addressed the problem of determining effective slab width of flat plat structures. Some researchers proposed empirical equations and some proposed different curves for determining α to facilitate engineers to estimate the effective slab width as accurately as possible to improve the economy of the construction. Some of the proposed solutions of the problem of finding effective slab width by different researchers are stated below:

2.3.1 Pecknold's Method

Pecknold (1975) proposed an equivalent effective slab width model shown in fig 2.2 in which the effective slab width is determined based on elastic plate theory. In his approach, the slab is treated just like an ordinary beam, as in a moment resisting frame and can be modeled easily in any elastic frame analysis program.



$M = \frac{12EI'\theta}{(2a)}$, $I' = (2b')\frac{h^3}{12}$, $2b'$ = Effective Width

Typical interior panel

Fig 2.2 Typical Interior Panel according to Pecknold (1975)

Pecknold (1975) proposed six curves as shown in fig 2.3, where the effective width is a function of column size (square column) for a variety of slab aspect ratio, using the rigid column approximation.

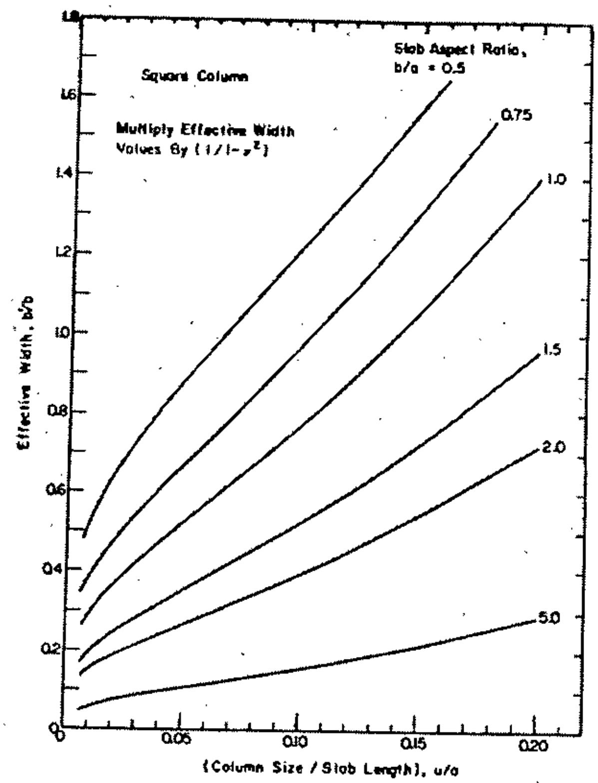


Fig 2.3 Proposed curves for Slab effective width by Pecknold (1975)

Sample calculation for Pecknold's (1975) method

For calculating effective slab strip ratio using Pecknold (1975) method, a typical building of span length 6.0 m, bay width 6.0 m and column size along span 750 mm is taken as follows.

For span length, 2a = 6.0 m

Column size along span, 2u = 750 mm = 0.75 m

Bay width, 2b = 6.0 m

Column size/span length, $\frac{2u}{2a} = \frac{u}{a} = \frac{0.75}{6.0} = 0.125$

Slab aspect ratio, $\frac{b}{a} = \frac{6}{6} = 1.0$

From $\frac{b'}{b}$ vs $\frac{u}{a}$ graph (Fig 2.3),

Effective width, $\frac{b'}{b} = 0.92$

Multiply effective width value by $\frac{1}{1-\nu^2}$

Let, Poisson's Ratio, $\nu = 0.15$

Effective slab strip ratio, $\alpha = \frac{b'}{b} \times \frac{1}{1-\nu^2}$

$$= 0.92 \times \frac{1}{1-(0.15)^2}$$

$$= 0.94$$

2.3.2 Smith and Coull's Method (1991)

Flat plate structures, in which the columns are cast integrally with the floor slabs, behave under horizontal loading similarly to rigid frame. The lateral deflections of the structure are a result of simple double curvature bending of the columns, and a more complex three-dimensional form of double bending of the slab.

If the columns are on a regular orthogonal grid, the response of the structure can be studied by considering each bay-width replaced by an equivalent rigid frame bent. The slab is replaced for the analysis by an equivalent beam with the same double bending stiffness. The flexural stiffness of the equivalent beam depends mainly on the width to length spacing of the columns and on the dimension of the column in the direction of drift.

Smith and Coull (1991) proposed five curves shown in fig. 2.4 where these parameters are used to present the effective width of the equivalent beam, that is, the width of the uniform-section beam having the same double curvature flexural stiffness as the slab, with same depth, span, and modulus of elasticity as the slab. This equivalent beam may be used only in the lateral loading analysis of flat plate structures. It is not appropriate for gravity or combined loading analysis.

When the slab width to span ratio exceeds 1.5, the effective width becomes virtually constant because the slab boundary regions parallel to the direction of drift deform negligibly and therefore contribute little to the stiffness.

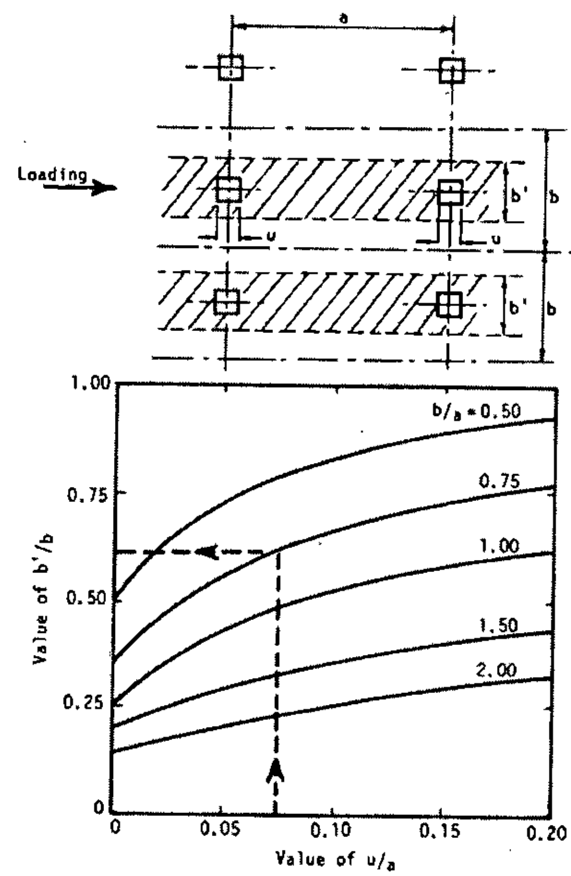


Fig 2.4 Curves proposed by Smith and Coull (1991) for effective width of slab.

Sample calculation for Smith and Coull's (1991) method

For calculating effective slab strip ratio using Smith and Coull's (1991) method, earlier a typical building of span length 6.0 m, bay width 6.0 m and column size along span 750 mm is taken as follows.

For span length, 2a = 6.0 m

Column size along span, 2u = 750 mm = 0.75 m

Bay width, 2b = 6.0 m

Column size/span length, $\frac{2u}{2a} = \frac{u}{a} = \frac{0.75}{6.0} = 0.125$

Slab aspect ratio, $\frac{b}{a} = \frac{6}{6} = 1.0$

From $\frac{b'}{b}$ vs $\frac{u}{a}$ graph (Fig 2.4),

Effective slab strip ratio, $\alpha = 0.56$

2.3.3 Grossman's Method (1997)

Grossman (1997) evaluated three design methodologies for effective width of slab for lateral loads. Each of the three methodologies describe by Grossman is put to a sensitivity review to match the UCB (University of California at Berkeley) test results. The UCB test encompasses a variety of parameters such as aspect ratios, gravity loads and construction procedure influences.
The three design methodologies are designated as follows:

1. Methodology TWR (Extracted from the various papers and meager research information reviewed by Vanderbilt. This method was modified based on engineering judgment)

2. Methodology JSG (one of several sensitivity studies of methodology TWR in which a few parameters has been altered)

3. Methodology HWNG (developed by UCB researchers)

2.3.3.1 Methodology TWR

In the late 1970s, Grossman assembled a design methodology to obtain the effective slab width which correlate to the acceptable drift limit of about $\frac{h_s}{400}$ to $\frac{h_s}{500}$.
The effective width at the center line of an interior, edge, exterior and corner support slab column joint is as follows:

$$\alpha l_2 = \left[0.3l_1 + c_1\left(\frac{l_2}{l_1}\right) + \frac{(c_2 - c_1)}{2}\right]\left(\frac{d}{0.9h}\right)(K_{FP})(K_d)$$

(2.5)

For the effective width of edge supports requires multiplying this equation by the factor $\left(l_3 + \frac{l_2}{2}\right)\Big/ l_2$.

This equation describes the effective width of slabs which have degraded in stiffness by lateral loads causing a critical story sway of about $\frac{h_s}{400}$.

Limits for $\alpha\, l_2$ is $(0.2)(K_d)(K_{FP})l_2 \le \alpha l_2 \le (0.5)(K_d)(K_{FP})l_2$

Where,

l_1 = Length of span (c/c of supports) in direction parallel to lateral load

l_2 = Length of span (c/c of supports) in transverse to lateral load

l_3 = Distance between the column centerline and the parallel edge of the slab

c_1 = Size of the support in the direction parallel to lateral load

c_2 = Size of the support in the direction transverse to lateral load

d = Effective depth of slab

h = Slab thickness

h_s = Story height

K_{FP} = 1.0 for interior supports

= 0.8 for exterior and edge supports

= 0.6 for corner supports

K_d = Factor considering degradation of stiffness of slabs at various lateral load level

At "Ambient" $1.5 \le K_d \le 2.0$ (For young structure K_d =2.0 and for old structure K_d =1.5).

For $\frac{h_s}{800}$ K_d =1.1

For $\frac{h_s}{400}$ K_d =1.0

For $\frac{h_s}{200}$ K_d =0.8

For $\frac{h_s}{100}$ $K_d = 0.5$

Sample calculation for Grossman's Methodology TWR

For calculating effective slab strip ratio using Grossman's Methodology TWR, a typical building is taken as follows.

Here,

$K_{FP} = 1.0$ for interior supports

K_d = Factor considering degradation of stiffness of slabs at various lateral load level

= 1.0

d = Effective depth of slab = 200 mm

For,

l_1 = Length of span (c/c of supports) in direction parallel to lateral load = 6 m

l_2 = Length of span (c/c of supports) in transverse to lateral load = 6 m

c_1 = Size of the support in the direction parallel to lateral load = 0.75 m

c_2 = Size of the support in the direction transverse to lateral load = 0.75 m

Effective Slab Strip Ratio, $\alpha = \left[0.3l_1 + c_1\left(\frac{l_2}{l_1}\right) + \frac{(c_2 - c_1)}{2}\right]\left(\frac{d}{0.9h}\right)(K_{FP})(K_d)\left(\frac{1}{l_2}\right)$

$= 0.443$

2.3.3.2 Methodology JSG

Methodology JSG is an offshoot of Methodology TWR and is one of many sensitivity reviews whose purpose is to evaluate how the various parameters influence the effective width of flat plates and to ascertain if improvements in the accuracy of predicting behavior can be realized.

$$\alpha l_2 = \left[0.3l_{1n} + c_1(x) + \frac{(c_2 - c_1)}{2}\right]\left(\frac{d}{0.9h}\right)(K_{FP}) \qquad (2.6)$$

Where,

$x = \frac{l_2}{l_1} \leq 1.0$

l_{1n} = Length of clear span in direction parallel to lateral load

Sample calculation for Grossman's Methodology JSG

For calculating effective slab strip ratio using Grossman's Methodology JSG, a typical building is taken as follows.

Here,

l_{1n} = Length of clear span in direction parallel to lateral load

K_{FP} = 1.0 for interior supports

K_d = Factor considering degradation of stiffness of slabs at various lateral load level

= 1.0

d = Effective depth of slab = 200 mm

For,

l_1 = Length of span (c/c of supports) in direction parallel to lateral load = 6 m

l_2 = Length of span (c/c of supports) in transverse to lateral load = 6 m

$x = \frac{l_2}{l_1} = 1$

c_1 = Size of the support in the direction parallel to lateral load = 0.75 m

c_2 = Size of the support in the direction transverse to lateral load = 0.75 m

Effective slab strip ratio, $\alpha = \left[0.3l_{1n} + c_1(x) + \frac{(c_2 - c_1)}{2}\right]\left(\frac{d}{0.9h}\right)(K_{FP})\left(\frac{1}{l_2}\right)$

$= 0.382$

2.3.3.3 Methodology HWNG

This methodology was developed by the researchers of the UCB tests.

For interior supports and edge connections with bending perpendicular to edge

$$\alpha l_2 = \left(2c_1 + \frac{l_1}{3}\right)\beta \qquad (2.7)$$

For edge supports with bending parallel to the edge

$$\alpha l_2 = \left(c_1 + \frac{l_1}{6}\right)\beta \qquad (2.8)$$

Where,

$$\beta = 5\frac{c_1}{l_1} - 0.2\left(\frac{LL}{40} - 1\right) \geq \frac{1}{3}$$

or, approximately $\beta = 4\frac{c_1}{l_1} \geq \frac{1}{3}$

Where,

LL = Live load or construction loads

β accounts for loss of stiffness under loads.

Sample calculation for Grossman's Methodology HWNG

For calculating effective slab strip ratio using Grossman's Methodology HWNG, a typical building is taken as follows.

Here,

l_1 = Length of span (c/c of supports) in direction parallel to lateral load = 6 m

l_2 = Length of span (c/c of supports) in transverse to lateral load = 6 m

c_1 = Size of the support in the direction parallel to lateral load = 0.75 m

c_2 = Size of the support in the direction transverse to lateral load = 0.75 m

$\beta = 4\frac{c_1}{l_1} \geq 0.333$

Effective slab strip ratio, $\alpha = \left(2c_1 + \frac{l_1}{3}\right)\beta\left(\frac{1}{l_2}\right)$

$= 0.213$

2.3.4 Lou and Durrani's Method (1995)

Based on the test results of 40 interior connections, an equivalent beam model is proposed by Luo and Durrani (1995) in which columns are modeled conventionally, and the effective slab width is determined as a function of column and slab aspect ratios and magnitude of the gravity load. The proposed approach is verified with selected experimental results and is found to be practical and convenient for analyzing flat-slabs buildings subjected to gravity and lateral loading.

By calibrating the results of pecknolds elastic solution, a somewhat simpler expression for the effective slab width is suggested by Luo and Durrani as follows

$$\alpha_l = \frac{R_{12}\left(\frac{c_1}{l_2}\right)}{0.05+0.002\left(\frac{l_1}{l_2}\right)^4 - 2\left(\frac{c_1}{l_1}\right)^3 - 2.8\left(\frac{c_1}{l_1}\right)^2 + 1.1\left(\frac{c_1}{l_1}\right)}$$

(2.9)

Where,

$$R_{12} = -0.0221\left(\frac{c_1}{c_2}\right)^4 + 0.0281\left(\frac{c_1}{c_2}\right)^3 + 0.1535\left(\frac{c_1}{c_2}\right)^2 + 0.773\left(\frac{c_1}{c_2}\right) + 0.0845$$

The preceding equation gives a very good approximation of the theoretical solution for the range $0.5 \leq \frac{l_1}{l_2} \leq 2.0$. For the case of $0.5 \leq \frac{c_1}{c_2} \leq 2.0$ and $0.5 \leq \frac{l_1}{l_2} \leq 2.0$ the preceding equation can be further simplified as

$$\alpha_l = \frac{1.02\left(\frac{c_1}{l_2}\right)}{0.05+0.002\left(\frac{l_1}{l_2}\right)^4 - 2\left(\frac{c_1}{l_1}\right)^3 - 2.8\left(\frac{c_1}{l_1}\right)^2 + 1.1\left(\frac{c_1}{l_1}\right)}$$

(2.10)

Where,

c_1 = Column dimension in bending direction

c_2 = Column dimension normal to bending direction

l_1 = Span length in bending direction, center-to-center of columns

l_2 = Span length in direction transverse to l_1, center-to-center of columns

The ratio of measured to calculate unbalanced moments tends to become smaller as the gravity shear increase, which suggests that the effective slab width factor must decrease with the increase of gravity load. Thus Luo and Durrani suggested a reduction factor for the theoretical effective width as

$$\chi = \left(1 - 0.4\frac{V_g}{4A_c\sqrt{f_c'}}\right)$$
(2.11)

Where,

χ = Stiffness reduction factor for gravity load

V_g = Direct shear force due to gravity load only

A_c = Area of slab critical section specified by ACI Building Code

f_c' = Compressive strength of concrete

Thus the effective slab strip ratio at interior connection is, $\alpha = \chi\alpha_i$

Sample calculation for Lou and Durrani's Method (1995)

Effective Slab Strip

$$\text{Ratio}, \alpha_i = \frac{1.02\left(\frac{c_1}{l_2}\right)}{0.05 + 0.002\left(\frac{l_1}{l_2}\right)^4 - 2\left(\frac{c_1}{l_1}\right)^3 - 2.8\left(\frac{c_1}{l_1}\right)^2 + 1.1\left(\frac{c_1}{l_1}\right)}$$

For,

c_1 = Column dimension in bending direction = 0.75 m

c_2 = Column dimension normal to bending direction = 0.75 m

l_1 = Span length in bending direction, center-to-center of columns = 6 m

l_2 = Span length in direction transverse to l_1, center-to-center of columns = 6 m

Effective Slab Width, $\alpha_i = 0.899$

Now,

d = Effective depth of slab = 188 mm

Column size 750 mm×750 mm

$$b_0 = \left(750 + 2\times\frac{750}{2}\right)\times 4 = 6000 \ mm = 6.0\,m$$

$A_c = b_0 \times d = 1.128\ m^2 = 1748.4\ \text{in}^2$

For, Live load = 40 psf, Partition Wall = 30 psf, Floor Finish = 20 psf, f_c' = 4000 psi

Direct shear force due to gravity load only, V_g =54000 lb

Stiffness reduction factor for gravity load, $\chi = \left(1 - 0.4\frac{V_g}{4A_c\sqrt{f_c'}}\right) = 0.95$

Thus the effective slab strip ratio at interior connection is,

$\alpha = \chi\alpha_i = 0.95 \times 0.899 = 0.854$

2.4 REMARKS

From the preceding results we can see that the effective slab strip ratio vary widely among different methods. Pecknold's(1975) method shows the highest value (0.94) followed by Lou and Durrani's Method (1995). Grossman's three methodology TWR, JSG, HWNG show the value of slab strip ratio as 0.443, 0.382 and 0.213 respectively. Each researcher use different parameter of a structure to find out effective slab strip ratio. Probable reasons for such a wide variation in α is discussed in chapter 4. However, one thing is clear from this exercise that determination of α still needs more research.

CHAPTER 3

FINITE ELEMENT MODELING

3.1 GENERAL

A building's response to loading is governed by the components that are stressed as the building deflects. Ideally, for ease and accuracy of the structural analysis, the participating components would include only the main structural elements, the slabs, beams, girders, and columns. In reality however other nonstructural elements are stressed and contribute to the buildings behavior, these include, for example, the staircases, partitions and cladding. To simplify the problem in modeling a building for analysis, it is required to include only the main structural members and to assure that the effects of the nonstructural components are not significant.

3.2 ASSUMPTIONS

An attempt to analyze a high rise building and accurately account for aspects of behavior of all the components and materials, even if their sizes and properties were known, would be virtually impossible. Simplified assumptions are necessary to reduce the problem to a viable size. Assumptions depend on the arrangement of the structure, its anticipated mode of behavior, and the type of analysis. The most common assumptions are stated below:

3.2.1 Materials

The material of the structure components is linearly elastic. This assumptions allows the superposition of actions and deflections and, hence, the use of linear methods of analysis. The development of linear methods and their solutions by computer has made it possible to analyze large complex statically indeterminate structures.

3.2.2 Participating Components

Only the primary structural components participate in the overall behavior, i.e. beam, column and slab. The effects of secondary structural components and nonstructural components are assumed to be negligible and conservative.

3.3 FINITE ELEMENT MODELING OF STRUCTURES

In reinforced concrete construction, slabs are used to provide a flat useful surface. A reinforced concrete slab is a broad, flat plate, usually horizontal, with top and bottom surface parallel or nearly so (Nilson et. al. 2003). It may be supported by reinforced concrete beam shown in fig 3.1 known as column line beam structure or directly on columns as shown in fig 3.2 known as flat plate structure.

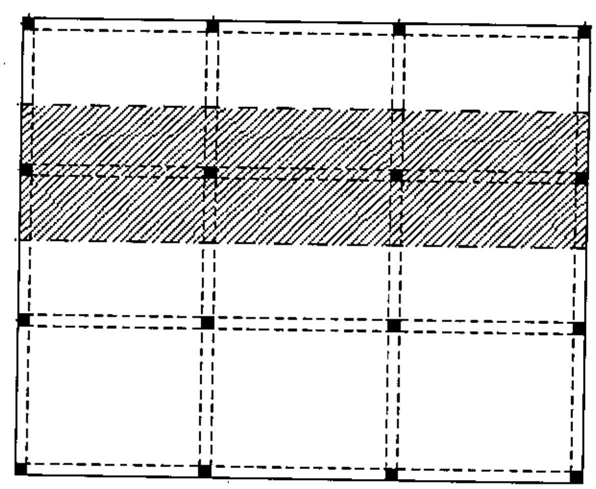


Fig.3.1 Plan of a typical slab with column line beam

3.3.1 Modeling of Slab

Four noded 3D shell element shown in fig 3.3 is used for modeling of slabs. It has both bending and membrane capabilities. Both in-plane and normal loads are permitted. The element has six degrees of freedom at each node; translations in the nodal x, y, and z directions and rotations about the nodal x, y and z-axes.

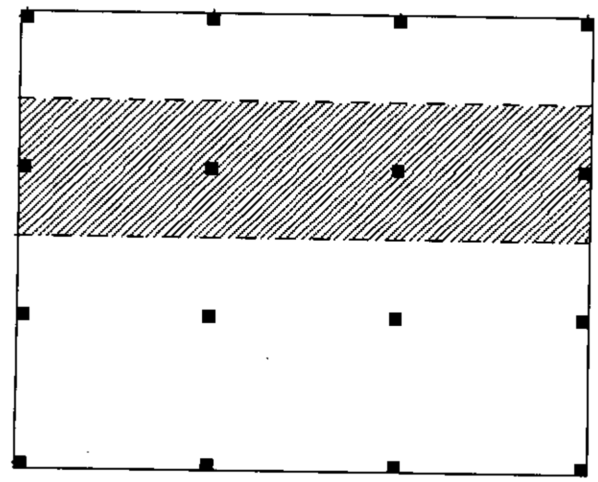


Fig.3.2 Plan of Typical Flat Plate Structure

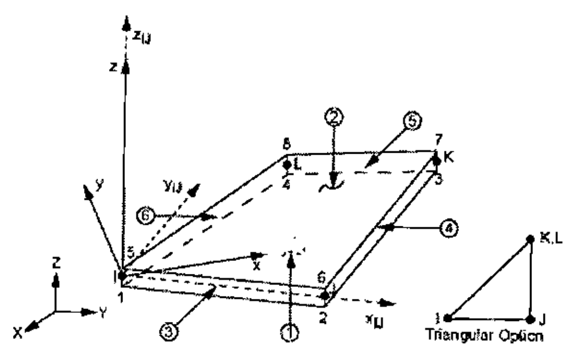


Fig 3.3: Four noded 3D shell element

3.3.2 Modeling of Beam

Two noded frame element shown in fig 3.4 is used for modeling of beams. It is a line element with tension, compression, torsion, and bending capabilities. The element has six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z-axes. This element allows end nodes to be offset from the centroidal axis of the beam.

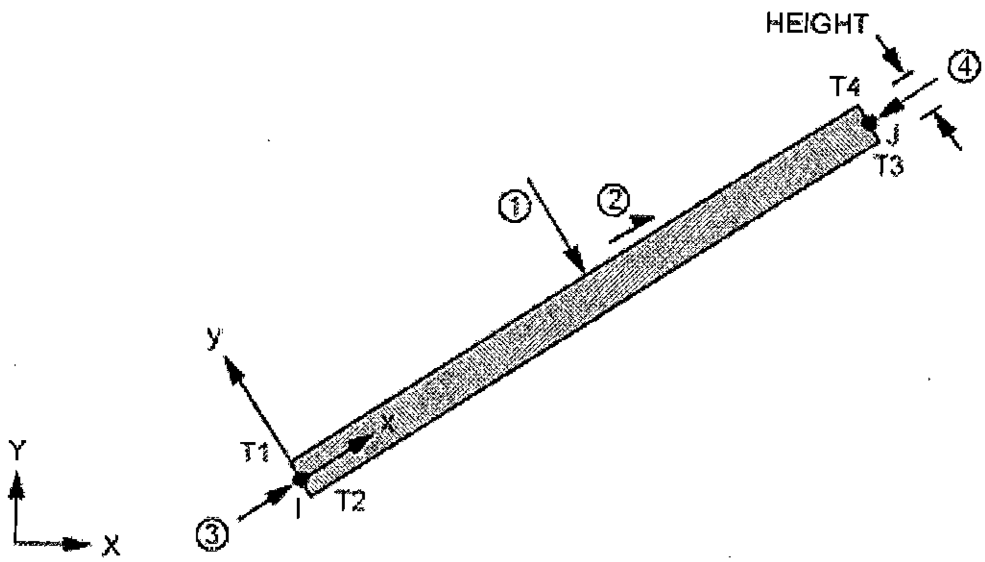


Fig 3.4: Two noded frame element

3.3.3 Modeling of Column

Eight noded solid element shown in fig 3.5 is used for modeling the columns in 3D model. It is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element is defined by eight nodes. In 2D model frame elements are used to model the columns as stated below. The justification of using solid element for columns is explained later in article 3.4.1.

3.3.4 Modeling of Beams and Columns in Plane Frame Model

Two noded plane frame element is used for the modeling of beams and columns in plane frame model. It is a uniaxial element with tension, compression, and bending capabilities. The element has three degrees of freedom at each node: translations in the nodal x and y directions and rotation about the nodal z-axis. The element is defined by two nodes, the cross-sectional area, the area moment of inertia, the height, and the material properties.

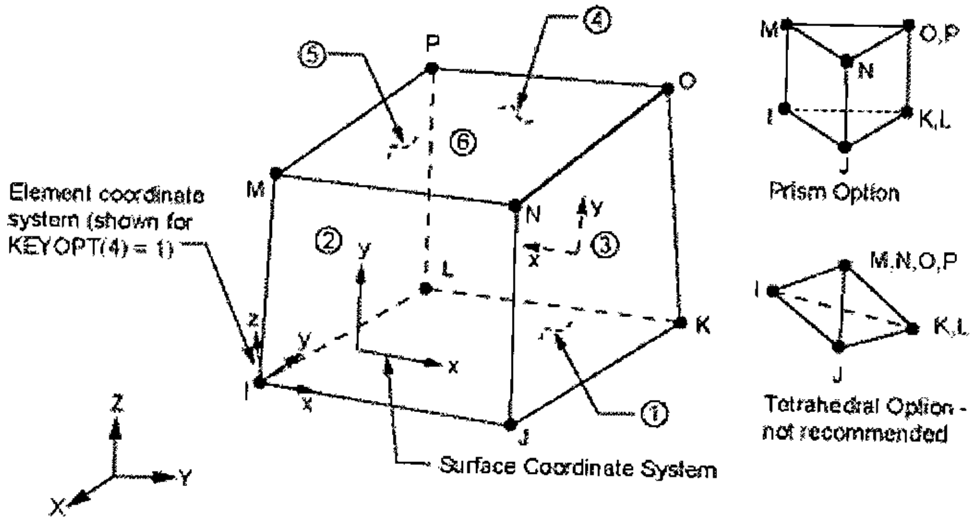


Fig 3.5: Eight noded solid element

3.3.5 Applied Force

In the present analysis we are comparing a 3D frame with its 2D equivalent. For this purpose, application of a system of lateral load is necessary. Since comparative behaviour of 2D frame with 3D structure is performed, any magnitude of lateral force shall be OK provided that the force is same in both 2D and 3D model. In the present investigation a lateral force having triangular distribution across floor level similar to earthquake loading is used. For interior frame the magnitude of this lateral force for each frame at a particular floor level arbitrarily set as,

$F = 4300 \times h$ Newton

Where,

h = Height of floor in meter above base.

3.4 DEVELOPMENT OF FINITE ELEMENT MODEL

In order to facilitate the investigation, the building frames of the problem is modeled both as a two-dimensional frame using frame element only and three-dimensional structure consisting of solid and shell elements. The results of the three dimensional modeling with shell and solid elements are considered to be representative of real behaviour. The 2D model is adjusted to match the corresponding results of 3D model.

3.4.1 Use of Solid Element for Modeling Column

In the previous chapter several approximate methods for determining α developed by various researchers (Pecnold (1975), Smith and coull (1991), Grossman (1997) etc.) are presented. It can be observed in all theses methods that column dimension along span is one of the parameters influencing the magnitude of α. Previous research of Islam (2003) shows that column dimension along span does not influence the magnitude of α. This research was conducted on the basis of finite element modeling, in which traditional frame element was used for modeling column. This element has only length as physical dimension in the finite element model co-ordinate space. Column dimension does not influence the finite element mesh (e.g. nodal co-ordinates). Thus whatever be the column dimension, the clear span between column remains the same. For this reasons such line element are incapable of capturing the effect of column dimension in the finite element x,y,z co-ordinate space. On the other hand eight noded solid element has all the three component (x,y,z) of physical dimension in finite element co-ordinate system. Therefore it is expected that modeling of column with solid element would provide more reasonable result consistent with the finding of earlier researchers.

3.4.2 Mesh Sensitivity

Investigating the effect of mesh sensitivity on results is an important step in any kind of study based on finite element modeling. To study the behavior of building of flat plate system a full 3D model has been developed. In this model, there were five columns along span, five columns along bay and there have been total six floors. Span length is 6 m, bay width is 5m, floor height is 3m, slab thickness is 225mm and columns are 600mmx600mm. An isometric view of this full 3D model is shown in fig 3.6. The model is laterally loaded in x direction.

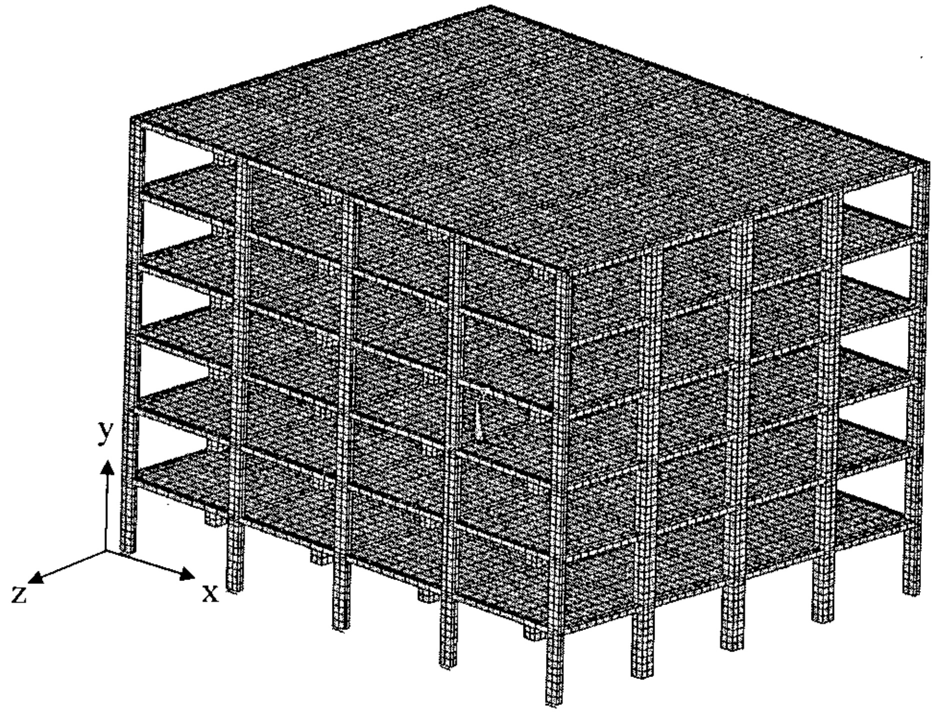


Fig 3.6: An isometric view of a full 3D model

For this model deflection at top has been studied for four different (gradually increasing division) sets of mesh which is summarized in table 3.1.

From observing the table 3.1 we can see that as the number of division increases, deflection converges to a unique value at set-3. When we further refine the division in set-4, the deflection does not vary appreciably, therefore the mesh division correspond to set-3 may be considered satisfactory for the present investigation.

3.4.3 Full Frame 3D vs Single Frame 3D Model

Full 3D finite element model describe in the previous article requires significant amount computational time. We can achieve the same result by modeling only a

Table 3.1: Variation of top deflection based on mesh size

	Set 1	Set 2	Set 3	Set 4
No of division along bay	2	3	5	6
No of division along span	4	6	8	10
No of division along column	5	8	10	12
Max deflection, m	0.0175	0.0181	0.0183	0.0183

single interior frame with proper boundary condition. This shall result in a significant saving in computational time. In the single frame 3D model, the portion of an interior frame bounded by two adjacent centerlines of bay is considered as shown in fig 3.7 and 3.8. Since the single frame model is only a part of the structure, proper

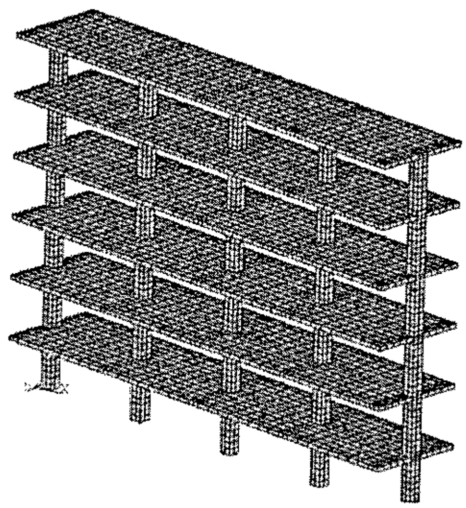


Fig 3.7 3D model of a single frame of a 3D structure

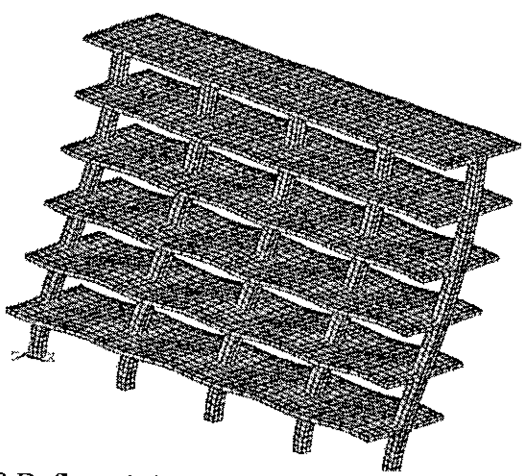


Fig 3.8 Deflected shape of a single frame of a 3D model

boundary condition along slab edge parallel to span must be imposed. Assuming that all the interior frame shall behave similarly and symmetrically about the panel centerline, the boundary condition along slab edge parallel to span shall be $\theta_X = 0$ and $\delta z = 0$ i.e. the rotation about span axis – x is zero and movement along bay axis – z is zero (fig 3.9).

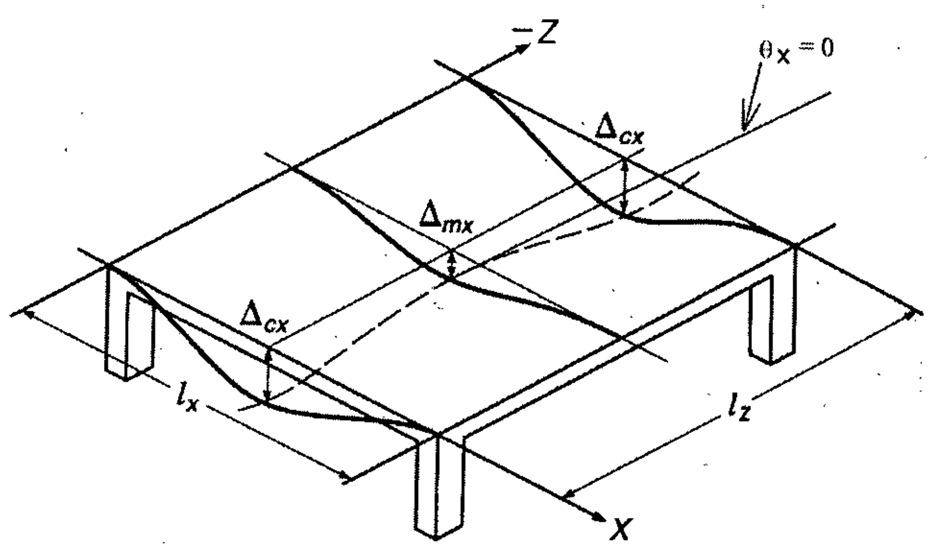


Fig 3.9: A slab region bounded by column centerlines

Based on such modeling the top sway of the single frame 3D model is compared with the top sway of full 3D model and the comparison is shown in table 3.2 along with the required computational time.

Table 3.2: Showing deflection and time of 3D model and actual structure

	Deflection, m	Time, sec
Single frame 3D model	0.01797	7.0
Full 3D Structure	0.01826	63.0

From the above we can see that single frame 3D model can complete the analysis in only 11 percent of the time required by the full frame model keeping acceptable level of accuracy in deflection. Therefore in the present investigation single frame 3D model is used instead of full 3D model to save valuable time.

3.4.4 Using 2-D Model

In our analysis, 3D model of a full structure is represented by an equivalent 2D model. Frame elements were used to model the beams and columns in 2D model shown in fig 3.10 and 3.11.

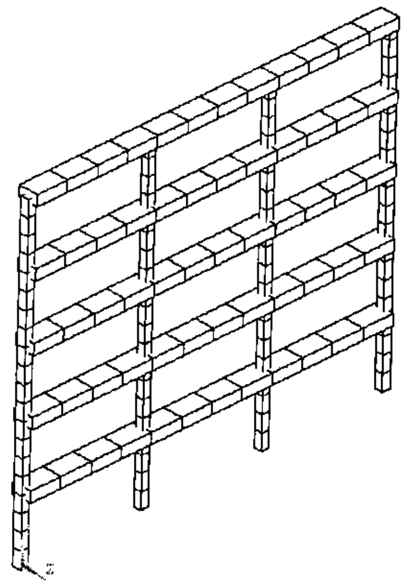


Fig.3.10 Equivalent 2-D Model of Typical Slab with column line beam

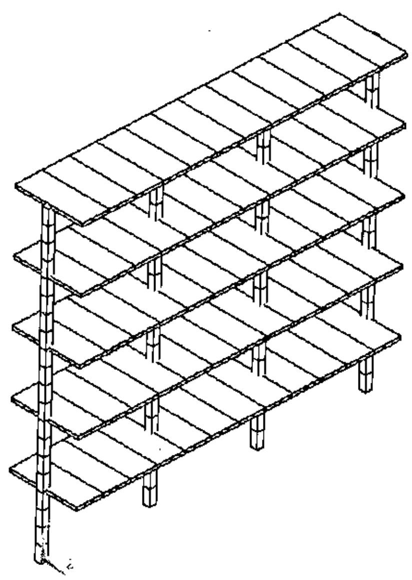


Fig.3.11 Equivalent 2-D Model of Typical Flat Plate Structure

3.4.5 Equivalence of 2D Model with 3D Model

The whole idea of present research is about establishing relation between actual 3D behaviour of flat plate structure and its 2D plane frame equivalent. The theoretical aspect of equivalence is describe in chapter 2 with fig 2.1 where it is shown that the non uniform curvature of slab bending across a section of width l_2 near column is equivalenced by the uniform curvature of the equivalent beam width αl_2. In reality this equivalence can be obtained by matching the lateral sway of 3D model and 2D model. In fact, the basis of establishing this equivalence can be any structural parameter like deflection, reaction, moment etc. In the present study we are trying to establish an equivalent beam corresponding to the effective part of the slab. Columns remain the same in both cases. Thus the present 2D equivalent model may be termed as equivalent beam model also. Presently the equivalence of 2D model with 3D model is established on the basis of matching the deflection. However, it can be shown that, once matching is done on the basis of deflection, other parameters like moment, reaction, shear force etc. are also matched automatically. To demonstrate this, a typical 12 storied frame having five span and six bay is modeled and analyzed in both 2D and 3D. In this frame span length is 5m, bay width is 5m and floor height is 4m. Slab thickness is taken 225 mm and column dimension along span is 900 mm and along bay is 600 mm. For this frame the floor level deflections are plotted in fig 3.15.

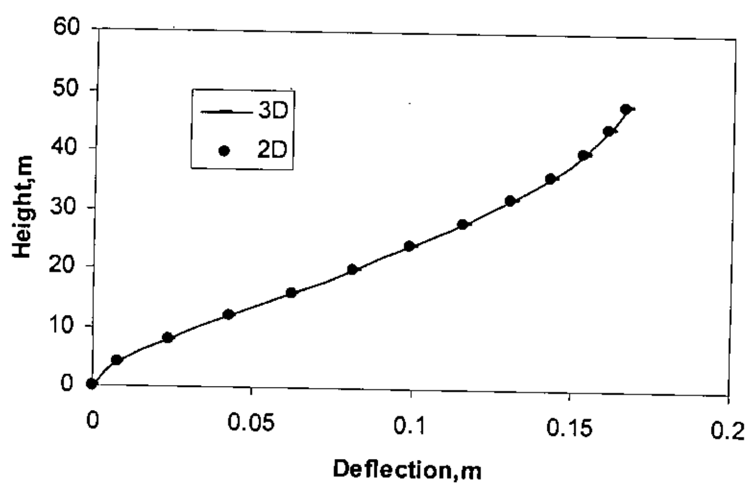


Fig 3.12 Deflection of 2D and 3D model with height

It can be observed from fig 3.12 that the results of 2D and 3D analysis are virtually identical at all floor levels. Similarly column shear, axial force and moment at column bases are compared in fig 3.13, fig 3.14 and fig 3.15 respectively.

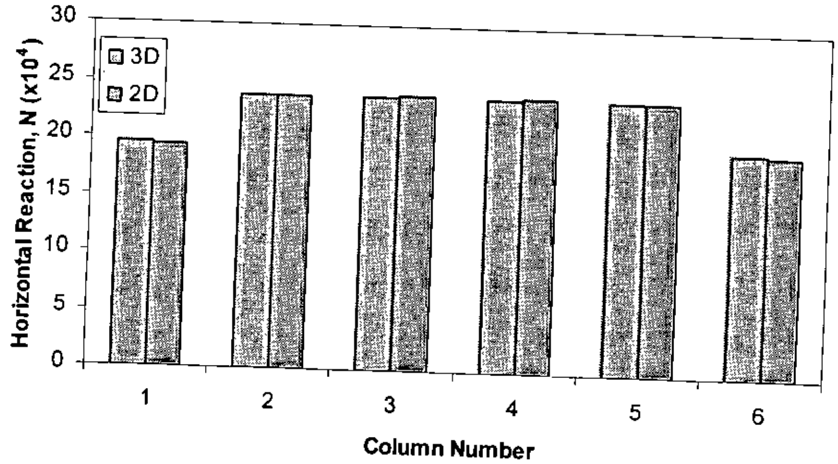


Fig 3.13 Comparison of horizontal reaction at column bases

which also show that the 2D result is matched acceptably with 3D result. In the present investigation, therefore, equivalence of 2D and 3D model is established on the basis of matching top sway onwards.

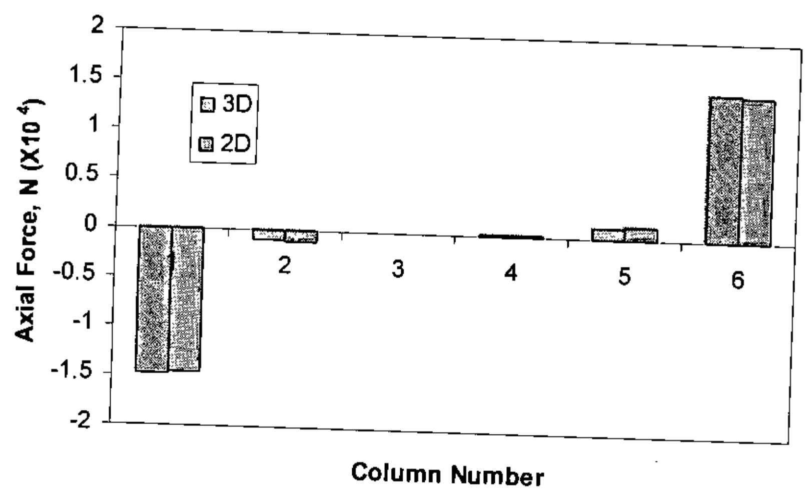


Fig 3.14 Comparison of axial force at column bases

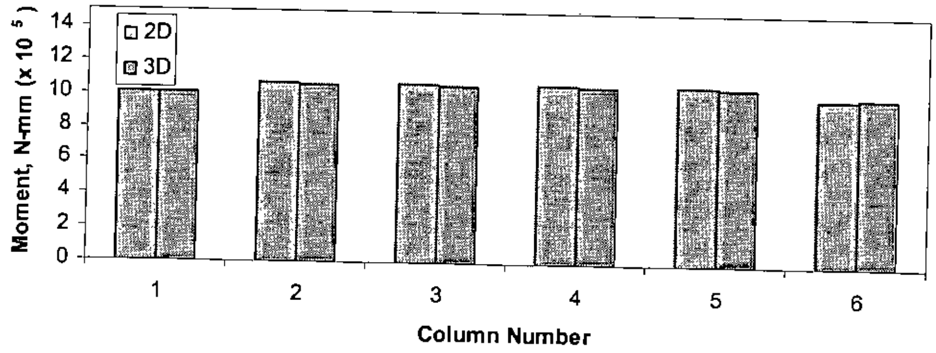


Fig 3.15 Comparison of moment at column bases

3.5 EXAMPLE PROBLEM FOR INVESTIGATION

In the present analysis, a 3D model is subjected to a lateral load and the top deflection is recorded. The same load is applied to 2D model of same structure. Dimensions of columns in 2D models are kept same as that of 3D model. The inertia of the beams are adjusted so that the deflection closely match with the deflection of the three dimensional structure when subjected to same load. Then width of the beam in two-dimensional model is used to determine the effective slab strip ratio in flat plate structure. This process is repeated for various parametric conditions to determine the influence of parameters on slab strip ratio. The study parameters of the a typical multi storied building are stated below in table 3.3

Table 3.3: Study Parameters for Typical Flat Plate Structure and Slab with column line beam

Flat Slab Structure	Slab with Column line Beam Structure
Slab Thickness	Slab Thickness
Span Length	Span Length
Bay Width	Bay Width
Span Number	Span Number
Floor Number	Floor Number
Floor Height	Floor Height
Column Dimension along span	Column Dimension along span
Column Dimension along bay	Column Dimension along bay
–	Beam Width
–	Total Beam Depth

3.6 SAMPLE CALCULATION FOR DETERMINATION OF EFFECTIVE SLAB STRIP RATIO

3.6.1 For Flat Plate Structure

To determination of effective slab strip ratio for flat slab based on finite element analysis results are shown below with an example,

Slab Thickness = 200mm
Span Length = 6m
Bay Width = 6m
Span Number = 6
Floor Number = 6
Floor Height = 4m
Column Dimension along span = 0.75m
Column Dimension along Bay = 0.75m

Top most horizontal deflection for 3-D model of the example problem = 0.02589 m
Width of beam of 2-D model having producing deflection as 3-D model = 4.24 m.
Beam depth is same as slab depth.

So, effective slab strip ratio, $\alpha = \dfrac{4.24}{6} = 0.707$

3.6.2 For Slab with column line Beam Structure

To determine the effective slab strip ratio for slab with column line beam shown in fig 3.15, earlier example is taken with following additional data,

Beam Width = 0.3m
Total Beam Depth = 0.6m

Top most horizontal deflection for 3-D model of the example problem = 0.00875 m
Moment of inertia of beam of 2-D model (Width 680mm, Depth 600mm) having same deflection as 3-D model

$$= \frac{680 \times 600^3}{12} = 12.24 \times 10^9$$

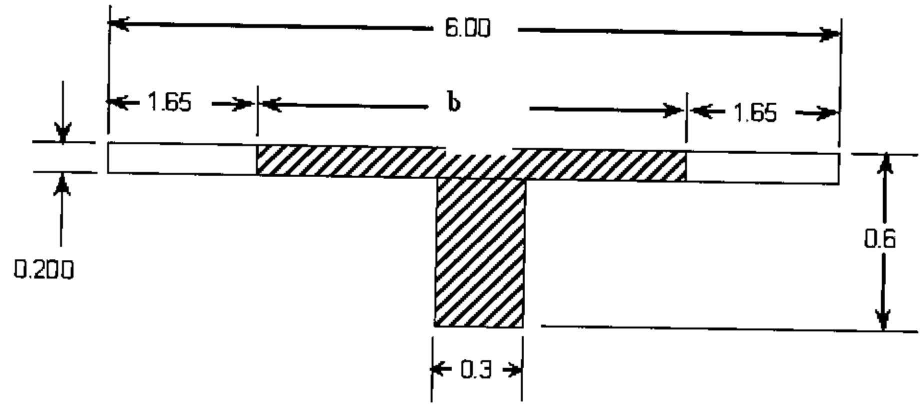


Fig.3.16 Section of slab strip of slab with column line beam

From fig 3.16

$$y = \frac{b \times 200 \times 100 + 300 \times 400 \times 400}{b \times 200 + 300 \times 400}$$

Where,

y = Distance of c.g. of effective slab strip section from top fiber

b = Effective slab strip width

$$I = \frac{b \times 200^3}{12} + b \times 200 \times (y - 100)^2 + \frac{300 \times 400^3}{12} + 300 \times 400 \times (400 - y)^2 = 12.24 \times 10^9$$

Solving the above equation we get, $b = 2.7$ m

So, Effective Slab Strip Ratio, $\alpha = \frac{2.7}{6} = 0.45$

CHAPTER 4

COMPUTATIONAL INVESTIGATION

4.1 GENERAL

To determine the effective slab strip ratio, parameters stated in table 3.1 were considered for investigation. For each parameter, the top deflection from 3-D model is noted and the equivalent width of 2-D model is determined for the same deflection. Effective slab strip ratio (α) is calculated for each parameter using that equivalent width of 2-D model.

4.2 DETERMINATION OF EFFECTIVE SLAB STRIP RATIO FOR FLAT PLATE STRUCTURE

To determine the effective slab strip ratio (α) a typical multi storied structure is considered with an arbitrary value of each parameter stated in table 3.3 of chapter 3. Now for each analysis only one parameter is varied and other considered parameters are remain fixed. For different value of variable parameters, different effective slab strip ratio (α) are calculated respectively as follows:

Effective slab strip Ratio = Equivalent width /Bay width.

4.2.1 Study Parameters

To determined effective slab strip ratio (α) flat plate structure is analyzed with following study parameters:

Table 4.1: Study Parameters for flat plate structures.

	Reference Value, m	Value for study
Bay width	6	3,4,5,6,7,8,9
No of floor	6	3,4,5,6,7,8,9
Column dimension along bay	0.75	0.3,0.45,0.6,0.75,0.9.1.05,1.2
Column dimension along span	0.75	0.3,0.45,0.6,0.75,0.9.1.05,1.2
Span length	6	3,4,5,6,7,8,9
Span number	6	3,4,5,6,7,8,9
Slab thickness	0.2	0.125,0.15,0.175,0.2,0.225,0.25,0.275
Floor height	4	3,3.5,4,4.5,5

4.2.2 Sensitivity Analysis

From the results of numerical analysis and parametric study, following discussion may be made according to respective involved parameter.

4.2.2.1 Effect of Slab Thickness

For flat plate structures, the effective slab strip ratios obtained for different slab thickness are shown in Fig. 4.1. It may be observed that the trend line is almost straight horizontal one under the study parameters. The magnitude of slab thickness is much smaller compare to the other physical dimensions of the structure. Thus it behaves more like a surface like element where variation in thickness only change its own stiffness but its relative influence with respect to other structural elements remain the same. For this reason, slab thickness does not demonstrate any appreciable effect on magnitude of effective slab strip ratio (α).

4.2.2.2 Effect of Span Length

For flat plate structures, the effective slab strip ratios obtained for different span length are shown in Fig. 4.2. It may be observed that the trend line is almost straight upward one under the study parameters. When span is increased the stiffness of the column strip decreases allowing more deflection and higher moment in column. This higher column moment must be transferred to the floor slab to maintain static equilibrium. Higher column moment is associated with higher rotation of column at floor column joint. This higher rotation of the column will cause greater area of the slab adjacent to column to bend causing an increase in the effective width of the beam. For this reason, effective slab strip ratio (α) increases with increase magnitude of span length.

4.2.2.3 Effect of Bay Width

For flat plate structures, the effective slab strip ratios obtained for different bay width are shown in Fig. 4.3. It may be observed that the trend line is downtrend with almost parabolic nature under the study parameters. When the structure is subjected to lateral load, certain width of the slab along column line is active as a beam. The rest of the slab may be considered non structural. When the bay width is increased, this only contributes to the non structural part. Therefore the proportion of the effective part to the total width decreases. For this reason, effective slab strip ratio (α) decreases with increase magnitude of bay width.

4.2.2.4 Effect of Number of Span

For flat plate structures, the effective slab strip ratios obtained for different number of spans are shown in Fig. 4.4. It may be observed that the trend line is straight horizontal one under the study parameters. Increases number of span does not make any appreciable change in the stiffness of the equivalent beam (Structurally active part of the slab). For this reason, number of spans does not demonstrate any effect on effective slab strip ratio (α).

4.2.2.5 Effect of Number of Floors

For flat plate structures, the effective slab strip ratios obtained for different floor numbers are shown in Fig. 4.5. It may be observed that the trend line is straight horizontal one under the study parameters. Increases number of floor does not make any appreciable change in the stiffness of the equivalent beam (Structurally active part of the slab). For this reason, floor number does not demonstrate any effect on effective slab strip ratio (α).

4.2.2.6 Effect of Floor Height

For flat plate structures, the effective slab strip ratios obtained for different floor heights are shown in Fig. 4.6. It may be observed that the trend line is straight horizontal one under the study parameters. Floor height changes the column stiffness but it does not change any physical property of the slab. Thus stiffness of the equivalent beam (Structurally active part of the slab) remains same as before. Therefore, floor height does not demonstrate any effect on effective slab strip ratio (α).

4.2.2.7 Effect of Column Dimension Along Span

For flat plate structures, the effective slab strip ratios obtained for different column dimension along span are shown in Fig. 4.7. It may be observed that the trend line is straight upward one under the study parameters. When column dimension along span is increased, the effective span length (clear distance) decrease causing increase in stiffness of the equivalent slab bend. This increase in stiffness is accommodated by corresponding increase in the width of the structurally active slab bend. For this reason, effective slab strip ratio (α) increases with increase magnitude of column dimension along span

4.2.2.8 Effect of Column Dimension Along Bay

For flat plate structures, the effective slab strip ratios obtained for different column dimension along bay are shown in Fig. 4.8. It may be observed that the trend line is almost straight upward one under the study parameters. When column dimension along bay is increased, it correspondingly increases the zone of influence in the lateral direction. For this reason, we observed slight increase of effective slab strip ratio (α) with increase magnitude of column dimension along bay.

4.3 DETERMINATION OF EFFECTIVE SLAB STRIP RATIO FOR SLAB WITH COLUMN LINE BEAM

To determine the effective slab strip ratio (α) a typical multi storied structure is considered with an arbitrary value of each parameter stated in table 3.3 of chapter 3. Now for each analysis only one parameter is varied and other considered parameters are remain fixed. For different value of variable parameters, different effective slab strip ratio (α) are calculated respectively as follows:

Effective slab strip ratio = Effective width/ Bay width

4.3.1 Study Parameters

To determined effective slab strip ratio (α) slab with column line beam structure is analyzed with following study parameters:

Table 4.2: Study Parameters for slab with column line beam structures

	Reference Value, m	Value for study, m
Bay width	6	3,4,5,6,7,8,9
No of floor	6	3,4,5,6,7,8,9
Column dimension along bay	0.75	0.3,0.45,0.6,0.75,0.9.1.05,1.2
Column dimension along span	0.75	0.3,0.45,0.6,0.75,0.9.1.05,1.2
Span length	6	3,4,5,6,7,8,9
Span number	6	3,4,5,6,7,8,9
Slab thickness	0.2	0.125,0.15,0.175,0.2,0.225,0.25,0.275
Floor height	4	3,3.5,4,4.5,5
Beam width	0.3	0.225,0.25,0.275,0.3,0.325,0.35,0.375
Beam depth	0.6	0.3,0.4,0.5,0.6,0.7,0.8,0.9

4.3.2 Sensitivity Analysis

From the experimental results following discussion may be described according to respective involved parameter.

4.3.2.1 Effect of Slab Thickness

For slab with column line beam structures, the effective slab strip ratios obtained for different slab thickness are shown in Fig. 4.9. It may be observed that the trend line is almost straight upward one under the study parameters. In buildings having column line beams, part of the slab along the column line and the beam together acts as effective beam. Increasing slab thickness increases its portion of share from the total stiffness of the effective beam which is probably the cause of increase the effective slab strip ratio (α). However, from the fig 4.9, it may be observed that change in effective slab strip ratio (α) is less prominent when compare to other cases.

4.3.2.2 Effect of Span Length

For slab with column line beam structures, the effective slab strip ratios obtained for different span length are shown in Fig. 4.10. It may be observed that the trend line is increasing upward under the study parameters. When span is increased, the stiffness of the column strip decreases allowing more deflection and higher moment in column. This higher column moment must be transferred to the floor slab to maintain static equilibrium. Higher column moment is associated with higher rotation of column at floor column joint. This higher rotation of the column will cause greater area of the slab adjacent to column to bend causing an increase in the effective width of the beam. For this reason, effective slab strip ratio (α) increases with increase magnitude of span length.

4.3.2.3 Effect of Bay Width

For slab with column line beam structures, the effective slab strip ratios obtained for different bay width are shown in Fig. 4.11. It may be observed that the trend line is downtrend with almost parabolic nature under the study parameters. When the structure is subjected to lateral load, certain width of the slab along column line is active as a beam. The rest of the slab may be considered non structural. When the bay width is increased, this only contributes to the non structural part. Therefore the proportion of the effective part to the total width decreases. For this reason, effective slab strip ratio (α) decreases with increase magnitude of bay width.

4.3.2.4 Effect of Number of Spans

For slab with column line beam structures, the effective slab strip ratios obtained for different number of spans are shown in Fig. 4.12. It may be observed that the trend line is almost horizontal one under the study parameters. Increases number of span does not make any appreciable change in the stiffness of the equivalent beam (Structurally active part of the slab). For this reason, number of spans does not demonstrate any effect on effective slab strip ratio (α).

4.3.2.5 Effect of Number of Floors

For slab with column line beam structures, the effective slab strip ratios obtained for different floor numbers are shown in Fig. 4.13. It may be observed that the trend line is almost straight horizontal one under the study parameters. Increases number of floor does not make any appreciable change in the stiffness of the equivalent beam (Structurally active part of the slab). For this reason, number of floors does not demonstrate any effect on effective slab strip ratio (α).

4.3.2.6 Effect of Floor Height

For slab with column line beam structures, the effective slab strip ratios obtained for different floor heights are shown in Fig. 4.14. It may be observed that the trend line is almost horizontal under the study parameters. Floor height changes the column stiffness but it does not change any physical property of the slab. Thus stiffness of the equivalent beam (Structurally active part of the slab) remains same as before. Therefore, floor height does not demonstrate any effect on effective slab strip ratio (α).

4.3.2.7 Effect of Column Dimension Along Span

For slab with column line beam structures, the effective slab strip ratios obtained for different column dimension along span are shown in Fig. 4.15. It may be observed that the trend line is inclined upward under the study parameters. When column dimension along span is increased, the effective span length (clear distance) decrease causing increase in stiffness of the equivalent slab bend. This increase in stiffness is accommodated by corresponding increase in the width of the structurally active slab bend. For this reason, effective slab strip ratio (α) increases with increase magnitude of column dimension along span.

4.3.2.8 Effect of Column Dimension Along Bay

For slab with column line beam structures, the effective slab strip ratios obtained for different column dimension along bay are shown in Fig. 4.16. It may be observed that the trend line is inclined upward under the study parameters. When column dimension along bay is increased, it correspondingly increases the zone of influence in the lateral direction. For this reason, we observed slight increase of effective slab strip ratio (α) with increase magnitude of column dimension along bay.

4.3.2.9 Effect of Beam Width

For slab with column line beam structures, the effective slab strip ratios obtained for different beam width are shown in Fig. 4.17. It may be observed that the trend line is almost horizontal under the study parameters. In buildings, having slab with column line beams, the beam and part of the slab act together like a T-beam. When the width of the beam changes, its contribution in changing the stiffness of T-beam is not vary significant. For this reason, the beam width does not demonstrate important role determining effective slab strip ratio (α).

4.3.2.10 Effect of Total Beam Depth

For slab with column line beam structures, the effective slab strip ratios obtained for different beam depth are shown in Fig. 4.18. It may be observed that the trend line is inclined downward under the study parameters. When beam depth increases, its contribution to the total stiffness or inertia of the effective beam (T-beam) increases in cubic proportion. For this reason, beam depth has pronounced effect on effective slab strip ratio (α).

4.4 COMPARATIVE STUDY FOR FLAT PLATE STRUCTURE

From the study made so far, it may be mentioned that following parameters of flat plate structure demonstrate effect on effective slab strip ratio.

a. Span length

b. Bay width

c. Column dimension along span

In the following articles, the procedures suggested by earlier researchers shall be used to determine α for various values of above parameters and comparison shall be made with the results of present analysis.

4.4.1 Effect of Span Length

For flat plate, the effective slab strip ratios obtained for different span lengths are shown in fig 4.19. From fig 4.19, it can be observed that Pecknold's values are highest among all methods closely followed by Lou and Durrani's method. Lowest value of α is given by Grossman's HWNG method. α given by Smith and Coull and Grossman's other two methods (TWR, JSG) lies in between. The result from present finite element analysis lies approximately in the middle of the other methods. It is thus observed that there is a wide variation of results among different methods.

4.4.2 Effect of Bay Width

For flat plate slab, the effective slab strip ratios obtained for different bay widths are shown in fig 4.20. From fig 4.20, it can be observed that Pecknold's values are highest among all methods closely followed by Lou and Durrani's method. Lowest value of α is given by Grossman's HWNG method. α given by Smith and Coull and Grossman's other two methods (TWR, JSG) lies in between. The result from present finite element analysis lies approximately in the middle of the other methods. It is thus observed that there is a wide variation of results among different methods.

4.4.3 Effect of Column Dimension along Span

For flat plate slab, the effective slab strip ratios obtained for different column dimensions along span are shown in fig 4.21. From fig 4.21, it can be observed that Pecknold's values are highest among all methods closely followed by Lou and Durrani's method. Lowest value of α is given by Grossman's HWNG method. α given by Smith and Coull and Grossman's other two methods (TWR, JSG) lies in between. The result from present finite element analysis lies approximately in the middle of the other methods. It is thus observed that there is a wide variation of results among different methods.

4.5 REMARKS

In Pecnold's method, the slab rotation at the contact area of slab column joint is equated with the beam rotation. Considering this slab rotation as rotation of the effective beams may be an over estimation. Because slab rotation, adjacent to the column junction, sharply varies across the width. An average of this rotation would have been more realistic as the rotation of the effective beam. Thus the over estimation of rotation actually increasing the stiffness of the effective beam. This increased stiffness requires a greater portion of the slab to act as the effective beam resulting in higher values in effective slab strip ratio (α). Lou and Durrani's method is based on assumption similar to Pecnold's method. But allowing for cracking reduces the stiffness by some amount. For this reason, effective slab strip ratio (α) values given by Lou and Durrani's method are little lower than Pecnold's method. On the other extreme Grossman's HWNG methodology is giving very low value of effective slab strip ratio (α). This method include a parameter called β which accounts for stiffness degradation under load and is calculated as β=4(C_1/L_1), where C_1= column size and L_1= Span length. This may be an over simplification and over estimation of actual stiffness degradation. For this reason effective slab strip ratio (α) values become lower in Grossman's HWNG methodology. The method of Smith and Coull as well as other two methods (TWR, JSG) gives reasonable value of α when compare to present finite element analysis results.

Wide variation of results among different analytical method suggested by earlier researchers may lead to confusion and indirectly justifies the necessity of present investigation. Results presented so far indicate that for flat plate structures, four parameters have significant influence on effective slab strip ratio (α). These parameters are span length, bay width, column dimension along span and column dimension along bay. Other parameters do not have any appreciable influence on

α for flat plate structures. For structures having slab with column line beam, the important parameter influencing α are span length, bay width, column dimension along span, column dimension along bay, slab thickness, beam width and total beam depth. In the next chapter we shall proceed on developing empirical relationship for estimating α on the basis of these parameters.

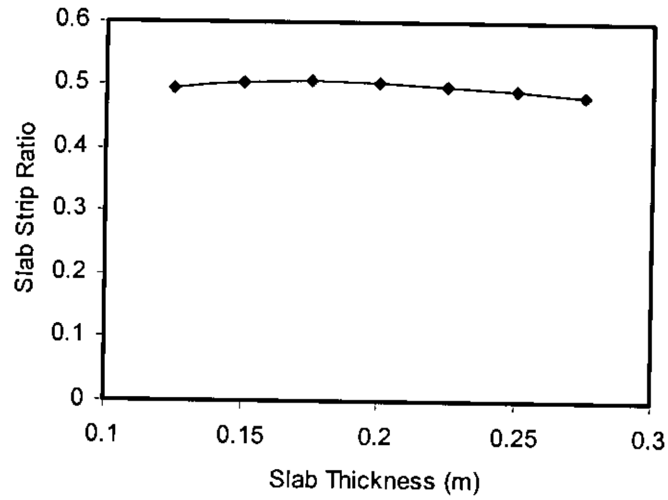


Fig 4.1: Effect of Slab Thickness on Effective Slab Strip Ratio of Flat Plate Structure

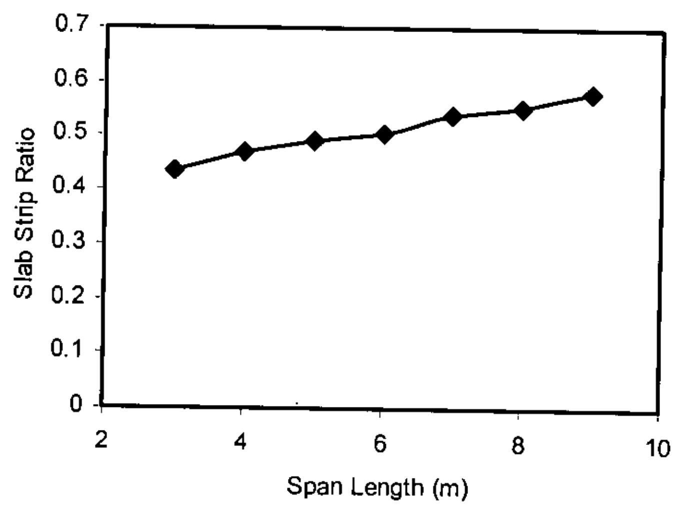


Fig 4.2: Effect of Span Length on Effective Slab Strip Ratio of Flat Plate Structure

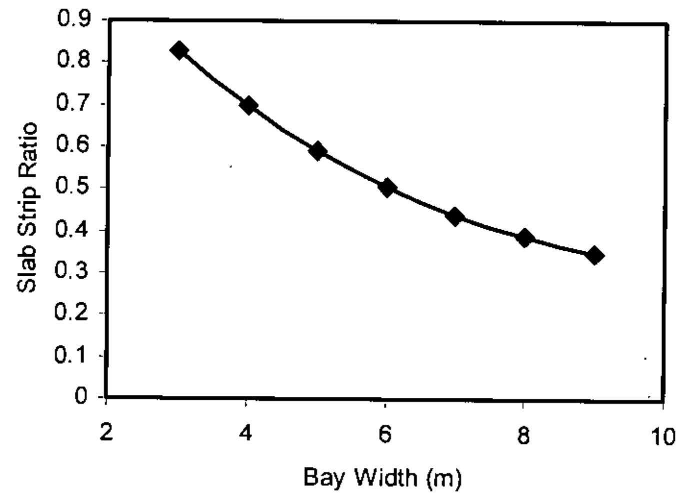


Fig 4.3: Effect of Bay Width on Effective Slab Strip Ratio of Flat Plate Structure

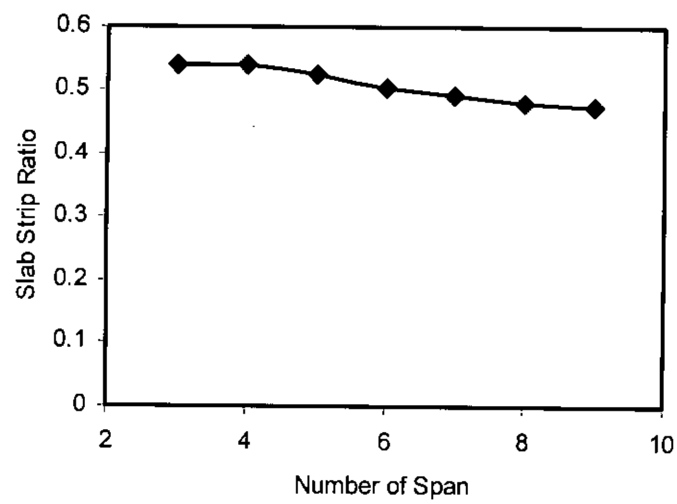


Fig 4.4: Effect of Number of Span on Effective Slab Strip Ratio of Flat Plate Structure

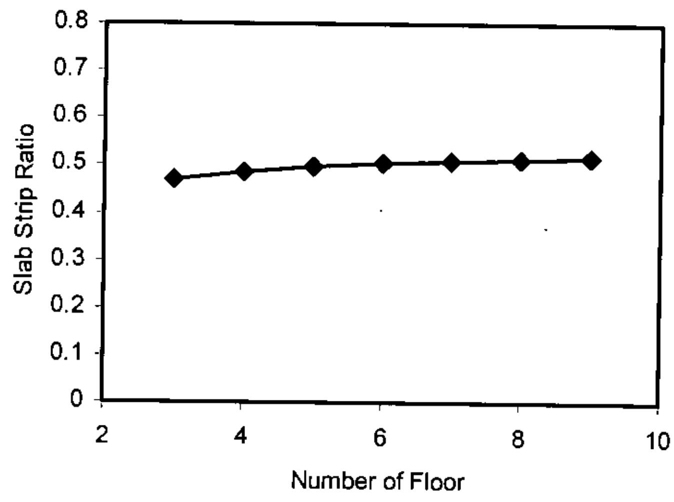


Fig 4.5: Effect of Number of Floor on Effective Slab Strip Ratio of Flat Plate Structure

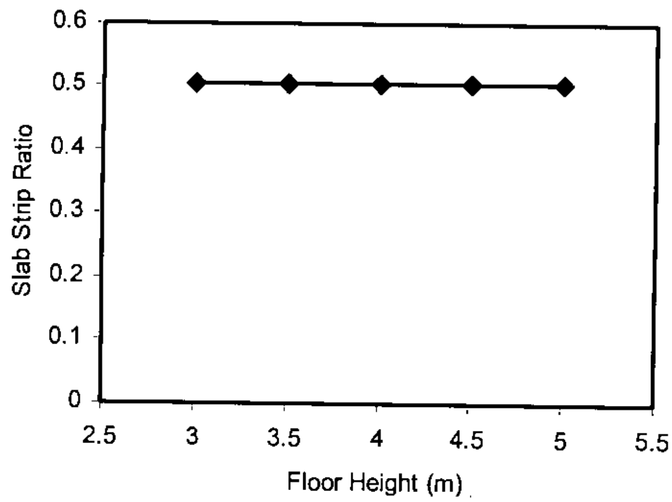


Fig 4.6: Effect of Floor Height on Effective Slab Strip Ratio of Flat Plate Structure

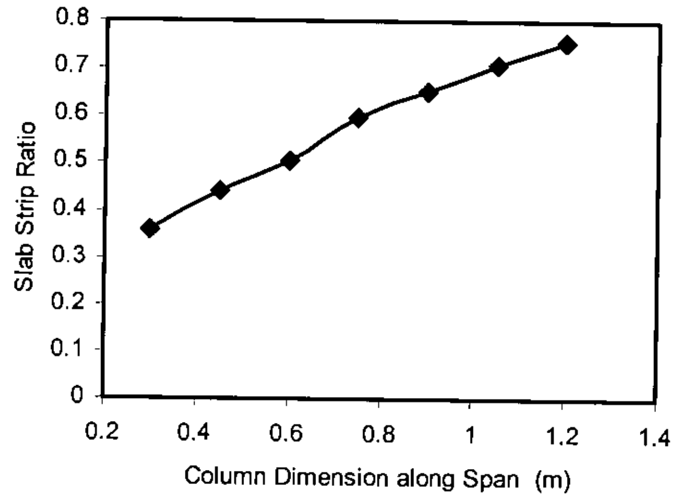


Fig 4.7: Effect of Column dimension along Span on Effective Slab Strip ratio of Flat Plate Structure

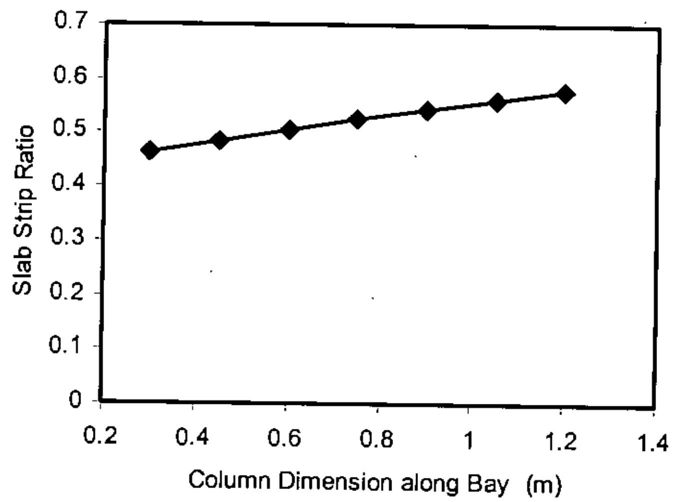


Fig 4.8: Effect of Column dimension along Bay on Effective Slab Strip Ratio of Flat Plate Structure

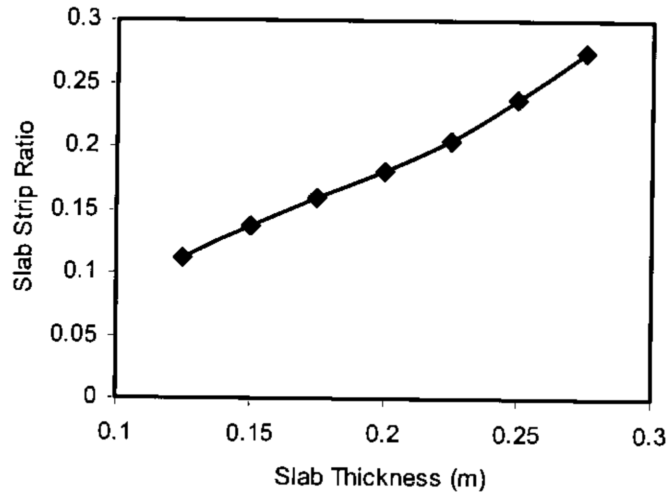


Fig 4.9: Effect of Slab Thickness on Effective Slab Strip Ratio of slab with column line beam Structure

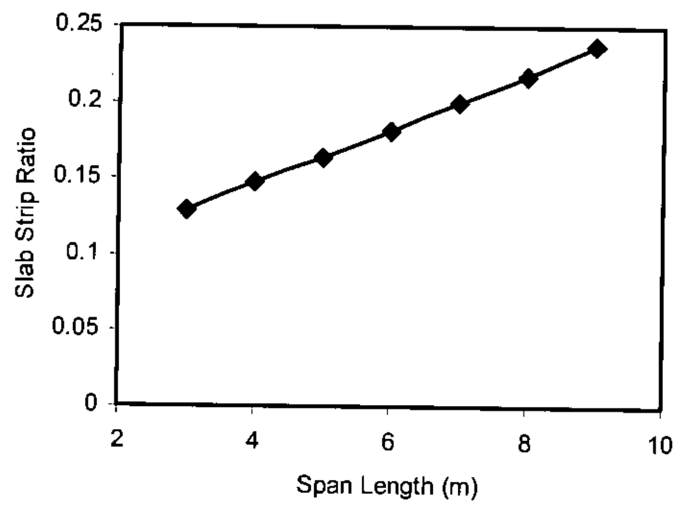


Fig 4.10: Effect of Span Length on Effective Slab Strip Ratio of slab with column line beam Structure

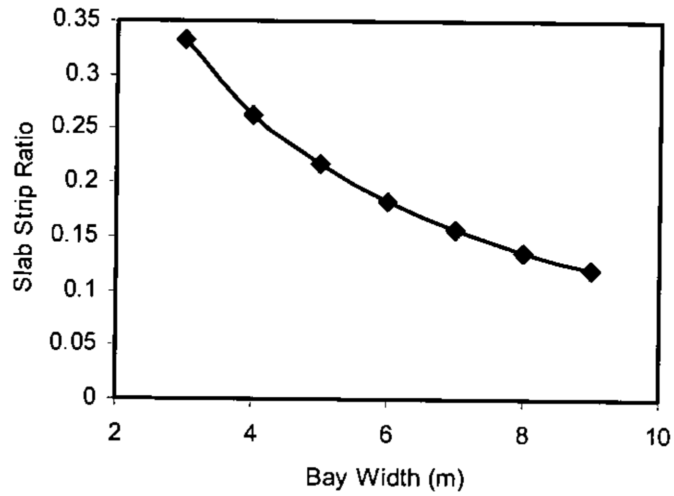


Fig 4.11: Effect of Bay Width on Effective Slab Strip Ratio of slab with column line beam Structure

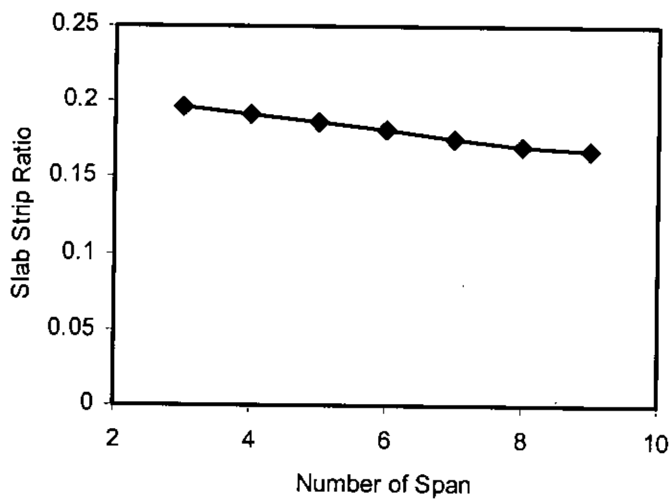


Fig 4.12: Effect of number of Span on Effective Slab Strip Ratio of slab with column line beam Structure

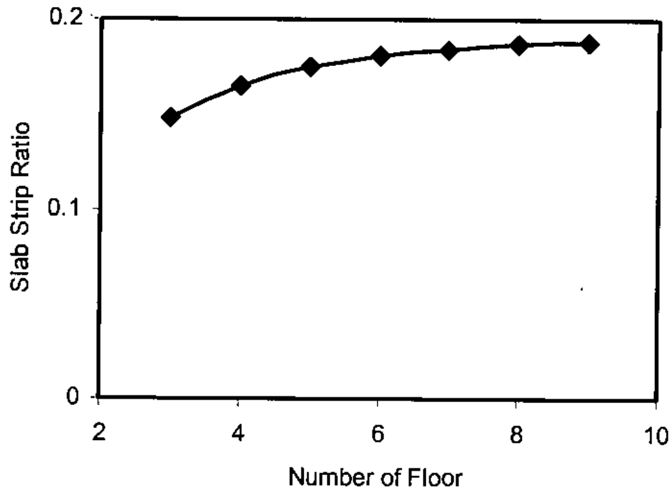


Fig 4.13: Effect of number of Floor on Effective Slab Strip Ratio
of slab with column line beam Structure

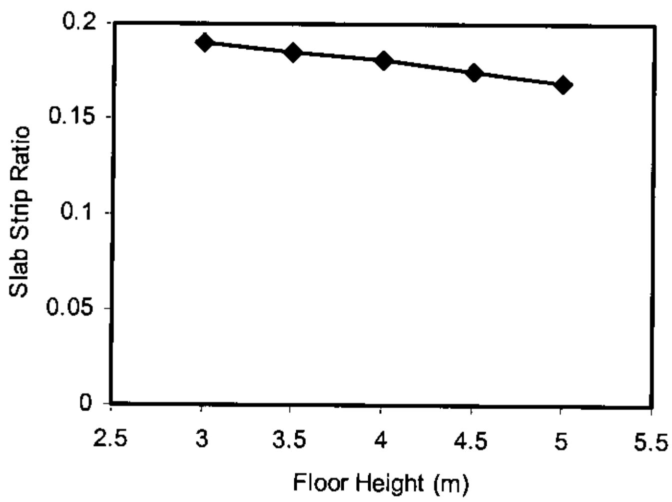


Fig 4.14: Effect of Floor height on Effective Slab Strip Ratio
of slab with column line beam Structure

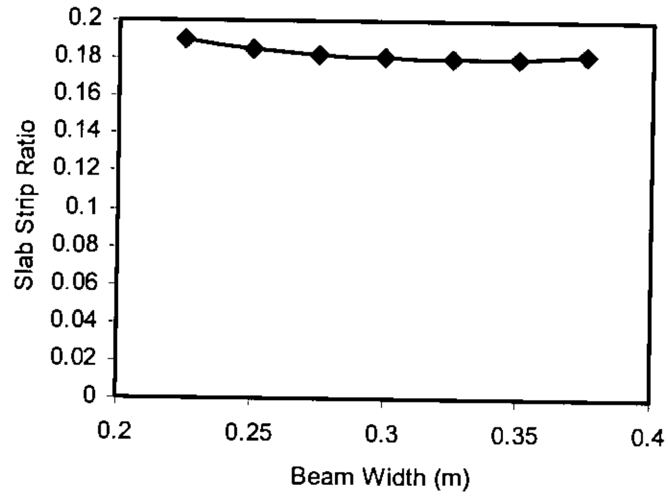


Fig 4.17: Effect of Beam Width on Effective Slab Strip Ratio of slab with column line beam Structure

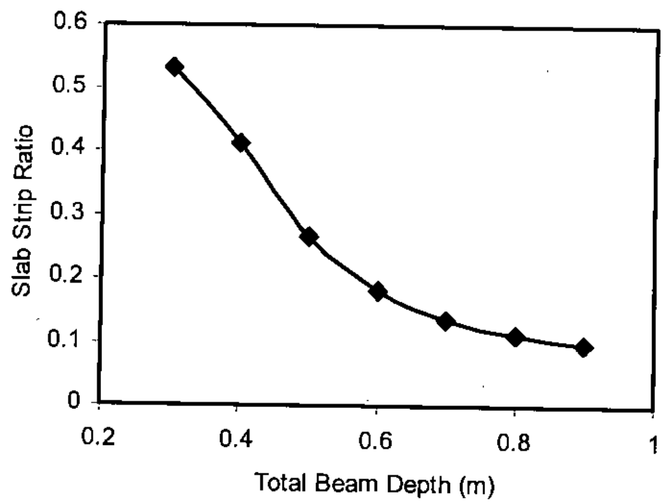


Fig 4.18: Effect of total beam depth on Effective Slab Strip Ratio of slab with column line beam Structure

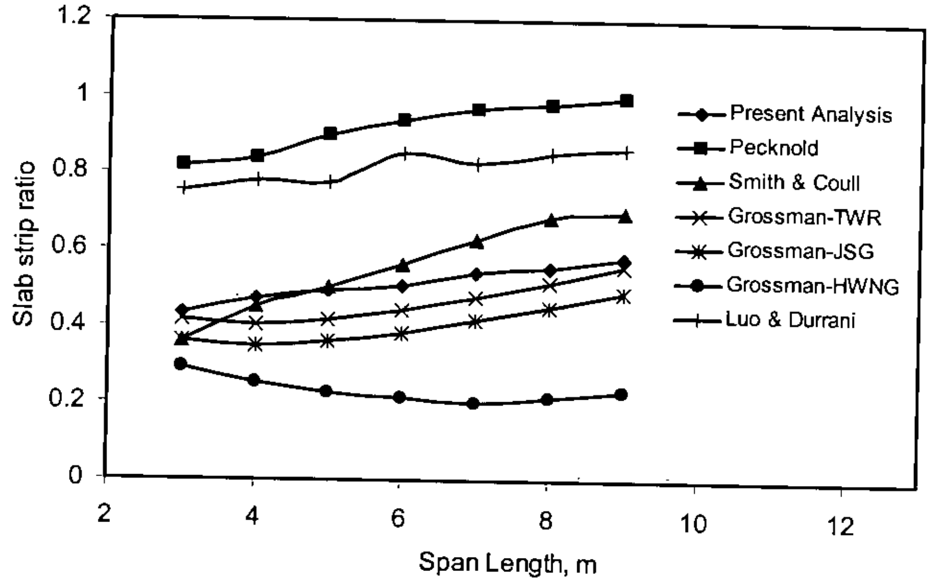


Fig.4.19 Comparison of α by different methods for varying span length.

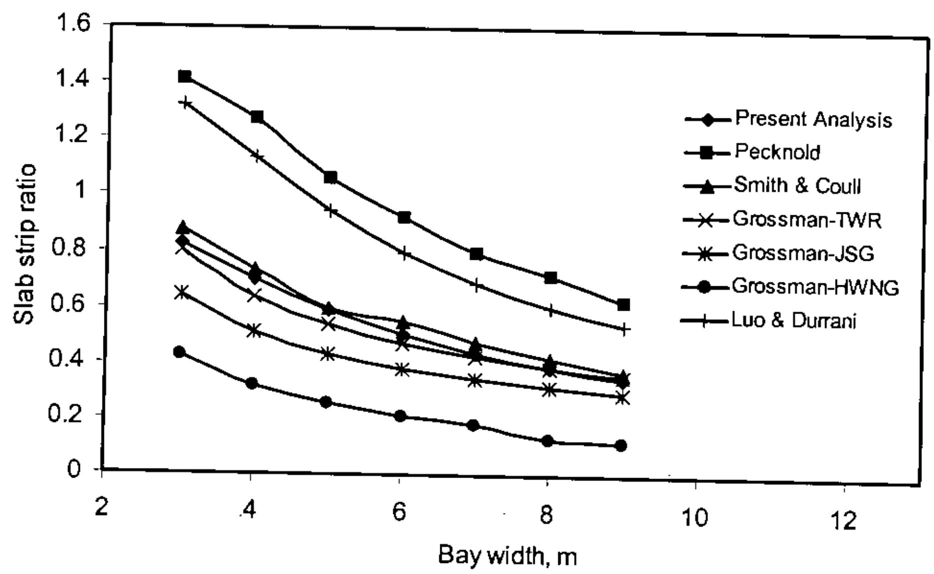


Fig.4.20 Comparison of α by different methods for varying span length.

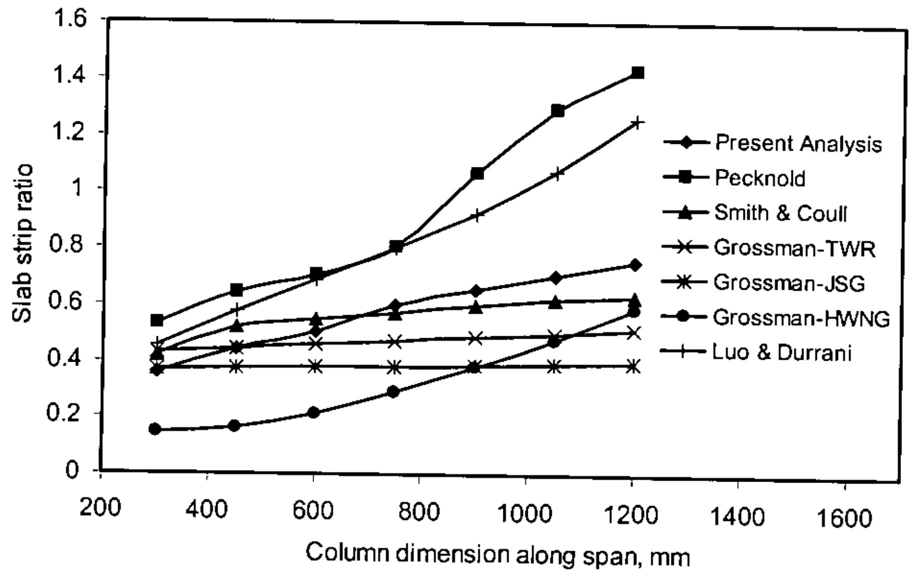


Fig.4.21 Comparison of α by different methods for different column dimension along span.

CHAPTER 5

A RATIONALE FOR EFFECTIVE SLAB STRIP RATIO

5.1 GENERAL

In this chapter we shall proceed on developing some guide line that shall enable us to estimate effective slab strip ratio provided that structural parameter like span length, column dimension along span, bay width etc. are given. Based on the sensitivity analysis presented in the previous chapter attempt shall be made to established an empirical relationship between these parameters that will enable us to determine the value of slab strip ratio.

5.2 EMPIRICAL RELATION FOR FLAT PLATE STRUCTURE

The sensitivity analysis presented in chapter 4 has enabled us to identify the most important structural parameters controlling the magnitude of effective slab strip ratio (α), which are stated above. For example, fig 4.2 demonstrate the variation of α with respect to span length thus this curve of fig 4.2 or its equation can be used to determine α for any value of span length within the range studied provided that other value of structural parameters are kept at their reference value as shown in article 4.2.1. In reality such a situation shall seldom occur. Therefore, we need to combine the effect of all important parameter in one equation which shall enable us to directly evaluate α for any set of parameters within the specified range. We can achieve this by combining or multiplying the expressions of α thus found for span length, bay width, column dimension along span, column dimension along bay. However such absolute multiplication of expressions may not be appropriate. Because in the desired combined expression, we need to have the influence of each parameter in a relative manner. We can achieve this goal by normalization, which is discussed in the next article.

5.2.1 Normalization

For flat plate structures, the effect of span length, bay width, column dimension along span and column dimension along bay are shown in fig 4.2, 4.3, 4.7, 4.8 respectively. In these figures, effect of parameter α is shown in absolute terms. We obtain normalized versions of these graphs by dividing the ordinates by corresponding median ordinate. After doing so we obtain the graph shown fig 5.1 to fig 5.4. The regression equations of these graphs are shown on the respective plots. In all these figures it can be observed that the median value is always unity. Thus these figs may be considered as depicting the relative influence of the corresponding parameters on α.

5.2.2 Empirical Relations

The expression (Equations) of α obtained for each of the four normalized graphs (fig 5.1 to fig 5.4) may now be combined into a single expression. On each of these fig 5.1 to fig 5.4, equation of the curve (Least square polynomial fit) is indicated as $y=f(x)$. We can now obtain the desired equation of α by combining the right hand sides of these equations through multiplication. Since all these component equations depicts relative influence of the parameter on α, we need to introduce a constant multiplier in front of the combined equation. Thus we obtain,

$$\alpha = k\, F_S F_M F_N F_W \tag{5.1}$$

where, $k = 0.6363$

$$F_S = 0.0457S + 0.7366$$
$$F_M = -0.2508M^2 + 1.119M + 0.2838$$
$$F_N = 0.244N + 0.8124$$
$$F_W = 0.0182W^2 - 0.3736W + 2.5896$$

Here,

S = Span Length (3m to 9m)

M = Column Dimension along span (0.3m to 1.2m)

N = Column Dimension along bay (0.3m to 1.2m)

W = Bay Width (3m to 9m)

5.2.3 Verification of the Proposed Empirical Equation

Since the proposed equation is of empirical nature, it is essential that its validity be demonstrated properly. Here it is done by calculating α for 25 different examples and then comparing the results with the same obtain from finite element analysis. For these 25 examples, data is chosen in random fashion within the applicable range. The results of the comparison are shown in table 5.1. It can be observed that α values predicted by proposed equation are close to the corresponding values predicted by finite element analysis. In all cases the error is less than 10 percent. Thus the suggested equation for determining α may be considered acceptable for flat plate structures.

5.3 EMPIRICAL RELATION FOR SLAB WITH COLUMN LINE BEAM

The procedure for developing an empirical expression for effective slab strip ratio (α) in terms of structural parameters is similar to that describe earlier in article 5.1. However, the presence of beam in the column line makes the thing little more complicated. Instead of directly evaluating effective slab strip ratio (α) in terms of structural parameters, it would be easier to develop an expression of moment of inertia (I) of the effective beam. Normalized variation of relative inertia (I/I_0) with respect to different parameters are shown in fig 5.5 to fig 5.11. These figures are accompanied by corresponding data table. In this data tables the moment of inertia of effective beam as well as its ratio to the total moment of inertia (I_0) is also calculated and shown. Here total inertia I_0 correspond to the inertia of the section of slab bounded between two adjacent panel center lines. Instead of normalizing α values we proceed on with normalizing the relative inertia value (I/I_0) by dividing with the median relative inertia value. In this manner we obtain the normalized graphs of fig 5.5 to fig 5.11. These figures now depict the relative influence of corresponding structural parameter on the relative inertia of effective beam. Following the procedure similar to that followed for flat plate structures, we now combine these graph.

Thus we obtain, $\frac{I}{I_0} = \beta\, C_S C_M C_N C_W C_B C_D C_T$ (5.2)

Where, $\beta = 0.685$

$C_S = 0.0359S + 0.7858$, $C_M = 0.5985M + 0.5243$

$C_N = 0.115N + 0.8994$, $C_W = 1.6455\ W^{-0.284}$

$C_B = -0.1564B + 1.0531$, $C_D = 0.8963D^2 - 2.1026D + 1.9504$

$C_T = -5.5911T^2 + 2.9969T + 0.6262$

Here,

I = Stiffness calculated from effective width

I_0 = Stiffness calculated from bay width

S = Span Length (3m to 9m)

M = Column Dimension along span (0.3m to 1.2m)

N = Column Dimension along bay (0.3m to 1.2m)

W = Bay Width (3m to 9m)

B = Beam Width (0.225m to 0.375m)

D = Total Beam Depth (0.3m to 0.9m)

T = Slab Thickness (0.125m to 0.275m)

5.3.1 Verification of the Empirical Relation

Since the proposed equation is of empirical nature, it is essential that its validity be demonstrated properly. Here it is done by calculating I/I_s for 25 different examples and then comparing the results with that obtain from finite element analysis. For these 25 examples, data is chosen in random fashion within the applicable range. The results of the comparison are shown in table 5.10. It can be observed that I/I_s values predicted by proposed equation are close to the corresponding values predicted by finite element analysis. In all cases the error is less than 10 percent. Thus the suggested equation for determining I/I_s (From which we can calculate α) may be considered acceptable for slab with column line beam structures.

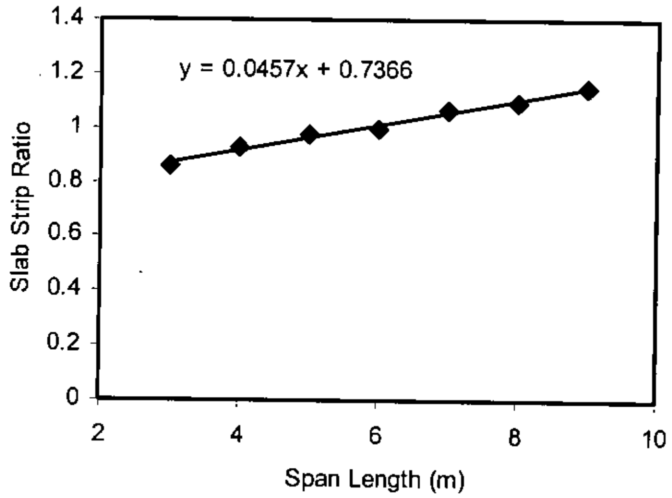


Fig: 5.1 Effect of Span length on Effective Slab Strip Ratio (with equation)

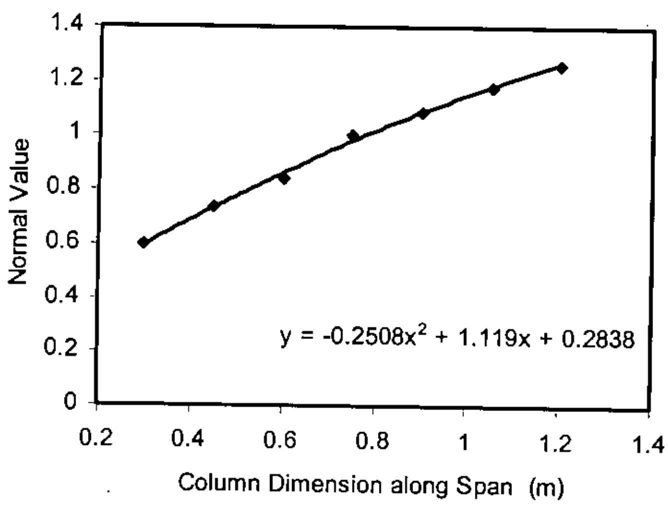


Fig: 5.2 Effect of column dimension along span vs effective slab strip ratio

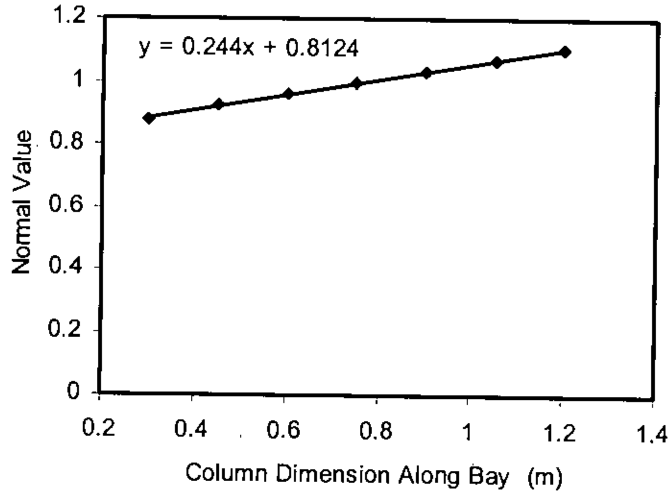


Fig: 5.3 Effect of column dimension along bay vs effective slab strip ratio

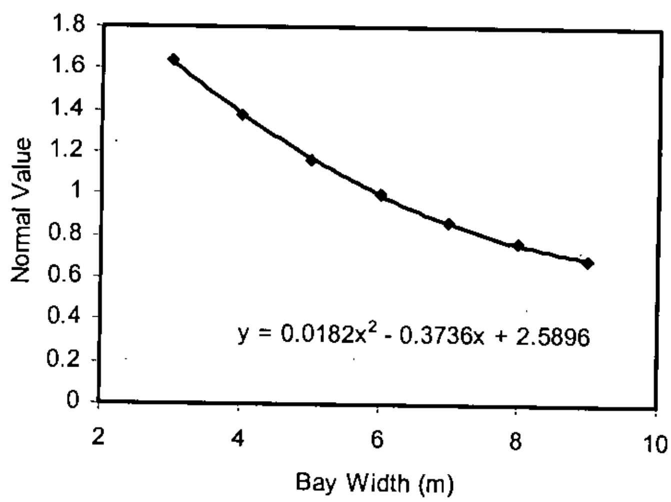


Fig: 5.4 Effect of bay width vs effective slab strip ratio

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Table 5.1: Comparison of α for flat plate system for 25 different sets of data.

Set No	Slab Thickness, (mm)	Span Length (m)	Bay Width (m)	Number of Spans	Number of Floors	Floor Height, (m)	Col Dimension along Span, (mm)	Col Dimension along Bay, (mm)	α From Eqn.5.1	α From Analysis	% of Deviation
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)
1	235	6	5	7	7	4.2	909	402	0.72	0.74	3.03
2	203	9	7	4	9	4.1	687	883	0.58	0.61	3.74
3	234	4	8	7	8	3.1	621	413	0.34	0.34	-2.33
4	195	8	5	7	9	4.4	458	758	0.59	0.60	2.94
5	209	4	9	7	9	4.2	529	816	0.32	0.32	-0.55
6	213	6	5	6	6	3.1	880	482	0.72	0.73	1.38
7	238	7	5	8	10	3.3	996	447	0.80	0.80	0.17
8	239	4	6	5	10	4.5	449	854	0.42	0.41	-1.9
9	209	6	8	8	10	4.1	606	937	0.43	0.43	0.07
10	230	3	7	6	6	4.2	689	644	0.41	0.42	0.24
11	199	5	5	4	9	3.5	545	595	0.54	0.58	6.75
12	233	5	6	8	8	3.0	701	540	0.52	0.53	1.02
13	226	6	6	7	8	4.9	624	407	0.50	0.48	-2.63
14	181	7	3	3	8	4.6	733	450	0.94	0.94	0.36
15	193	3	6	3	8	3.7	459	480	0.37	0.35	-5.12
16	192	5	3	8	5	4.8	841	826	1.01	1.00	0.00
17	183	8	8	8	7	3.4	766	587	0.49	0.46	-7.19
18	163	3	6	7	5	3.8	589	970	0.47	0.50	4.70
19	217	9	6	4	8	3.8	552	600	0.56	0.60	6.77
20	249	6	8	6	10	3.7	879	471	0.47	0.49	4.67
21	177	4	6	3	9	3.8	528	638	0.43	0.46	5.34
22	150	7	3	7	6	4.8	875	972	1.18	0.95	-5.37
23	215	5	9	3	7	3.9	964	904	0.48	0.47	1.00
24	206	3	4	8	5	3.3	445	589	0.51	0.49	-3.92
25	202	8	7	4	9	4.5	871	633	0.60	0.63	4.39

Table 5.2: Data table for effective slab strip ratio vs span length of slab with column line beam.

Span Length (m)	Bay Width(m)	Effective Width (m)	Effective Slab Strip Ratio (α)	I / Is	Normal Value
(a)	(b)	(c)	(d)	(e)	(f)
3	6	0.792	0.132	0.536	0.89
4	6	0.888	0.148	0.560	0.93
5	6	1.00	0.167	0.585	0.97
6	6	1.092	0.182	0.603	1.0
7	6	1.242	0.207	0.630	1.045
8	6	1.35	0.225	0.647	1.073
9	6	1.47	0.245	0.665	1.103

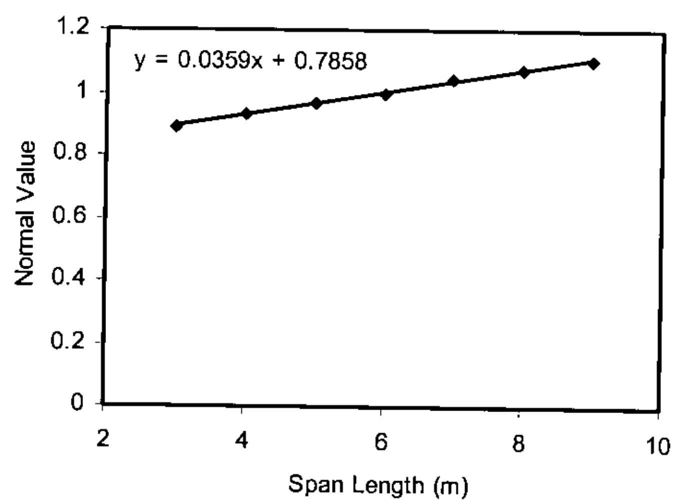

Fig 5.5: Effect of span length vs effective slab strip ratio.

Table 5.3: Data table for effective slab strip ratio vs column dimension along span of slab with column line beam.

Column Dimension along Span (mm)	Bay Width (m)	Effective Width (m)	Effective Slab Strip Ratio (α)	I / Is	Normal Value
(a)	(b)	(c)	(d)	(e)	(f)
300	6	0.6	0.100	0.480	0.703
450	6	0.768	0.128	0.530	0.776
600	6	1.092	0.182	0.603	0.883
750	6	1.608	0.268	0.683	1.0
900	6	2.04	0.340	0.733	1.073
1050	6	2.598	0.433	0.785	1.150
1200	6	3.3	0.550	0.839	1.230

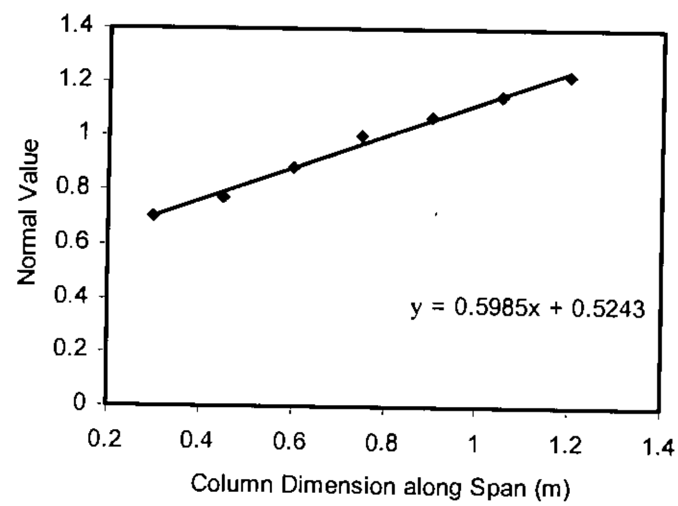

Fig 5.6: Effect of Column dimension along Span vs effective slab strip ratio.

Table 5.4: Data table effective slab strip ratio vs column dimension along bay of slab with column line beam.

Column Dimension along Bay(mm)	Bay Width (m)	Effective Width (m)	Effective Slab Strip Ratio (α)	I / Is	Normal Value
(a)	(b)	(c)	(d)	(e)	(f)
300	6	0.888	0.148	0.560	0.910
450	6	1.02	0.170	0.590	0.959
600	6	1.092	0.182	0.603	0.980
750	6	1.158	0.193	0.615	1.0
900	6	1.182	0.197	0.620	1.008
1050	6	1.212	0.202	0.625	1.016
1200	6	1.242	0.207	0.630	1.024

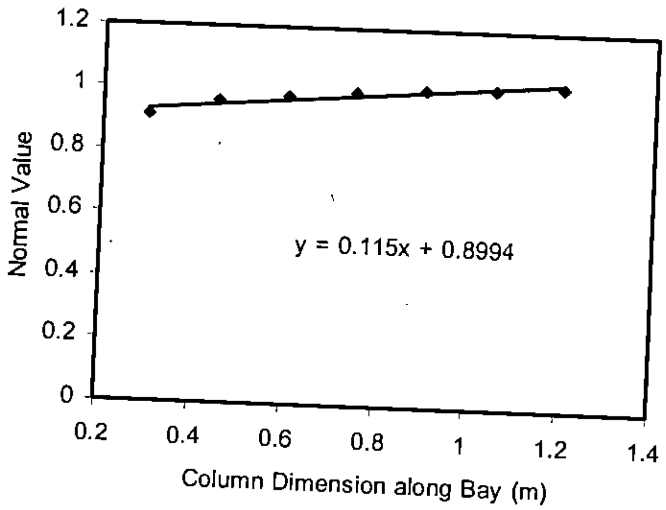

Fig 5.7: Effect of Column dimension along bay vs effective slab strip ratio.

Table 5.5 Data table effective slab strip ratio vs bay width of slab with column line beam.

Bay Width (m)	Bay Width (m)	Effective Width (m)	Effective Slab Strip Ratio (α)	I / I_s	Normal Value
(a)	(b)	(c)	(d)	(e)	(f)
3	3	0.999	0.333	0.715	1.186
4	4	1.052	0.263	0.672	1.114
5	5	1.09	0.218	0.637	1.056
6	6	1.092	0.182	0.603	1.00
7	7	1.092	0.156	0.573	0.95
8	8	1.088	0.136	0.547	0.90
9	9	1.089	0.121	0.524	0.869

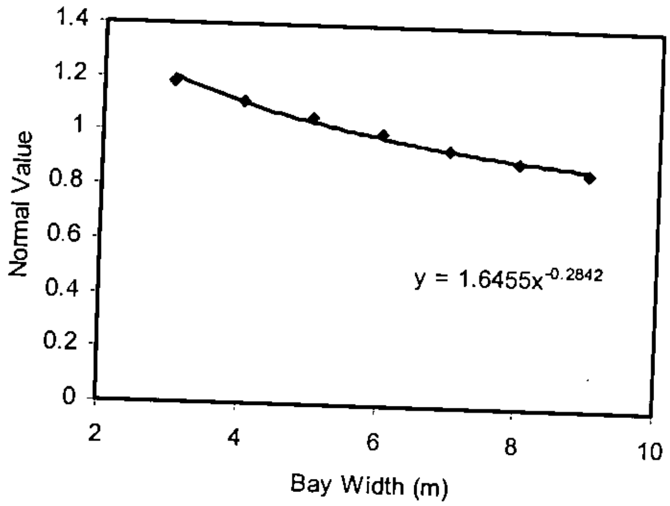

Fig 5.8: Effect of bay width vs effective slab strip ratio.

Table 5.6: Data table effective slab strip ratio vs beam width of slab with column line beam.

Beam Width (mm)	Bay Width (m)	Effective Width (m)	Effective Slab Strip Ratio (α)	*1 / Is*	Normal Value
(a)	(b)	(c)	(d)	(e)	(f)
225	6	1.188	0.198	0.620	1.028
250	6	1.152	0.192	0.614	1.018
275	6	1.08	0.180	0.600	0.995
300	6	1.092	0.182	0.603	0.995
325	6	1.098	0.183	0.604	1.0
350	6	1.08	0.180	0.600	1.002
375	6	1.11	0.185	0.606	1.004

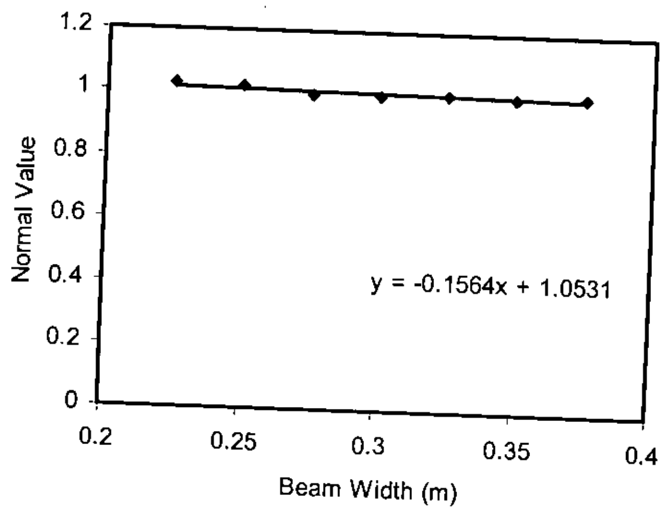

Fig 5.9: Effect of beam width vs effective slab strip ratio.

Table 5.7: Data table effective slab strip ratio vs total beam depth of slab with column line beam.

Total Beam Depth (mm)	Bay Width(m)	Effective Width (m)	Effective Slab Strip Ratio (α)	I/Is	Normal Value
(a)	(b)	(c)	(d)	(e)	(f)
300	6	3.18	0.530	0.830	1.37
400	6	2.508	0.418	0.777	1.29
500	6	1.602	0.267	0.682	1.13
600	6	1.092	0.182	0.603	1.0
700	6	0.828	0.138	0.546	0.905
800	6	0.672	0.112	0.503	0.834
900	6	0.600	0.100	0.480	0.796

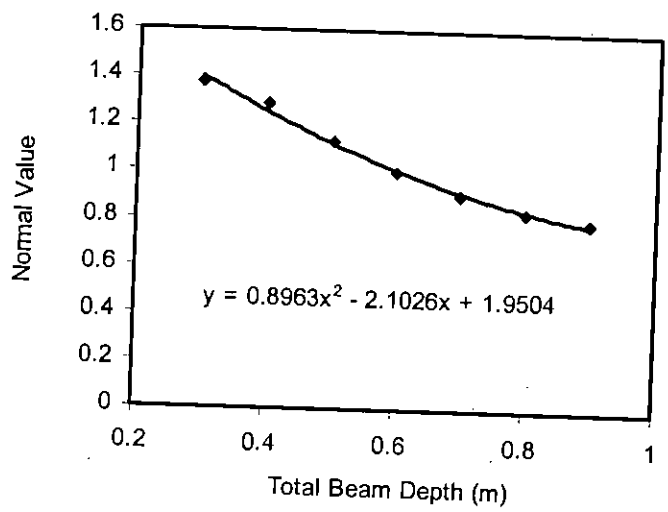

Fig 5.10: Effect of total beam depth vs effective slab strip ratio.

Table 5.8: Data table effective slab strip ratio vs slab thickness of slab with column line beam.

Slab Thickness, (mm)	Bay Width(m)	Effective Width (m)	Effective Slab Strip Ratio (α)	*I / Is*	Normal Value
(a)	(b)	(c)	(d)	(e)	(f)
125	6	0.672	0.112	0.550	0.912
150	6	0.828	0.138	0.572	0.948
175	6	0.954	0.159	0.595	0.987
200	6	0.1.086	0.181	0.603	1.00
225	6	1.23	0.205	0.610	1.012
250	6	1.428	0.238	0.620	1.028
275	6	1.65	0.275	0.620	1.028

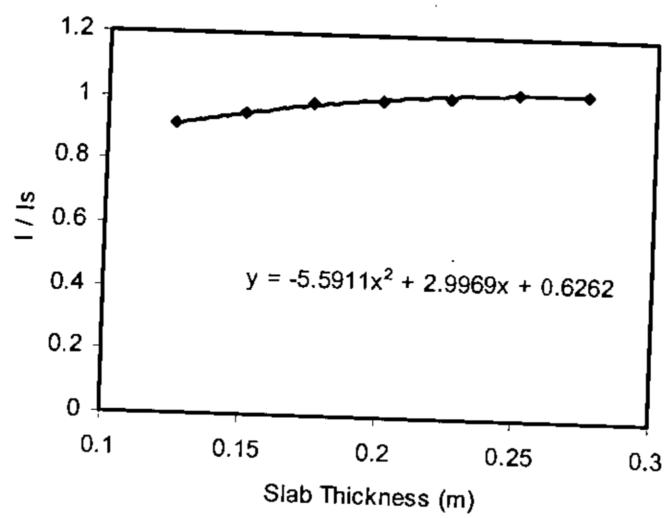

Fig 5.11: Effect of slab thickness vs effective slab strip ratio.

Table 5.9: 25 different sets of data for slab with col. Line beam.

Set No	Slab Thickness, (mm)	Span Length (m)	Bay Width, (m)	Number of Spans	Number of Floors	Floor Height (m)	Column Dimension Along Span, (mm)	Column Dimension Along Bay, (mm)	Total Beam Depth (mm)	Beam Width (mm)
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)
1	182	8	6	7	4	3.7	467	718	895	257
2	208	5	3	3	7	4.1	421	429	716	261
3	199	7	6	7	9	3.2	814	813	638	268
4	219	6	5	7	7	4.1	830	891	450	257
5	190	7	8	3	8	4.0	483	560	854	241
6	235	6	7	9	5	4.6	923	857	609	228
7	173	7	9	9	8	4.0	421	490	748	269
8	227	7	3	6	5	4.5	695	690	767	261
9	223	5	8	9	5	5.0	447	532	548	255
10	239	8	3	7	7	3.6	763	689	603	250
11	158	6	3	6	4	4.4	601	459	467	253
12	208	8	6	9	6	4.6	471	562	493	254
13	240	8	9	7	6	5.0	424	659	634	272
14	158	4	8	4	5	3.1	589	713	855	262
15	236	7	6	3	6	4.7	500	562	537	261
16	163	3	7	8	7	3.1	632	969	586	260
17	247	7	5	9	10	3.5	466	564	715	226
18	236	7	4	7	8	4.0	902	969	554	230
19	185	8	4	5	6	4.5	579	579	572	272
20	154	4	5	6	4	4.7	658	595	707	243
21	181	5	9	6	9	3.7	829	922	862	250
22	180	7	6	7	9	3.1	711	665	898	273
23	189	5	7	6	7	4.2	723	784	799	274
24	201	7	5	5	5	4.6	621	629	681	241
25	168	3	7	8	8	3.5	879	809	755	235

Table 5.10 Comparison of α for 25 different sets of data.

Set No	α from Analysis	Effective width (m)	I/I_0 from Analysis	I/I_0 from Equation 5.2	% of Deviation
(a)	(b)	(c)	(d)	(e)	(f)
1	0.086	0.516	0.476	0.468	-9.17
2	0.174	0.522	0.563	0.561	3.37
3	0.279	1.674	0.742	0.721	6.39
4	0.731	3.655	0.913	0.925	-0.31
5	0.060	0.480	0.451	0.430	3.96
6	0.372	2.604	0.786	0.759	10.00
7	0.060	0.540	0.453	0.420	7.04
8	0.308	0.924	0.707	0.731	0.94
9	0.083	0.664	0.490	0.525	-8.48
10	0.575	1.725	0.868	0.930	1.38
11	0.368	1.104	0.759	0.825	4.63
12	0.200	1.200	0.651	0.677	-5.90
13	0.087	0.783	0.511	0.520	-9.98
14	0.066	0.528	0.452	0.410	7.29
15	0.265	1.590	0.702	0.651	7.93
16	0.111	0.777	0.557	0.554	-9.97
17	0.133	0.665	0.575	0.568	0.11
18	0.843	3.372	0.958	0.977	-0.55
19	0.294	1.176	0.721	0.741	0.97
20	0.106	0.530	0.506	0.547	0.60
21	0.081	0.729	0.517	0.499	3.08
22	0.118	0.708	0.532	0.528	6.64
23	0.106	0.742	0.536	0.520	3.66
24	0.193	0.965	0.653	0.635	5.82
25	0.117	0.819	0.574	0.544	10.00

CHAPTER 6

CONCLUSION

6.1 GENERAL

The thesis started with an aim to find out the behavior of flat plate structures as well as slab with column line beam structures under lateral load, with special emphasis on determination of effective slab strip ratio under various parametric conditions. And to do that, firstly, some parameters are chosen for flat plate structures and slab with column line beam followed by analysis using finite element method. The effective slab strip ratio, α is determined by adjusting the moment of inertia of the 2D model maintaining the same deflection as obtained from 3D analysis. Figures (graphs) showing variation of α with respect to different parameters are presented and studied. From these figures, controlling parameters for effective slab strip ratio for both flat plate structure and slab with column line beam are determined. Then, two empirical relations for determining α involving the controlling parameters for both flat plate structure and slab with line beam are developed and their validity are verified with typical arbitrary examples.

6.2 FINDINGS

The outcome of the thesis is summarized as follows:

a. For flat plate structures, effective slab strip ratio varies with span length, bay width, column dimension along span and column dimension along bay

b. Effective slab strip ratio does not vary with slab thickness, number of span, number of floor and floor height for flat plate structures.

c. For slab with column line beam type floors, effective slab strip ratio varies with slab thickness, span length, bay width, column dimension along span, column dimension along bay, beam width and beam depth.

d. Effective slab strip ratio does not vary with number of span, number of floor and floor height for slab with column line beam.

e. Column line beam structures have reduce effective slab strip ratio than flat plate structures by approximately 63.33%.

6.3 EMPIRICAL RELATION FOR ESTIMATING EFFECTIVE SLAB STRIP RATIO

In this thesis, based on the findings of computational finite element investigation, two empirical relations for flat plate structure and slab with column line beam for determining α have been developed. The validity of these equations has been established by determining α from these equations and comparing them with finite element analysis results for several examples. It has been shown that the equations can reasonably predict the value of equivalent slab strip within its limit of applicability.

6.4 SCOPE FOR FUTURE INVESTIGATION

The study presented in this thesis was limited in scope. For simplicity, slenderness of the structures was not considered. Twisting moment at the end due to variation of bay widths on opposite sides of column line may be investigated in future. Only geometric parameters were studied in this thesis. Other parameters such as live load, horizontal load acting from diagonal direction which may influence the effective slab strip ratio may be studied. Also the study may be further extended to include non-linear material effects.

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9) Nilson A. H., Darwin D.Dolan C. W., 2003, "Design of Concrete Structures", McGraw-Hill, 13th Edition.

10) Pecknold D. A., 1975, "Slab Effective Width for Equivalent Frame Analysis", ACI Journal, Proceedings V. 72, No. 4.

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12) Vanderbilt M. D. and Corley W. G., 1983, "Frame Analysis of Concrete Buildings", Concrete Int., Vol. 5, No. 12.

13) Vainiunas P, Popovas V. and Jarmolajev A., 2002, "Punching Shear Behaviour Analysis of RC Flat Floor Slab-to-Column Connection", Journal of Civil Engineering and Management, Department of Architectural Engineering, Vilnius Gediminas Technical University, Lithuania.

Appendix to Chapter 4

Table 1: Effective Slab Strip Ratio and Span Length of Flat Plate Structure

Span Length (m)	Deflection (m)	Effective Slab Strip Ratio(α)						
		Present Analysis	Pecknold	Smith and Coull	Grossman			Lou and Durrani
					TWR	JSG	HWNG	
3	0.079	0.435	0.82	0.36	0.417	0.358	0.293	0.755
4	0.088	0.470	0.84	0.45	0.404	0.346	0.253	0.782
5	0.095	0.492	0.90	0.50	0.417	0.358	0.229	0.776
6	0.101	0.505	0.94	0.56	0.443	0.382	0.213	0.854
7	0.104	0.539	0.97	0.625	0.476	0.414	0.202	0.828
8	0.107	0.552	0.98	0.687	0.514	0.451	0.215	0.852
9	0.109	0.580	1.0	0.7	0.555	0.490	0.233	0.865

Table 1.1: Effective Slab Strip Ratio and Span Length of Flat Plate Structure (Pecknold)

Span length 2a (m)	Bay width 2b(m)	Column size along span 2u(m)	Column size /Span length $\frac{u}{a}$	Slab Aspect Ratio $\frac{b}{a}$	Effective width $\frac{b'}{b}$	Effective Slab Strip Ratio α
3	6	0.75	0.25	2.0	0.80	0.82
4	6	0.75	0.187	1.5	0.80	0.84
5	6	0.75	0.15	1.2	0.77	0.90
6	6	0.75	0.125	1.0	0.92	0.94
7	6	0.75	0.107	0.86	0.95	0.97
8	6	0.75	0.094	0.75	0.96	0.98
9	6	0.75	0.083	0.67	0.98	1.0

Table 1.2: Effective Slab Strip Ratio and Span Length of Flat Plate Structure (Smith and Coull)

Span length 2a (m)	Bay width 2b(m)	Column size along span 2u(m)	Column size /Span length $\frac{u}{a}$	Slab Aspect Ratio $\frac{b}{a}$	Effective Slab Strip Ratio α
3	6	0.75	0.25	2.0	0.36
4	6	0.75	0.187	1.5	0.45
5	6	0.75	0.15	1.2	0.50
6	6	0.75	0.125	1.0	0.56
7	6	0.75	0.107	0.86	0.625
8	6	0.75	0.0937	0.75	0.687
9	6	0.75	0.083	0.67	0.7

Table 1.3: Effective Slab Strip Ratio and Span Length of Flat Plate Structure (Grossman-TWR)

l_1 (m)	l_2 (m)	c_1 (m)	c_2 (m)	α
3	6	0.75	0.75	0.417
4	6	0.75	0.75	0.404
5	6	0.75	0.75	0.417
6	6	0.75	0.75	0.443
7	6	0.75	0.75	0.476
8	6	0.75	0.75	0.514
9	6	0.75	0.75	0.555

Table 1.4: Effective Slab Strip Ratio and Span Length of Flat Plate Structure (Grossman-JSG)

l_1 (m)	l_2 (m)	c_1 (m)	c_2 (m)	l_{1n} (m)	x	α
3	6	0.75	0.75	2.25	2.0	0.358
4	6	0.75	0.75	3.25	1.5	0.346
5	6	0.75	0.75	4.25	1.2	0.358
6	6	0.75	0.75	5.25	1.0	0.382
7	6	0.75	0.75	6.25	0.857	0.414
8	6	0.75	0.75	7.25	0.75	0.451
9	6	0.75	0.75	8.25	0.67	0.490

Table 1.5: Effective Slab Strip Ratio and Span Length of Flat Plate Structure (Grossman-HWNG)

l_1 (m)	l_2 (m)	c_1 (m)	c_2 (m)	β	α
3	6	0.75	0.75	0.8	0.293
4	6	0.75	0.75	0.6	0.253
5	6	0.75	0.75	0.48	0.229
6	6	0.75	0.75	0.40	0.213
7	6	0.75	0.75	0.343	0.202
8	6	0.75	0.75	0.333	0.215
9	6	0.75	0.75	0.333	0.233

Table 1.6: Effective Slab Strip Ratio and Span Length of Flat Plate Structure (Lou and durrani)

l_1 (m)	l_2 (m)	c_1 (m)	c_2 (m)	$\frac{c_1}{l_1}$	$\frac{c_1}{l_2}$	$\frac{l_1}{l_2}$	α_i	$\chi\alpha_i$
3	6	0.75	0.75	0.25	0.125	0.5	1.07	0.755
4	6	0.75	0.75	0.187	0.125	0.67	0.879	0.782
5	6	0.75	0.75	0.15	0.125	0.833	0.872	0.776
6	6	0.75	0.75	0.125	0.125	1.0	0.899	0.854
7	6	0.75	0.75	0.107	0.125	1.167	0.931	0.828
8	6	0.75	0.75	0.094	0.125	1.33	0.957	0.852
9	6	0.75	0.75	0.083	0.125	1.5	0.971	0.865

Table 2: Effective Slab Strip Ratio and Bay Width of Flat Plate Structure

Bay Width (m)	Deflection (m)	Effective Slab Strip Ratio(α)						
		Present Analysis	Pecknold	Smith and Coull	Grossman			Lou and Durrani
					TWR	JSG	HWNG	
3	0.047	0.827	1.41	0.875	0.805	0.642	0.427	1.32
4	0.049	0.698	1.27	0.735	0.639	0.512	0.32	1.135
5	0.050	0.590	1.06	0.60	0.539	0.435	0.256	0.946
6	0.051	0.505	0.92	0.55	0.472	0.383	0.213	0.8
7	0.051	0.440	0.797	0.48	0.425	0.346	0.183	0.69
8	0.051	0.389	0.716	0.42	0.389	0.318	0.133	0.606
9	0.051	0.349	0.624	0.37	0.361	0.296	0.118	0.539

Table 2.1: Effective Slab Strip Ratio and Bay Width of Flat Plate Structure (Pecknold)

Span length 2a (m)	Bay Width 2b (m)	Column size along span 2u(m)	Column size / Span length $\frac{u}{a}$	Slab Aspect Ratio $\frac{b}{a}$	Effective width $\frac{b'}{b}$	Effective Slab Strip Ratio α
6	3	0.75	0.125	0.5	1.38	1.41
6	4	0.75	0.125	0.67	1.24	1.27
6	5	0.75	0.125	0.833	1.04	1.06
6	6	0.75	0.125	1.0	0.9	0.92
6	7	0.75	0.125	1.167	0.78	0.797
6	8	0.75	0.125	1.33	0.7	0.716
6	9	0.75	0.125	1.5	0.61	0.624

Table 2.2: Effective Slab Strip Ratio and Bay Width of Flat Plate Structure (Smith and Coull)

Span length 2a (m)	**Bay Width 2b (m)**	**Column size along span 2u(m)**	**Column size / Span length** $\frac{u}{a}$	**Slab Aspect Ratio** $\frac{b}{a}$	**Effective Slab Strip Ratio** α
6	3	0.75	0.125	0.5	0.875
6	4	0.75	0.125	0.67	0.735
6	5	0.75	0.125	0.833	0.60
6	6	0.75	0.125	1.0	0.55
6	7	0.75	0.125	1.167	0.48
6	8	0.75	0.125	1.33	0.42
6	9	0.75	0.125	1.5	0.37

Table 2.3: Effective Slab Strip Ratio and Bay Width of Flat Plate Structure (Grossman-TWR)

l_1 (m)	l_2 (m)	c_1 (m)	c_2 (m)	α
6	3	0.75	0.75	0.805
6	4	0.75	0.75	0.639
6	5	0.75	0.75	0.539
6	6	0.75	0.75	0.472
6	7	0.75	0.75	0.425
6	8	0.75	0.75	0.389
6	9	0.75	0.75	0.361

Table 2.4: Effective Slab Strip Ratio and Bay Width of Flat Plate Structure (Grossman-JSG)

l_1 (m)	l_2 (m)	c_1 (m)	c_2 (m)	l_{1n} (m)	X	α
6	3	0.75	0.75	5.25	0.5	0.642
6	4	0.75	0.75	5.25	0.67	0.512
6	5	0.75	0.75	5.25	0.833	0.435
6	6	0.75	0.75	5.25	1.0	0.383
6	7	0.75	0.75	5.25	1.17	0.346
6	8	0.75	0.75	5.25	1.33	0.318
6	9	0.75	0.75	5.25	1.5	0.296

Table 2.5: Effective Slab Strip Ratio and Bay Width of Flat Plate Structure (Grossman-HWNG)

l_1 (m)	l_2 (m)	c_1 (m)	c_2 (m)	β	α
6	3	0.75	0.75	0.4	0.427
6	4	0.75	0.75	0.4	0.32
6	5	0.75	0.75	0.4	0.256
6	6	0.75	0.75	0.4	0.213
6	7	0.75	0.75	0.4	0.183
6	8	0.75	0.75	0.333	0.133
6	9	0.75	0.75	0.333	0.118

Table 2.6: Effective Slab Strip Ratio and Bay Width of Flat Plate Structure (Lou and Durrani)

l_1 (m)	l_2 (m)	c_1 (m)	c_2 (m)	$\frac{c_1}{l_1}$	$\frac{c_1}{l_2}$	$\frac{l_1}{l_2}$	α_i	$\chi\alpha_i$
6	3	0.75	0.75	0.125	0.25	2.0	1.48	1.32
6	4	0.75	0.75	0.125	0.187	1.5	1.27	1.135
6	5	0.75	0.75	0.125	0.15	1.2	1.06	0.946
6	6	0.75	0.75	0.125	0.125	1.0	0.899	0.8
6	7	0.75	0.75	0.125	0.107	0.857	0.775	0.69
6	8	0.75	0.75	0.125	0.094	0.75	0.681	0.606
6	9	0.75	0.75	0.125	0.06	0.083	0.67	0.539

Table 3: Effective Slab Strip Ratio and Column dimension along span of Flat Plate Structure

Column dimension along span (mm)	Deflection (m)	Effective Slab Strip Ratio(α)						
		Present Analysis	Pecknold	Smith and Coull	Grossman			Lou and Durrani
					TWR	JSG	HWNG	
300	0.261	0.360	0.532	0.42	0.43	0.368	0.144	0.455
450	0.162	0.442	0.644	0.52	0.44	0.373	0.161	0.577
600	0.122	0.505	0.705	0.55	0.458	0.378	0.213	0.688
750	0.101	0.599	0.808	0.57	0.472	0.383	0.291	0.800
900	0.087	0.652	1.07	0.60	0.486	0.388	0.380	0.925
1050	0.077	0.707	1.29	0.62	0.5	0.393	0.478	1.073
1200	0.069	0.757	1.43	0.63	0.514	0.397	0.586	1.26

Table 3.1: Effective Slab Strip Ratio and Column dimension along span of Flat Plate Structure (Pecknold)

Span length 2a (m)	Bay width 2b(m)	Column size along span 2u(m)	Column size /Span length $\frac{u}{a}$	Slab Aspect Ratio $\frac{b}{a}$	Effective width $\frac{b'}{b}$	Effective Slab Strip Ratio α
6	6	0.30	0.05	1.00	0.52	0.532
6	6	0.45	0.073	1.00	0.63	0.644
6	6	0.60	0.10	1.00	0.79	0.705
6	6	0.75	0.125	1.00	0.79	0.808
6	6	0.9	0.15	1.00	1.05	1.07
6	6	1.05	0.175	1.00	1.25	1.29
6	6	1.20	0.20	1.00	1.4	1.43

Table 3.2: Effective Slab Strip Ratio and Column dimension along span of Flat Plate Structure (Smith and Coull)

Span length 2a (m)	Bay width 2b(m)	Column size along span 2u(m)	Column size /Span length $\frac{u}{a}$	Slab Aspect Ratio $\frac{b}{a}$	Effective Slab Strip Ratio α
6	6	0.30	0.05	1.0	0.42
6	6	0.45	0.075	1.0	0.52
6	6	0.60	0.1	1.0	0.55
6	6	0.75	0.125	1.0	0.57
6	6	0.9	0.15	1.0	0.60
6	6	1.05	0.175	1.0	0.62
6	6	1.20	0.2	1.0	0.63

Table 3.3: Effective Slab Strip Ratio and Column dimension along span of Flat Plate Structure (Grossman-TWR)

l_1 (m)	l_2 (m)	c_1 (m)	c_2 (m)	α
6	6	0.30	0.75	0.43
6	6	0.45	0.75	0.44
6	6	0.60	0.75	0.458
6	6	0.75	0.75	0.472
6	6	0.9	0.75	0.486
6	6	1.05	0.75	0.5
6	6	1.20	0.75	0.514

Table 3.4: Effective Slab Strip Ratio and Column dimension along span of Flat Plate Structure (Grossman-JSG)

l_1 (m)	l_2 (m)	c_1 (m)	c_2 (m)	l_{1n} (m)	x	α
6	6	0.30	0.75	5.7	1.0	0.368
6	6	0.45	0.75	5.55	1.0	0.373
6	6	0.60	0.75	5.4	1.0	0.378
6	6	0.75	0.75	5.25	1.0	0.383
6	6	0.9	0.75	5.1	1.0	0.388
6	6	1.05	0.75	4.95	1.0	0.393
6	6	1.20	0.75	4.8	1.0	0.397

Table 3.5: Effective Slab Strip Ratio and Column dimension along span of Flat Plate Structure (Grossman-HWNG)

l_1 (m)	l_2 (m)	c_1 (m)	c_2 (m)	β	α
6	6	0.30	0.75	0.33 (0.2)	0.144
6	6	0.45	0.75	0.33 (0.3)	0.161
6	6	0.60	0.75	0.4	0.213
6	6	0.75	0.75	0.5	0.291
6	6	0.9	0.75	0.6	0.380
6	6	1.05	0.75	0.7	0.478
6	6	1.20	0.75	0.8	0.586

Table 3.6: Effective Slab Strip Ratio and Column dimension along span of Flat Plate Structure (Lou and Durrani)

l_1 (m)	l_2 (m)	c_1 (m)	c_2 (m)	$\frac{c_1}{l_1}$	$\frac{c_1}{l_2}$	$\frac{l_1}{l_2}$	α_i	$\chi\alpha_i$
6	6	0.30	0.75	0.05	0.05	1.00	0.511	0.455
6	6	0.45	0.75	0.075	0.075	1.00	0.649	0.577
6	6	0.60	0.75	0.1	0.1	1.00	0.772	0.688
6	6	0.75	0.75	0.125	0.125	1.00	0.899	0.800
6	6	0.9	0.75	0.150	0.150	1.00	1.04	0.925
6	6	1.05	0.75	0.175	0.175	1.00	1.20	1.073
6	6	1.20	0.75	0.200	0.200	1.00	1.42	1.26