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# SEISMIC VULNERABILITY OF FLAT SLAB STRUCTURES

*A thesis submitted by*
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*In partial fulfillment of the requirement for the degree of*

**MASTER OF SCIENCE
IN
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# CERTIFICATE

This is to certify that the thesis entitled "**Seismic Vulnerability of Flat Slab Structures"** being submitted by Mr. Kshitij Charana Shrestha (061/MSS/R/108), in partial fulfillment for the award of degree of Master of Science in Structural Engineering at Institute of Engineering, Tribhuvan University, Nepal is as a record of bonafide works carried out by him under my supervision and guidance and that no part of this thesis has been published or submitted for the award of any degree or diploma elsewhere.

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# ABSTRACT

The effectiveness of flat slab construction is very well known, however its vulnerability when subjected to seismic excitation also needs to be studied owing to its flexibility. Flat slab buildings though prove to take gravity loads effectively, their performance under earthquake excitation has always been in question. For the study purpose, a 5-storey regular building has been taken. For the modeling of flat slab, an effective beam width concept has been incorporated where the portion of the slab that participates in stiffness sharing is formulated. The analytical procedure to be followed for the analysis procedure has been linear static method. Here the vertical distribution of base shear to different floor levels has been done in accordance with the Indian Standard IS 1893 (Part 1) : 2002. The seismic performance of the given building model for flat slab system as well as for the corresponding conventional slab-beam-column system has been studied. The check for limit states for inter-storey drifts as well as punching shear has been done. Comparison has been for the exceedence of the above mentioned limits states for the two systems. Flat slab buildings are found to show higher inter-storey drift values as compared to those shown by conventional framed system. Cost analysis has been performed for the two systems taking into consideration the different parameters: quantity of concrete volume, reinforcement, formwork, total volume of building and the time scale factor. The total cost involved in construction for the two systems is compared for different configurations of building to state the effectiveness of flat slab building over the conventional beam-slab-column system. Flat slab system is found to be cost effective for panel size ranging upto 6m x 6m and not so much effective afterwards.

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# 1.0 INTRODUCTION

## 1.1 General

The designation of high seismic zone labeled for Nepal definitely arises the need for awareness upon the seismic hazard and mitigation of the corresponding vulnerability of the structural and non-structural components in the living environment over here. It is very much appropriate to consider the expected damage as a measure of seismic vulnerability.

Collapse of non-structural components in structural system like flat slabs can cause serious damage to life and property, hence proper study regarding their vulnerability towards the earthquake excitation needs to be performed. The fragility information obtained can then be used by design engineers, researchers, reliability experts and insurance experts to analyze, evaluate and improve the seismic performance of both the structural and non-structural components.

Flat slab construction for high rise buildings doesnot seem quite practicable owing to its flexibility, however its usage in mid-rise buildings, 4 to 5 storey can be looked upon for investigation since these buildings could be regarded sufficiently stiff to warrant the drift demands which higher-rise construction may not be able to satisfy. This study hence has been put forth so as to have an idea upon the feasibility of flat slab construction in seismically vulnerable region like Nepal where seismic performance of the structure is given prior importance.

The study involves assessment of structural performance with the usage of SAP2000, Finite Element Method Program, for different configurations of flat slab structures under given seismic loading compared with the corresponding configuration for conventional slab-beam-column system. The result obtained can be used then after to check for the applicability and vulnerability of flat slab structures considering the storey drift limitations and also under punching shear stress limitation for the given flat slab.

## 1.2 Problems and issues

Flat slab construction possesses major advantages over conventional slab-beam-column construction. As being one of the special reinforced concrete structural forms, flat-slab systems need further attention.

A flat-plate frame is a structural system with solid slabs supported directly on columns. From the construction viewpoint, the flat-plate frame has proved economical because it utilizes the simplest possible formwork and achieves the minimum storey height. Furthermore, this framing makes the placement of utilities feasible, which allows more flexibility for architectural treatments.

Gravity load performances of flat-plate structures has been studies and proved to be reliable through several decades of research and service. However, several aspects of structural performances of flat-plate frames under lateral loads remain in question.

Hence, though the flat plate structures posses many advantages in terms of architectural flexibility, use of space, easier formwork and shorter construction time, the structural efficiency of the flat slab system is hindered by its poor performance under earthquake loading. This undesirable behavior has originated from the insufficient lateral resistance due to the absence of deep beams or shear walls in the flab-slab system. This primarily gives rise to excessive lateral deformations; hence drift limits associated with non-structural damage can be prematurely attained.

## 1.3 Research Objectives

The primary objective for the research is to investigate the vulnerability of the flat-slab reinforced systems. This could give one an idea upon the performance of the flat slab structures imposed to earthquake excitation.

The study also highlights upon the applicability of flat slab construction over the conventional slab-beam-column system. For the sake of it cost analysis for the two systems is performed taking into account the parameters like formwork, reinforcement, concrete volume, total volume of building and time scale factor.

Storey-drift limitations and punching shear limitations for the given flat slab construction are looked upon. Also several measures that can be taken to make the flat slab stiffer in its behavior have been investigated and their applicability towards making flat slab construction less vulnerable towards the earthquake excitation is studied.

### 1.4 Scope of study

The scope of the study concentrates on making the construction of flat slab building more frequent in mid rise construction of buildings since its advantages over conventional framed structure is very well known. For the sake of it, the modeling of flat slab building has been done by taking an effective width of slab that participates in stiffness sharing. The approach used is effective beam width approach.

The study puts forth the advantages of flat slab construction taking into consideration the parameters like formwork, reinforcement, total volume of building and time scale factor by comparing them with the conventional slab-beam-column construction. Hence stating the applicability of flat slab construction over conventional framed structure in mid rise construction.

### 1.5 Distribution of Chapters

The overall report consists of total five chapters. The second chapter includes the literature survey on the field of modeling of flat slab structures and on the strength of flat slab structures. The third chapter deals with the theoretical formulation involved in the study concerning moment resisting frame with flat slab system; it includes the structural configuration, determination of limit states and the structural analysis procedure that has been incorporated. The fourth chapter covers the parametric studies concerning the structural analysis approach performed in the study, the cost analysis and finally the results and discussions part. The fifth chapter contains the major conclusions. It also includes the recommendations for the effectiveness of flat slab system for earthquake resistance over conventional slab-beam-column system for different configurations based on the various limit states defined and the cost analysis performed.

# 2.0 LITERATURE REVIEW

## 2.1 General

Reviews of literature survey concerning the lateral-load stiffness of slab-column frame and the lateral-load strength of the flat plate structures are listed in following sub sections:

## 2.2 Lateral-load Stiffness

The lateral-load stiffness of the slab-column frame is often represented using an equivalent slab-beam to account for the flexural stiffness of the slab. One approach, commonly referred to as the effective beam width method, provides a simple and reasonably accurate means to model the lateral-load stiffness of slab of the slab-column frame. An alternative approach, the equivalent frame model, represents the stiffness of the slab-column frame using an equivalent beam in series with a spring representing the torsional stiffness of the slab adjacent to the connection region.

Based on finite element analysis, **Banchik (1987)** introduced the following effective beam width factors to define the uncracked slab moment-rotation stiffness:

$$\alpha l_2 = \left(5c_1 + \frac{l_1}{4}\right)\frac{1}{1-\nu^2} \text{ : For interior frame lines } \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.1)$$

$$\alpha l_2 = \left(3c_1 + \frac{l_1}{8}\right)\frac{1}{1-\nu^2} \text{ : For exterior frame lines } \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.2)$$

The above two equations apply only for the column aspect ratio ($c_2/c_1$) between 1/2 and 2, and slab aspect ratio ($l_2/l_1$) between 2/3 and 3/2, where $c_1$ is the dimension of rectangular column parallel to loading direction, $c_2$ is the length of the column transverse to $c_1$, $l_1$ is the length of span parallel to loading direction, and $l_2$ is the length of span perpendicular to loading direction.

**Luo et al. (1994; 1995)** proposed an effective beam width model combined with the equivalent frame model, based on column and slab aspect ratios and the magnitude of the gravity load.

## 2.3 Lateral-load Strength

**Luo et al. (1995)** carried out seismic reliability assessment of existing R/C flat–slab buildings. The reliability of existing reinforced-concrete flat-slab buildings, designed and detailed to resist gravity loads only, was studied for punching failure at connections under earthquake-type loading. Results from previous experimental results on the seismic resistance of slab-column connections were employed to establish the effective slab widths, unbalanced moment-transfer capacity of connections and their punching strengths. Random earthquake time histories were generated with Kanai-Taijimi power spectrum. The limit-state function was based on the punching failure capacity of the interior slab-column connections. Based on the reliability analysis, the probability of failure of existing flat-slab buildings were presented for different soil conditions and peak ground accelerations varying from 0.05g to 0.2g.

**ERBERIK et al. (2003)** carried out study on seismic vulnerability of flat-slab structure to develop the fragility of flat-slab construction as a structural form not implemented in HAZUS and to implement the fragility information of flat-slab structures into HAZUS and compare with the fragility curves of moment-resisting frames. Large flexibility of flat-slab frames should be considered in seismic design, due to possible damage to structural & non-structural components and overall stability of the frame under excessive drifts.

**Loo et al. (1997)** carried out a study on cracking and punching shear failure analysis of RC Flat plates. The study presented a nonlinear layered finite element method capable of analyzing cracking and punching shear failure of reinforced concrete flat plates with spandrel beams or torsion strips. A comparative study based on a series of 11 half-scale reinforced concrete flat plate models and four single slab-column specimens were performed. The proposed method was found to have satisfactorily predicted the punching shear strengths, the deflections, and the crack patterns, as well as the collapse loads of the models. The performance of the proposed method was found satisfactory and consistent for the flat plates with either spandrel beams or torsion strips.

**Krüger et al. (1998)** carried out study on punching tests in RC flat slabs with eccentric loading. The study was to investigate the phenomenon on the reduction of the punching resistance of slabs due to moment transfer from slab to column because of unsymmetrical loading, unequal spans or boundary conditions. For the sake of it, total of six flat slabs were tested with normal concrete and varying eccentricities of loading. Tests on large flat slabs with varying eccentricities were presented. The results indicated a strong diminution of the punching load with increased eccentricity (up to 36%). The diminution was linear with increased eccentricity. The use of stirrups appeared to guarantee a better behaviour as far as the eccentricity is concerned.

**Aktan et al. (1991)** carried out study on seismic vulnerability of flat slab-core buildings. 27–storey reinforced concrete flat slab core building located in Cincinnati, Ohio (Sander Tower) was taken as a sample building. The sample building was designed in 1967 and based on 1964 Ohio Building Code, which only considered wind lateral load. The unique characteristic of the building is that it exhibited undesirable seismic attributes that are known to accentuate vulnerabilities caused by inadequate detailing. The study primarily concentrated on the evaluation of the seismic vulnerability of a mid-rise RC flat slab-core building that had not been designed for such forces and forward suggestions for improving the FEMA handbook addressing the effects of seismic events on critical regions of a flat-slab building such as slab-column and slab-wall connections are needed in the Midwest and Eastern parts of the United States. The model was constructed in conjunction with ETABS software. Results indicated that the EW flexibility correlated well with the measured value and the NS flexibility of the model was 35% larger than the measured value. (This increase can be attributed to improperly simulated slab coupling of the two cores in the NS direction.). The lateral flexibility coefficients were used as a starting point for sensitivity analyses to estimate the seismic demand envelopes.

**Hueste et al. (1999)** carried out a study on nonlinear punching shear failure for interior slab-column connections. They developed a model for predicting punching shear failures interior slab-column connections based on experimental results obtained at various universities. This case study was used to develop recommendations for establishing the value for the critical rotation required to define the punching shear failure model for a particular structure. A four-storey RC frame building was taken as a study building. The study building was evaluated for three ground motions scaled to the same peak ground accelerations. The results indicated that the inclusion of punching shear failures can modify the overall building response in terms of drift, fundamental period, inelastic activity, and base shear distribution. With the inclusion of punching, the lengthening of the fundamental period and increase in the maximum drift values were similar for the three ground motion records. However, a comparison of the time histories of average building drift indicated that the record having the longest duration of higher intensity motion caused a significant offset in the roof displacement.

**Farhey et al. (1993)** carried out a study on RC flat slab-column sub-assemblages under lateral loading. The study presented the results of laboratory tests on four reinforced concrete flat slab-interior column connections, carrying quasi-static, cyclic, horizontal loadings. The major aspects of the study were the resistance and final failure mechanisms, the relative influence of the cross-sectional width of the column, and the contribution of vertical gravity loading on the propagation of failure. They found out through test results that there was occurrence of combined primary bending, slab failures, and final one-side punching-shear failures. The study suggested on the use of either the full slab width between the field centerlines, beam analogies, or the linear shear stress distribution on a critical perimeter around the column.

**Hwang et al. (1993)** carried out an experimental study of Flat-Plate Structures under vertical and lateral loads. The study involved an experimental study of reinforced concrete flat-plate structure at four-tenths of full scale. The test structure modeled a prototype structure having three bays in each direction. The floor slab was supported on columns without beams, drop panels, or slab shear reinforcement. Gravity load tests were conducted to observe structural response at the service load level. Lateral load tests were conducted to monitor service load behavior as well as ultimate capacities. Post failure behavior was also investigated. As for the results that were concluded from the different experiments done the connection stiffness due to cracking under service loads is a function of connection geometry, materials, reinforcement quantity, and applied loadings. Also concerning the deformation capacity the test slab was deformed to four percent drift before failure. The large drift capacity is attributed to the fact that gravity load and shear stresses were relatively low. And also for detailing purpose, bottom slab reinforcement should be placed directly over the columns of flat plates to prevent progressive collapse in the event of a connection punching failure.

**Ghobarah et al. (1998)** suggested five damage levels for performance evaluation. An ultimate inter-storey drift for collapse prevention of 5.6 % has been adopted, whereas a limit of 3% was associated with repairable damage.

**Dymiotis et al. (1999)** derived a statistical distribution for the critical inter-storey drift using experimental results obtained from the literature. The study utilized data from tests conducted using shaking tables, pseudo-dynamic, monotonic and cyclic loading. It was concluded that the ultimate drift of 3% lies in the lower tail of the statistical distribution. The mean inter-storey drift values obtained from the distribution were 4.0 and 6.6 for near failure and failure, respectively.

**Limniatis (2001)** stated that inter-storey drift ratios of 1% and 3% are commonly suggested for reinforced concrete buildings, corresponding to the attainment of the serviceability and ultimate limit states, respectively. However, there may be some deviations from these values based on the structural system under consideration. According to Limniatis, since flat-slab buildings are known to behave in a more flexible manner to earthquake excitation, it is reasonable to expect increased drift values. Above discussions reveal that the drift values suggested for global limit states show a high scatter, especially for the ultimate or collapse limit state (2-6.6%).

# 3.0 MOMENT RESISTING FRAME WITH FLAT SLAB SYSTEM

## 3.1 General

This chapter basically includes the structural configuration that has been adopted for the given study and also the material properties that have been taken. This chapter also involves the identification of various limit states that has been taken into account for assessing the structural performance of the structural components given building. The chapter also involves the structural analysis procedure followed and the design concept adopted for the design of RC elements.

## 3.2 Structural Configuration

The typical building model that has been adopted is a five storey office building with span varying accordingly. For the modeling of the flat slab building and the corresponding one with slab-beam-column connections, the section properties have been developed applying certain thumb rules. The equivalent lateral load calculation has been performed for the given seismic weight of the building. The next step is to prepare a realistic analytical model of the building structure under concern. After this step, linear static analyses is done for the full loading condition of the structure and finally study the database for storey displacement and the punching shear coming onto the flat slab building and the corresponding conventional framed structure. Finally, evaluation of the seismic response of the flat-slab structure in comparison to the conventional framed structure is done.

At the outset, a regular building of the following characteristics is chosen for the analysis purpose (Refer Fig.3.1):
A typical office building of 5 storeys is taken. Each storey with sixteen square slab panels with dimensions 5m×5m and accordingly vary the span lengths to check for different cases of configurations. Storey height is selected as 3m for conventional slab-beam-column and 2.735m for flat slab building with slab thickness of 210mm.

For the modeling of the slabs different literatures have put forth different conceptions. Primarily objective in analytical modeling is to determine the portion of the slab that contributes to the frame analysis. Two of the most simplified methods that exist are the Effective Beam Width and the Equivalent Frame Method. SAP 2000 analysis program also has features to perform more exact analysis for the slab modeling, the Finite Element Method for the distribution of stresses in the structural members through proper meshing for the slab modeled as shell element. In this method of analysis, loads are concentrated at nodes, and displacements and stresses at each node are solved so as to satisfy equilibrium and boundary condition requirements. The finite element technique can accept almost any boundary condition, structural geometry, and the interaction among columns. Thus it is a powerful analytical tool to study elastic behavior of the flat plate. A finite element mesh needs to be developed so as to give local effects correctly. Although the mesh done may not be able to show local effects correctly, sensitivity studies indicate that this mesh is adequate for showing global behavior and local moment-rotation behavior of connections.

**Luo et al. (1994; 1995)** proposed an effective beam width model combined with the equivalent frame model, based on column and slab aspect ratios and the magnitude of the gravity load (Fig. 3.2). The effective beam width factors suggested by Luo et al. (1994; 1995) are written as:

$$\alpha_i = \frac{1.02\left(\frac{c_2}{l_2}\right)}{0.05 + 0.002\left(\frac{l_1}{l_2}\right)^4 - 2\left(\frac{c_1}{l_1}\right)^3 - 2.8\left(\frac{c_1}{l_1}\right)^2 + 1.1\left(\frac{c_1}{l_1}\right)} \quad \text{..................(3.1)}$$

$$\alpha_e = \frac{K_t}{K_t + K_s} \quad \text{.........................................................(3.2)}$$

where $Ks = \frac{(4E_{cs})I}{l_1}$ is the flexural stiffness of slab, and I is the gross moment if inertia of the full width slab. The above equation applies only for $0.5 \le (c_2/c_1) \le 2.0$ and $0.5 \le (l_2/l_1) \le 2.0$.

Based on the review of 40 interior connection tests, Luo and Durrani (1995) suggested the following reduction factor χ be introduced for both interior and edge connections.

$$\chi = 1 - 0.4 \frac{V_g}{(1/3)A_c\sqrt{f_c'}} \quad \text{.........................................(3.3)}$$

where $V_g$ is the gravity force to be transferred from the slab to the column in unit of MPa, $A_c$ is the area of slab critical section and $f'_c$ is the compressive strength of concrete in unit of MPa.

**3.3 Material properties:**

The material properties taken for the given building are taken as follows:

Modulus of elasticity of concrete = $5000\sqrt{f_{ck}}$

where $f_{ck}$ = strength of concrete 20 $N/mm^2$

Steel with $f_y$ of 415 $N/mm^2$

**3.4 Inter storey drift limitations:**

Separate limit state criteria are appropriate for the assessment of structural response with respect to the global and local levels. For the global level, the most accepted criterion used is the inter-storey drift. The advantage of this quantity is that it is easy to measure during the analysis and has physical meaning that is well-understood. Inter-storey drift values for different limit states have also been suggested by seismic codes and guidelines. The relationship between the desired seismic performance and the maximum transient drift ratio for the framed structures recommended by FEMA 273(1997) is given in Table3.1.

As per **IS 1893(Part I):2002**, the storey drift in any storey due to the minimum specified design lateral force, with partial load factor of 1.0 shall not exceed **0.004 times the storey height.**

### 3.5 Shear in Flat slabs:

**Checking for one-way shear:**

The critical section for one-way shear is a distance equal to the effective depth from the face of the column. The area from which the load is to be transferred is known as the tributary areas. The magnitude of shear stress is given by

$$\tau = V/(bd) \quad \ldots\ldots(3.4)$$

where d = Effective depth

V = Shear force at the critical section

b = Breadth of the section

**Checking for two-way shear:**

Case1. For normal punching shear calculations without extra shear reinforcements with rectangular column size $c_1$ x $c_2$ and effective depth of slab d,

$$b_o = 2(c_1 + d + c_2 + d) \quad \ldots\ldots(3.5)$$

$$= 4(c + d) \text{ (for square column of size c)} \quad \ldots\ldots(3.6)$$

Case 2. When shear reinforcements in the form of steel bears are provided for a length "a" beyond face of column for a square column of size c

$$b_o = 4(c + \sqrt{2}\, a) \quad \ldots\ldots(3.7)$$

Case 3. When fabricated shear head reinforcement is provided for a square column,

$$b_o = 4\sqrt{2}\left[\frac{c}{2} + \frac{3}{4}\left(L_v - \frac{c}{2}\right)\right] \quad \ldots\ldots(3.8)$$

The tributary area of the slab for punching shear will be the area outside the critical section of the panel being examined.

The area resisting the shear = (Perimeter) x (Depth of slab)

The punching shear stress $v_p$ is calculated as

$$v_p = \frac{V_w}{b_o d} \quad \text{......................................}(3.9)$$

where

$V_w$ = Factored shear from relevant contributory area

$b_o$ = Perimeter length of the critical section

d = Effective depth

**Permissible Punching Shear:**

For a structure to be safe, the punching shear stress should be less than the safe value. The ultimate safe value of the punching shear of concrete is given by the least value of the following equations:

$$\tau_p = 0.25\sqrt{f_{ck}} \quad \text{......................................}(3.10)$$

$$\tau_p' = (0.5 + \beta_c)\,\tau_p \quad \text{......................................}(3.11)$$

$$\tau_p'' = \left(0.5 + \frac{\alpha_s d}{4b_o}\right)\tau_p \quad \text{......................................}(3.12)$$

Equation (3.10) is the initial value suggested for a square column but research has shown that its magnitude is affected by the shape of the column so that it can be expressed for a rectangle column by equation (3.11), where $\beta_c$ = ratio of short side to long side of column capital. Further research has shown that the ratio of the effective depth, d to critical perimeter, $b_o$ also has an influence on $\tau_p$ as in equation (3.12). In this equation we take the following values for $\alpha_s$:

$\alpha_s$ = 40 for an interior column

= 30 for an edge column

= 20 for a corner column

The value used is the smallest of the $\tau_p$ values obtained from equations (3.10) to (3.12). When the shear strength is inadequate, we may resort to the following changes:

- Use a thicker slab
- Use a large column
- Use higher strength concrete
- Use additional shear reinforcement

**3.6 Structural Analysis:**

The analytical procedure to be followed for the analysis procedure could be linear elastic, linear dynamic, nonlinear static and nonlinear dynamic. The choice of analytical method is subject to limitations set on building type,, geometry, and degree of inelastic response. The linear procedures express displacements in terms of forces for the sole purpose of ease of implementation. In this study, linear static method is followed. Response spectrum method using the response spectra of IS-1893-2002 has also been used both manually as well as with the usage of SAP2000 program.

**3.7 Seismic coefficient method:**

Design seismic base shear is calculated as:

$$V_b = A_h W \qquad (3.13)$$

Where

$A_h$ = Design horizontal acceleration spectrum value using the fundamental natural period $T_a$ in the considered direction of vibration.

= $(ZIS_a)/(2Rg)$

I = a factor depending upon the importance of the structure

Z = Zone factor

R= Response reduction factor

$S_a/g$ = Average response acceleration coefficient based on appropriate natural periods and damping of the structure.

W = Seismic weight of building

The distribution of forces along the height of the building is given by the following formula:

$$Q_i = V_B \times \frac{W_i h_i^2}{\sum W_i h_i^2} \quad \text{.......................................(3.14)}$$

where,

$Q_i$ = lateral force at $i^{th}$ storey

$V_B$ = Base shear

$W_i$ = Weight of $i^{th}$ storey

$h_i$ = Height of storey

**3.8 Response Spectrum Method:**

Response spectrum method gives a convenient means to express the peak response of all possible linear single degree of systems to a particular component of ground motion and summarize the result. A plot of peak value of a response quantity as a function of the natural vibration period (T) of the system is called response spectrum for that quantity. Response spectrum in general case is representative of ground motions recorded at the site during past earthquakes. For the time being, the response spectrum function of IS1893-2002 has been adopted for our purpose.

**3.9 Design of RC elements:**

The design of RC elements is done using Limit State Method design concept. The elements are designed for the maximum stresses coming, taking into account the different load combinations as per Indian Standards IS 456-2000.

**Table3.1 Structural Performance Levels Recommended by FEMA 273 (October 1997)**

| Performance Level | Inter-storey drift | |
|---|---|---|
| | Concrete Frames | Concrete Walls |
| Immediate Occupancy | 1% transient, negligible permanent | 0.5% transient, negligible permanent |
| Life Safety | 2% transient, 1% permanent | 1% transient, 0.5 permanent |
| Collapse Prevention | 4% transient or permanent | 2% transient or permanent |

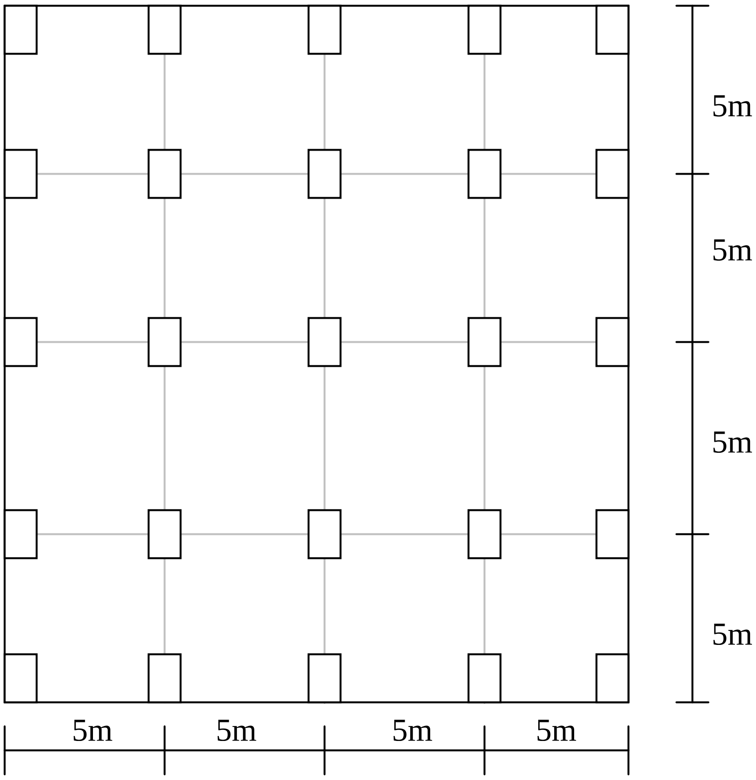


**Fig. 3.1A Typical plan of the building**

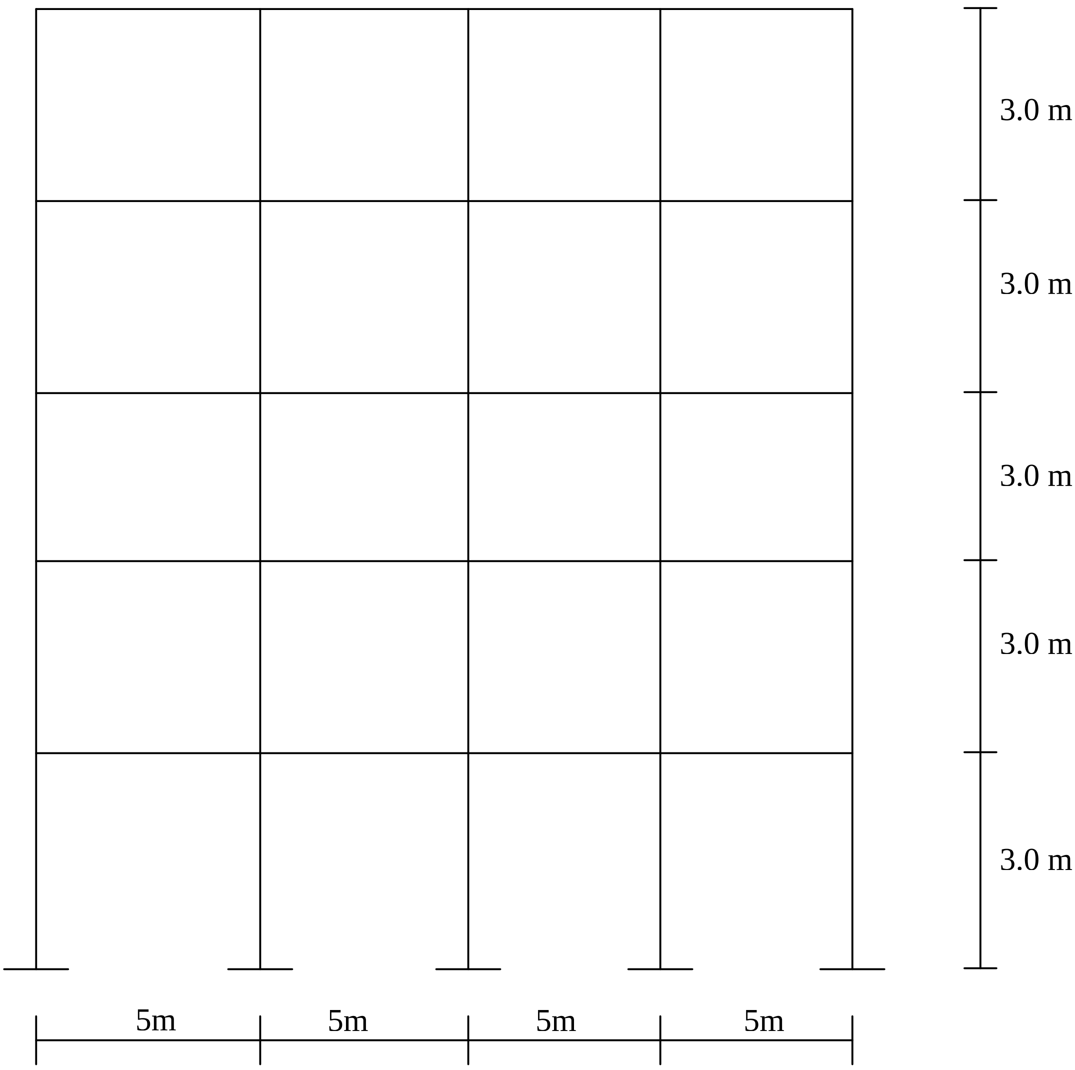


**Fig. 3.1B Typical elevation of the building**

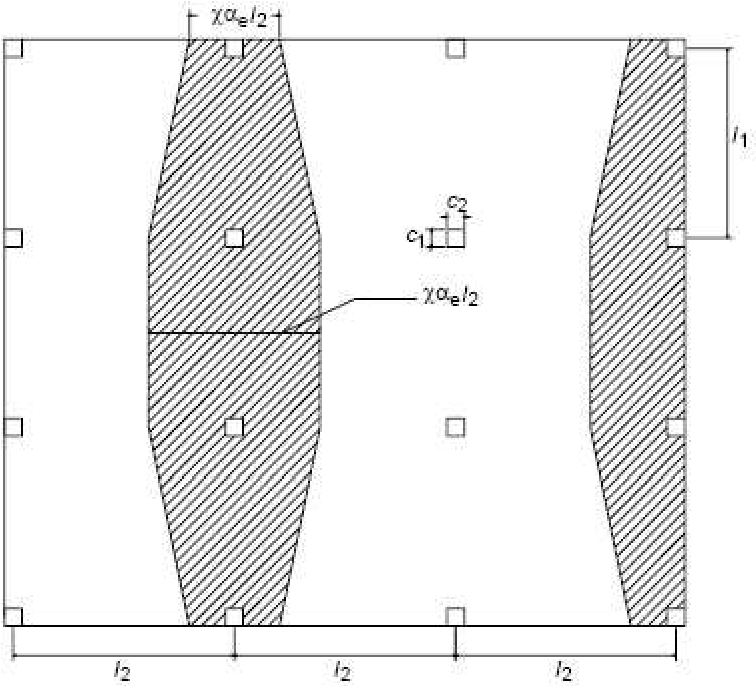


**Fig. 3.2 Effective beam width model proposed by Luo et al. (1994)**

# 4.0 PARAMETRIC STUDY

## 4.1 General

The building that has been adopted for the given study has been a typical 5 storey office building. Parametric study basically consists of three parts. The first part includes the materials and loading taken for the given structure. The second part includes the structural analysis and the cost analysis that has been performed for the given study. The cost analysis includes the assessment of different parameters like formwork, reinforcement, concrete volume, etc. taken into considerations for the two types of building construction viz. conventional slab-beam-column building and flat slab building. And finally the third part of this chapter includes the result and discussion part.

## 4.2 Materials and loading:

| | |
|---|---|
| Unit weight of RCC | = 25 KN/$m^3$ |
| Unit weight of brick masonry | = 19 KN/$m^3$ |
| Live Load | = 4 KN/$m^2$ for rooms |
| | = 1.5 KN/$m^2$ for accessible roof |

## 4.3 Structural Analysis:

The assessment of flat slab system for the earthquake excitation has been done and compared with the conventional slab-beam-column system. A typical office building of 5-storey having total 16 square panels of sizes 5m x 5m was taken. For the comparison purpose, the building configuration was changed to lager sized panel. The size of the beam, column and slab has been adopted following certain thumb rules.

The modeling of the flat slab system is done by taking the effective beam width concept to define the portion of slab that actually participates in stiffness sharing in the structure. For this purpose, empirical formulation put forth by Luo et al. (1994;

1995) has been adopted. For the flat-slab structure under consideration, both $\alpha_i$ and $\alpha_e$ were calculated and the average of the two was taken as the effective width used in the model. This value is **3.79m,** for panel of size 5m x 5m. Similarly for panel of size 6m x 6m, the effective width of 4.06m and for panel of size 7m the effective width of 4.31m is taken.

The comparison for the two systems of construction is also done for the panel of different configurations with panel of sizes 6m x 6m, 7m x 7m and thereafter. Thereby the applicability of the flat slab system can be investigated for the different configurations.

For the analysis purpose, the response of the structure has been studied taking into account the different combinations of dead load, imposed load and designated earthquake load taking appropriate partial safety factors for limit state design of reinforced concrete as stated in Indian Standards IS 1893 (Part 1) : 2002.

The analytical procedure to be followed for the analysis procedure has been linear static method. Here, the vertical distribution of base shear to different floor levels has been done in accordance with the Indian Standard IS 1893 (Part 1) : 2002. Response spectrum method using the response spectra of IS-1893-2002 has also been used to see whether the static method that has been adopted holds good for the given structure in terms of the participation for the mass in different modes. The result shows that first mode mass contribution is significant and hence the static method viz. seismic coefficient method appears sufficient to meet our requirements in accessing the structural response in terms of storey drift and punching shear coming.

The sections for the structural components have been fixed considering the above mentioned two limit states, thereby checking for whether our structural systems' response is within the defined limit states as discussed in the preceding chapter.

### 4.4 Cost Analysis:

Cost analysis for the sample buildings taken is done for the conventional slab-beam-column building and the flat slab building. The comparison has been performed taking following parameters into considerations, viz. reinforcement (in kgs), formwork (in $m^2$), concrete volume (in $m^3$), total volume change of building, time factor for the completion of the system in terms of stripping time taken for the formworks.

A tentative figure for the total cost has been derived for the given conventional slab-beam-column building and the flat slab building. Cost based comparison has been performed for drawing general idea on the two types of constructions stated above. Possible conclusions can be drawn by developing similar trend of comparisons for the above mentioned parameters for buildings with varying configurations. Hence leading to the possibility of applicability of flat building systems for mid rise construction in big terms as regards to the cost involved in the construction of RC buildings.

### 4.5 Results and discussion:

For the assessment of structural performance of the flat slab system and corresponding conventional slab-beam-column system, the main emphasis has been given for the storey displacements, precisely speaking the inter-storey drift values. The results for the inter-storey drifts observed for different models of two systems when subjected to earthquake excitation are tabulated in Table 4.1A through 4.1C. The same has been shown in graph plotted for storey displacements versus storey level and can be seen in Fig. 4.1A through 4.1C for different configurations of the system.

Fig 4.1 shows that storey displacements in flat slab buildings are significantly high as compared to conventional slab-beam-column buildings. The displacements seem to be higher for higher storey level. This performance of flat slab system is very much evident owing to its flexibility. From Table 4.1A and Fig 4.1A, for panel of size 5m x 5m, flat slab modeled as effective beam width of 3.798m, with depth of 235mm seems to satisfy the inter-storey drift limitations. Similarly from Table 4.1B and Fig

4.1B, for panel of size 6m x 6m, flat slab modeled as effective beam width of 4.060m, with depth of 245mm seems to satisfy the inter-storey drift limitations. And finally for panel of size 7m x 7m, as seen in Table 4.1C and Fig 4.1C, for flat slab of effective width 4.309m, the inter-storey drift limitation is satisfied for depth of slab equal to 260mm.

Table 4.2A through 4.2C shows cost analysis performed for two systems of constructions for different configurations of building. Cost involved for quantity of reinforcement and formwork needed for flat slab construction is lesser than that for conventional framed system. However, the cost for the quantity for volume of concrete involved in flat slab building construction is higher as compared to that for conventional slab-beam-column system. From Table 4.2A and 4.2B, for panel sizes of 5m x 5m and 6m x 6m, the total cost for construction as being observed for flat slab construction is less than that for conventional slab-beam column system. And as the panel size is increased to 7m x 7m, the cost involved changes drastically, hence making the cost effectiveness of the flat slab construction cease down.

The feasibility of flat slab construction in mid rise construction has been found satisfactory in terms of the limit states defined for the storey drift limitations and the punching shear limitations.

As seen from the cost analysis performed for the two types of construction the effectiveness of flat slab construction lies in economizing the cost in terms of formwork quantity required and the quantity of reinforcement needed. Flat slab construction also has its own effectiveness in formwork placing as compared to slab-beam-column construction and also the time required for the completion of the given construction.

From the comparison performed for the different configurations of conventional framed structures and corresponding flat slab structures, it has been seen that flat slab construction has been found cost effective for building having spans of 6m or less. The effectiveness of the flat slab construction ceases in terms of the total cost that is required for the spans ranging from 7m and more.

Table 4.1A Storey drifts for panel of size 5m x 5m

Effective beam of depth 210mm and effective width of 3.798m

| Story level | Story displacement(mm) | Drift in mm | Drift in percentage |
|---|---|---|---|
| 1 | 7.499481 | 7.499481 | 0.274204059 |
| 2 | 20.616864 | 13.117383 | 0.47961181 |
| 3 | 33.770005 | 13.153141 | 0.480919232 |
| 4 | 44.442317 | 10.672312 | 0.390212505 |
| 5 | 51.283447 | 6.84113 | 0.250132724 |

Effective beam of depth 220mm and effective width of 3.798m

| Story level | Story displacement(mm) | Drift in mm | Drift in percentage |
|---|---|---|---|
| 1 | 7.173145 | 7.173145 | 0.261316758 |
| 2 | 19.436918 | 12.263773 | 0.446767687 |
| 3 | 31.619807 | 12.182889 | 0.443821093 |
| 4 | 41.45597 | 9.836163 | 0.358330164 |
| 5 | 47.669616 | 6.213646 | 0.226362332 |

Effective beam of depth 230mm and effective width of 3.798m

| Story level | Story displacement(mm) | Drift in mm | Drift in percentage |
|---|---|---|---|
| 1 | 6.887377 | 6.887377 | 0.249995535 |
| 2 | 18.40297 | 11.515593 | 0.417988857 |
| 3 | 29.747891 | 11.344921 | 0.411793866 |
| 4 | 38.873392 | 9.125501 | 0.331234156 |
| 5 | 44.567065 | 5.693673 | 0.206666897 |

Effective beam of depth 235mm and effective width of 3.798m

| Story level | Story displacement(mm) | Drift in mm | Drift in percentage |
|---|---|---|---|
| 1 | 6.758154 | 6.758154 | 0.244860652 |
| 2 | 17.934724 | 11.17657 | 0.404948188 |
| 3 | 28.903873 | 10.969149 | 0.397432935 |
| 4 | 37.714148 | 8.810275 | 0.319212862 |
| 5 | 43.181289 | 5.467141 | 0.198084819 |

Slab-Beam-Column Model (Slab 150mm, Beam 225 x 475, Column 550mm)

| Story level | Story displacement(mm) | Drift in mm | Drift in percentage |
|---|---|---|---|
| 1 | 6.390197 | 6.390197 | 0.209514656 |
| 2 | 17.85025 | 11.460053 | 0.375739443 |
| 3 | 29.515196 | 11.664946 | 0.382457246 |
| 4 | 39.137568 | 9.622372 | 0.315487607 |
| 5 | 45.523841 | 6.386273 | 0.209386 |

Table 4.1B Storey drifts for panel of size 6m x 6m

Effective beam of depth 235mm and effective width of 4.060m

| Storey level | Displacements in mm | Drift in mm | Drift in percentage |
|---|---|---|---|
| 1st | 7.216356 | 7.216356 | 0.261462174 |
| 2nd | 19.416886 | 12.20053 | 0.442048188 |
| 3rd | 31.488846 | 12.07196 | 0.437389855 |
| 4th | 41.226127 | 9.737281 | 0.352800036 |
| 5th | 47.34793 | 6.121803 | 0.221804457 |

Effective beam of depth 245mm and effective width of 4.060m

| Story level | Story displacement(mm) | Drift in mm | Drift in percentage |
|---|---|---|---|
| 1 | 6.96015 | 6.96015 | 0.251268953 |
| 2 | 18.480143 | 11.519993 | 0.415884224 |
| 3 | 29.792055 | 11.311912 | 0.408372274 |
| 4 | 38.887425 | 9.09537 | 0.328352708 |
| 5 | 44.542705 | 5.65528 | 0.204161733 |

Slab-Beam-Column Model (Slab 150mm, Beam 225 x 510, Column 550mm)

| Story level | Story displacement(mm) | Drift in mm | Drift in percentage |
|---|---|---|---|
| 1 | 6.817803 | 6.817803 | 0.223534525 |
| 2 | 19.022909 | 12.205106 | 0.40016741 |
| 3 | 31.319304 | 12.296395 | 0.403160492 |
| 4 | 41.209856 | 9.890552 | 0.324280393 |
| 5 | 47.481475 | 6.271619 | 0.205626852 |

Table 4.1C Storey drifts for panel of size 7m x 7m

Effective beam of depth 235mm and effective width of 4.309m

| Story level | Story displacement(mm) | Drift in mm | Drift in percentage |
|---|---|---|---|
| 1 | 7.306327 | 7.306327 | 0.264721993 |
| 2 | 19.806873 | 12.500546 | 0.452918333 |
| 3 | 32.19799 | 12.391117 | 0.448953514 |
| 4 | 42.143849 | 9.945859 | 0.36035721 |
| 5 | 48.354075 | 6.210226 | 0.225008188 |

Effective beam of depth 260mm and effective width of 4.309m

| Story level | Story displacement(mm) | Drift in mm | Drift in percentage |
|---|---|---|---|
| 1 | 6.99307 | 6.99307 | 0.252002523 |
| 2 | 18.588981 | 11.595911 | 0.417870667 |
| 3 | 29.951464 | 11.362483 | 0.409458847 |
| 4 | 39.026617 | 9.075153 | 0.327032541 |
| 5 | 44.595202 | 5.568585 | 0.20066973 |

Effective beam of depth 265mm and effective width of 4.309m

| Story level | Story displacement(mm) | Drift in mm | Drift in percentage |
|---|---|---|---|
| 1 | 6.90127 | 6.90127 | 0.248247122 |
| 2 | 18.228813 | 11.327543 | 0.407465576 |
| 3 | 29.290104 | 11.061291 | 0.397888165 |
| 4 | 38.113972 | 8.823868 | 0.317405324 |
| 5 | 43.501574 | 5.387602 | 0.193798633 |

Effective beam of depth 270mm and effective width of 4.309m

| Story level | Story displacement(mm) | Drift in mm | Drift in percentage |
|---|---|---|---|
| 1 | 6.815259 | 6.815259 | 0.24471307 |
| 2 | 17.889461 | 11.074202 | 0.397637415 |
| 3 | 28.668117 | 10.778656 | 0.38702535 |
| 4 | 37.257689 | 8.589572 | 0.308422693 |
| 5 | 42.478297 | 5.220608 | 0.187454506 |

Slab-Beam-Column Model (Slab 150mm, Beam 235 x 535, Column 550mm)

| Story level | Story displacement(mm) | Drift in mm | Drift in percentage |
|---|---|---|---|
| 1 | 6.89973 | 6.89973 | 0.226220656 |
| 2 | 18.20147 | 11.30174 | 0.370548852 |
| 3 | 29.12303 | 10.92156 | 0.358083934 |
| 4 | 38.541706 | 9.418676 | 0.308809049 |
| 5 | 43.495942 | 4.954236 | 0.162433967 |

Table 4.2A Comparison of parameters involved in cost analysis for flat slab system and conventional beam-slab system for panel of size 5m x 5m

| Case | Parameters | Conventional framed Structure | | | | Flat slab structure | | | | % increment in flat slab construction |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Beam | Column | Slab | Total | Beam | Column | Slab | Total | |
| 1 | Time factor(in days) | | | | 287 | | | | 267 | -6.97 |
| 2 | Reinforcement in kgs | 21880 | 10028 | 27000 | 58908 | | 11661 | 30400 | 42061 | -28.6 |
| 3 | Formwork in $m^2$ | 778.75 | 825 | 364.81 | 1968.56 | | 759 | 400 | 1159 | -41.12 |
| 4 | Concrete volume $m^3$ | 106.875 | 113.4375 | 300 | 520.3125 | | 104.360 | 470 | 574.360 | +10.38 |
| 5 | Volume of building $m^3$ | | | | 6000 | | | | 5520 | -8.0 |

| Case | Parameters | Rate | Change in cost for constrution in Rs |
|---|---|---|---|
| 1 | Reinforcement in kgs | Rs 51/kg | -859197 |
| 2 | Formwork in $m^2$ | Rs $240/m^2$ | -194294.4 |
| 3 | Concrete volume $m^3$ | Rs $6700/m^3$ | 362118.25 |
| | Balance | | -691373.15 |

Table 4.2B Comparison of parameters involved in cost analysis for flat slab system and conventional beam-slab system for panel of size 6m x 6m

| Case | Parameters | Conventional framed Structure | | | | Flat slab structure | | | | % increment in flat slab construction |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Beam | Column | Slab | Total | Beam | Column | Slab | Total | |
| 1 | Time factor(in days) | | | | 287 | | | | 267 | -6.97 |
| 2 | Reinforcement in kgs | 30838 | 10237 | 38880 | 79955 | | 12380 | 43776 | 56156 | -29.76 |
| 3 | Formwork in $m^2$ | 1019.15 | 838.75 | 533.61 | 2391.51 | | 761.75 | 576 | 1337.75 | -44.06 |
| 4 | Concrete volume $m^3$ | 141.75 | 115.33 | 432 | 689.08 | | 104.75 | 705.6 | 810.35 | +17.5 |
| 5 | Volume of building $m^3$ | | | | 8784 | | | | 7977.6 | -9.18 |

| Case | Parameters | Rate | Change in cost for constrution in Rs |
|---|---|---|---|
| 1 | Reinforcement in kgs | Rs 51/kg | -1213749 |
| 2 | Formwork in $m^2$ | Rs 240/$m^2$ | -252902.4 |
| 3 | Concrete volume $m^3$ | Rs 6700/$m^3$ | 812509 |
| | Balance | | -654142.4 |

Table 4.2C Comparison of parameters involved in cost analysis for flat slab system and conventional beam-slab system for panel of size 6m x 6m

| Case | Parameters | Conventional framed Structure | | | | Flat slab structure | | | | % increment in flat slab construction |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Beam | Column | Slab | Total | Beam | Column | Slab | Total | |
| 1 | Time factor(in days) | | | | 287 | | | | 267 | -6.97 |
| 2 | Reinforcement in kgs | 41834 | 10568 | 52920 | 105322 | | 14675 | 59584 | 74259 | -31.39 |
| 3 | Formwork in $m^2$ | 1206.15 | 838.75 | 734.41 | 2779.31 | | 765.875 | 784 | 1549.875 | -44.23 |
| 4 | Concrete volume $m^3$ | 166.95 | 115.52 | 588 | 870.47 | | 105.31 | 1058.4 | 1163.71 | +29.18 |
| 5 | Volume of building $m^3$ | | | | 11975.6 | | | | 10917.2 | -8.83 |

| Case | Parameters | Rate | Change in cost for constrution in Rs |
|---|---|---|---|
| 1 | Reinforcement in kgs | Rs 51/kg | -1584213 |
| 2 | Formwork in $m^2$ | Rs 240/$m^2$ | -295064.4 |
| 3 | Concrete volume $m^3$ | Rs 6700/$m^3$ | 1964708 |
| | Balance | | 85430.6 |

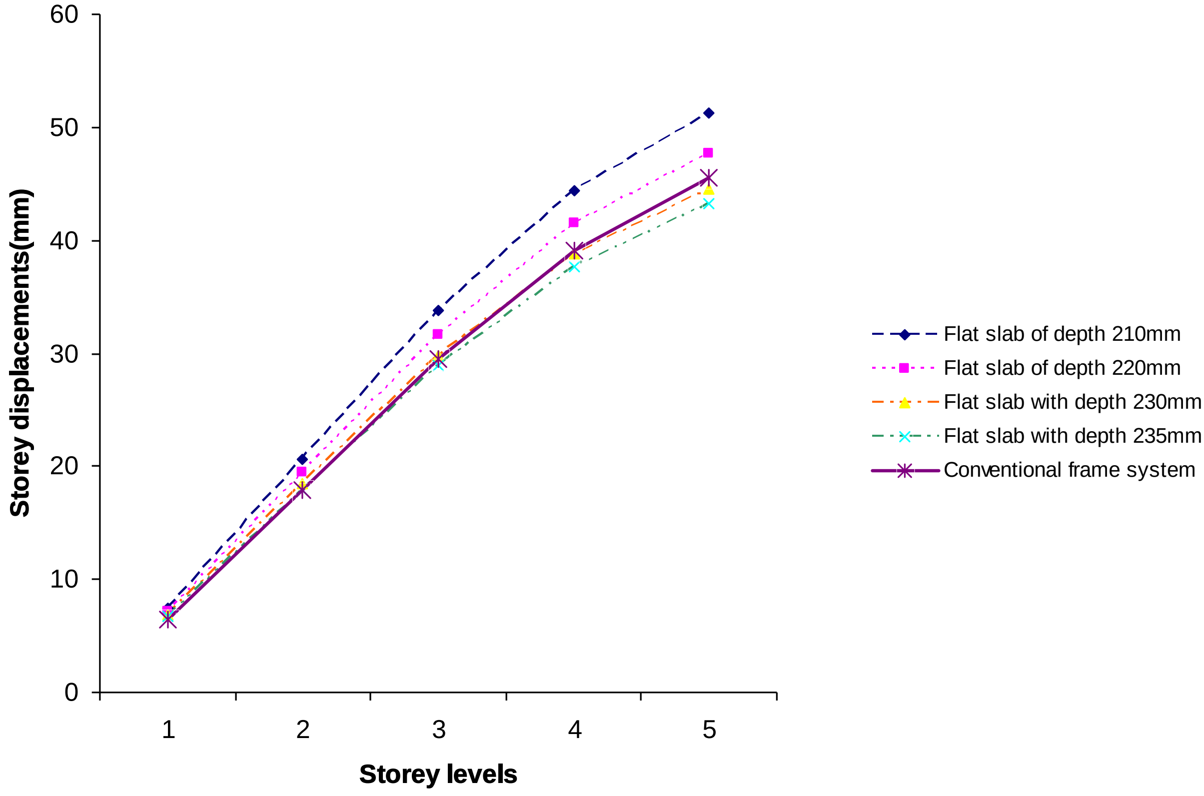


Fig. 4.1A Comparison of storey displacements in conventional beam-slab systems and flat slab system with 5m x 5m panel size.

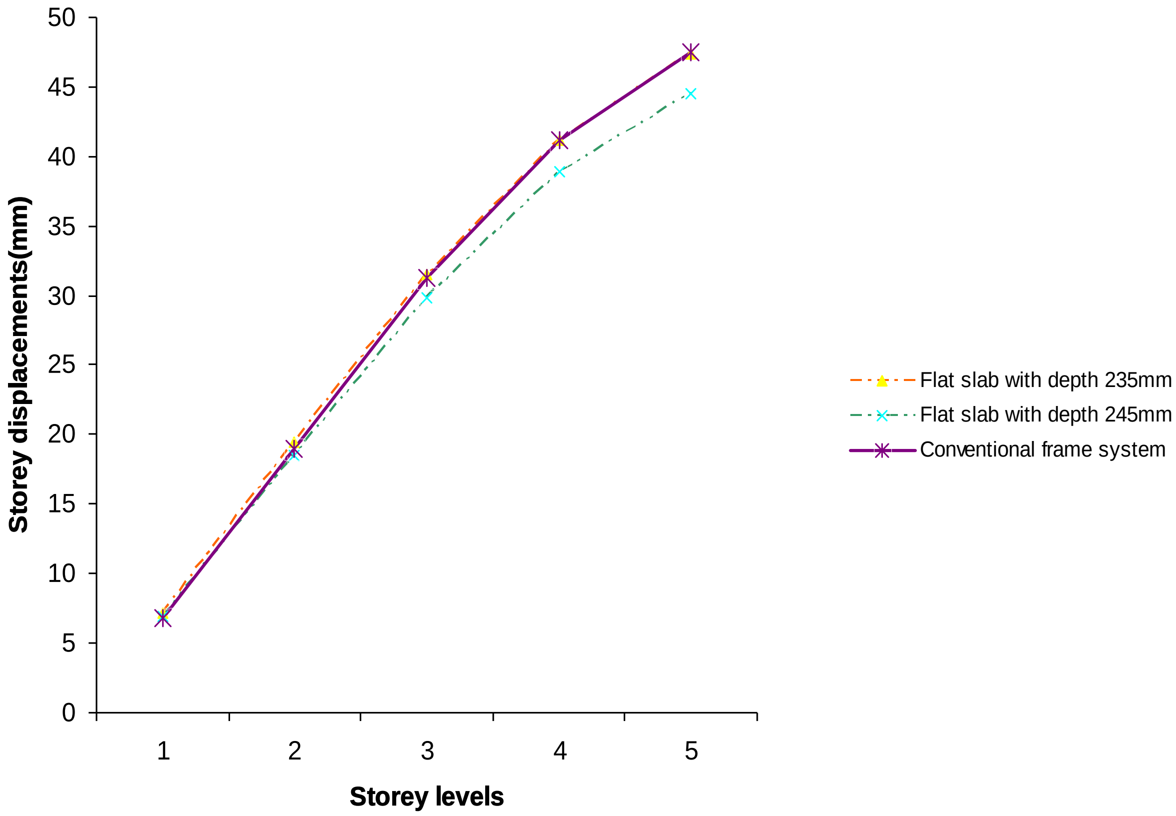


Fig. 4.1B Comparison of storey displacements in conventional beam-slab systems and flat slab system with 6m x 6m panel size.

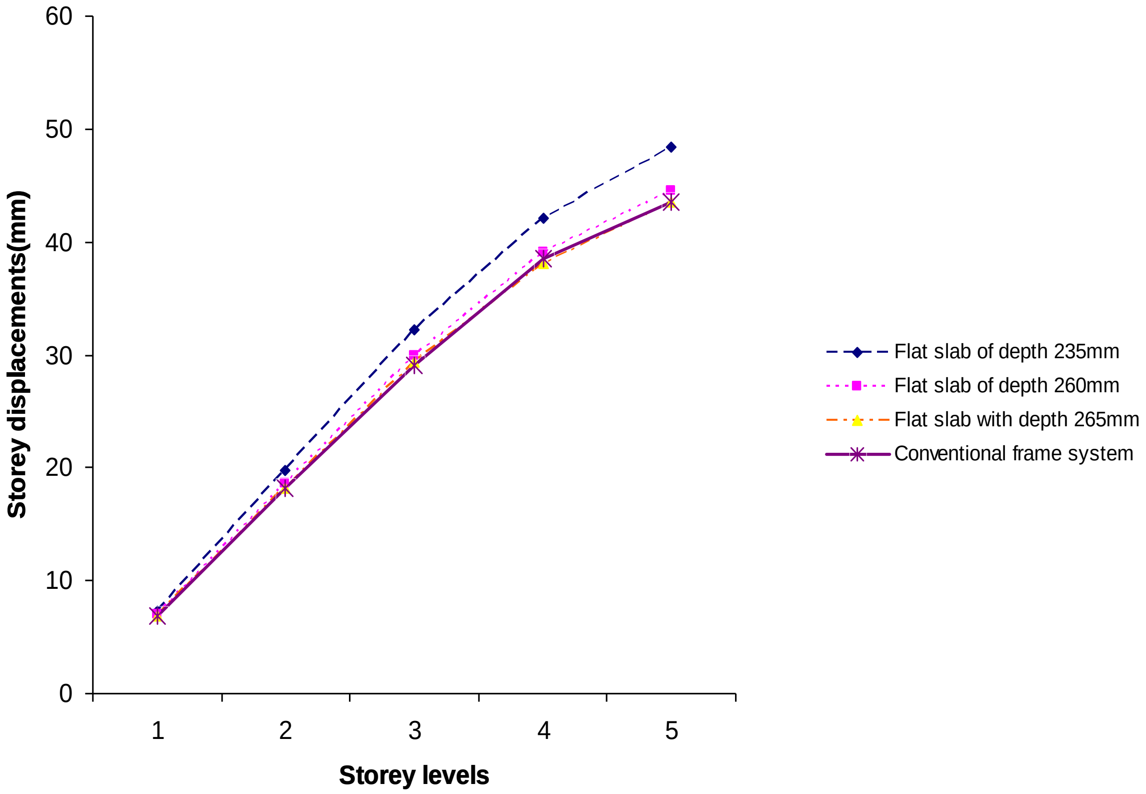


Fig. 4.1B Comparison of storey displacements in conventional beam-slab systems and flat slab system with 7m x 7m panel size.

# 5.0 CONCLUSION AND RECOMMENDATIONS

## 5.1 General

Five-storied R. C. office building was considered for the purpose of the study. The flat slab system was modeled using effective beam width concept proposed by Luo et al. (1994; 1995) to define the portion of the slab that actually participates in stiffness sharing in the structure. The comparison of the two systems of construction was done for the panel of different configurations.

For the analysis purpose, the response of the structure was studied taking into account for different load combinations appropriate partial safety factors for limit state design of reinforced concrete as stated in Indian Standard IS 1893 (Part 1) : 2002. The analytical procedure to be followed for the analysis purpose was linear static method. The vertical distribution of base shear to different floor levels was done in accordance to the above mentioned code provisions.

The performance of the building was checked for the exceedence of the limit states for inter-storey drift and punching shear for the two systems separately. Cost analysis for the two systems was done taking into account following parameters, concrete volume, quantity of reinforcement, formwork, total volume of building and time scale for completion.

## 5.2 Major conclusions:

The following main conclusions are obtained from the study:

1. Flat slab buildings are vulnerable to seismic excitation in terms of the inter-storey drift limitations.
2. The exceedence of drift limitations in flat slab buildings not so significant for mid-rise building, upto 5 storey.

3. Effective beam width concept addresses both the moment transfer capacity and stiffness of the interior and exterior slab-column connections.
4. The storey displacement goes on increasing with the storey height.
5. The depth of flat slab goes on increasing with the increment in panel size.
6. Flat slab construction seems cost effective for panel of size ranging up to 6m x 6m and it loses its effectiveness as we increase the panel size furthermore.

## 5.3 Recommendations:

The following topics re recommended for study as extension of work:

1. Non-linear analysis to assess the vulnerability of flat slab structures can be done.
2. Study on vulnerability of flat slab structures with column capitals and drop slabs can be done.
3. Study for irregular shaped building and higher rise construction can be done.

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