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[1.] Mohamed A. A. El-SHAER

SEISMIC LOAD ANALYSIS OF DIFFERENT R.C. SLAB SYSTEMS FOR TALL BUILDING

[1.] Civil and Construction Engineering Department, higher Technological Institute, 10th of Ramadan City, EGYPT

Abstract: *This paper introduced the lateral analysis for tall buildings due to the seismic performance for different reinforced concrete slab systems. It study three systems, flat slab, ribbed slab, and panelled beam slab. The three systems are from the most attractive and commonly used floor systems, especially in high-rise constructions. In high seismicity regions, the declared non-ductile flat slab system poses a significant risk, brittle punching failure arises from the transfer of shearing forces and unbalanced moments between slab and columns that may trigger a progressive building collapse. This system is inherently flexible due to the non-rigid slab-column connections, and the building high aspect (height/width) ratio. Hence, in regions of high seismic risk, design codes recommended the use of slab-column frames to resist slabs, and require another stiffer system to resist lateral wind and seismic forces. From this standpoint, the choose of a system that provide rigid concrete slab than flat slab to resist lateral wind and seismic forces. This system is chosen to be the ribbed slab, and the panelled beam slab. These two systems of concrete slabs are ductile, and balanced moments between slab and columns. As the different types of seismic load resisting systems generally presented. Then, three systems of slabs performance for systems high-rise buildings during seismic loads are introduced. Some seismic design, analysis and performance assessment aspects of flat slab, and ribbed slab, and panelled beams systems for high-rise buildings are subsequently discussed. Finally, suggestions to improve the seismic performance of high - rise buildings horizontal members in slabs (ribs or beams-column) buildings are presented. ETABS version 9.5 is for analysis under lateral loads. ETABS is a programmer for linear, nonlinear, static and dynamic analysis, and the design of building systems. Multistory buildings constitute a very special class of structures and therefore deserve special treatment. The program is used to calculate the drifts for the systems and we noticed that the minimum drift was occurred in the ribbed slab system.So that, in high seismic risk regions, ribbed-slab-column frames is recommended to be gravity load resisting systems for building of high values of height/width ratios.*
Keywords: *Flat slab; Beam-column; Ribbed slab; Seismic load; Drift*

1. INTRODUCTION

The flat slab system since its inception in the USA by Turner in 1906 has been gaining popularity all over the world, as evidence of the large portion of the newly constructed buildings which employ that system. Flat slab systems in current construction practice are commonly used for relatively light residential loads and for spans from 4.5m to 6m. For heavy industrial or office building loads and/or for larger spans, flat slabs are used with drop panels or column capitals. The flat slab type of construction provides architectural flexibility, more clear space, less building height, easier formwork, and consequently, shorter construction time. However, flat slabs are susceptible to significant reductions in stiffness as a consequence of slab cracking that can arise from construction loads, service gravity loads, temperature and shrinkage effects, and lateral loads. Due to their inherent flexibility, flat slab/plate systems (especially in multi-story high-rise buildings) experience excessive lateral drifts (displacement) when subjected to wind loads or seismic excitations. Also they possess non-ductile overall response, local seismic hysteretic response, and poor energy dissipations. Furthermore, their potential of brittle punching failure at the slab-column connections. Therefore in regions of high seismic risk, modern seismic design codes prohibit the use of flat slab/plate as a lateral load resisting system, but allow its use as a vertical (gravity) load resisting system.

After that, this paper introduces several systems that is used in high rise building of 30 stories.

Three types are selected, flat slab, paneled beams and ribbed slab floor systems, with the same lateral loads resistance systems (core &shear wall system).

2. LATERAL LOADS RESISTING SYSTEM

Lateral loads resisting system may be on or more of the following systems: Braced frame, Rigid frame, Infilled frame, Shear walls, Wall frame, Frame tube, Outrigger braced, Suspended, Space structures, and Core system. The last system (Core system) is the subject of the study in this search.

Response Analysis

The analysis of seismic response of tall buildings under seismic loads can be carried out by one of the following methods:

a. Elastic static analysis

This procedure is generally used in the preliminary stages of planning the building, where the suitability for number of choices for the lateral load resisting systems is being investigated. The analysis is carried out on the system model subject to the equivalent static seismic forces

b. Modal response spectrum

This procedure is more appropriate to flexible structures where the first mode alone is not able to reasonably represent the system response. Therefore, higher modes (second, third, fourth, etc.) contribution to the response shall be considered. This method is more appropriate for high-rise buildings the previous method during the preliminary planning process.

The different modes of vibrations and their frequencies (or their natural periods of vibrations) are needed to conduct the modal analysis. Therefore the free vibration analysis of the lateral load resisting system shall be performed prior to the modal response analysis.

c. Elastic dynamic time-history

The adequacy of the selected lateral load system for the serviceability limit state shall be checked under earthquake of 10 years return period. Seismic design codes require the system to continue its elastic behavior and sustain no damage, maintaining mits elastic behavior. It can also be used to approximate the seismic response of the building when subject to larger earthquakes of 50 years return period, where the building is expected to suffer minor structural damages.

Response Spectrum analysis for earthquakes

In order to perform the seismic analysis and design of a structure to be built at a particular location, the actual time history record is required. However, it is not possible to have such records at each and every location. Further, the seismic analysis of structures cannot be carried out simply based on the peak value of the ground acceleration as the response of the structure depend upon the frequency content of ground motion and its own dynamic properties. To overcome the above difficulties, earthquake response spectrum is the most popular tool in the seismic analysis of structures. There are computational advantages in using the response spectrum method of seismic analysis for prediction of displacements and member forces in structural systems. The method involves the calculation of only the maximum values of the displacements and member forces in each mode of vibration using smooth design spectra that are the average of several earthquake motions.

This paper deals with response spectrum method and its application to various types of the structures.

Response spectra are curves plotted between maximum response of SDOF system subjected to specified earthquake ground motion and its time period (or frequency) as in figure (1). Response spectrum can be interpreted as the locus of maximum response of a SDOF system for given damping ratio. Response spectra thus helps in obtaining the peak structural responses under linear range, which can be used for obtaining lateral forces developed in structure due to earthquake thus facilitates in earthquake-resistant design of structures.

Usually response of a SDOF system is determined by time domain or frequency domain analysis, and for a given time period of system, maximum response is picked. This process is continued for all range of possible time periods of SDOF system. Final plot with system time period on x-axis and response quantity on y-axis is the required response spectra pertaining to specified damping ratio and input ground motion. Same process is carried out with different damping ratios to obtain overall response spectra.

Consider a SDOF system subjected to earthquake acceleration, the equation of motion is given by:

$$m\ddot{x}(t)+c\dot{x}(t)+kx(t)=-m\ddot{x}_g(t) \qquad Eq.(1)$$

where: $m\ddot{x}(t)$: is mass times acceleration; $c\dot{x}(t)$: is the damping term and equals to zero for undampedmotion; $kx(t)$: displacement times stiffness.

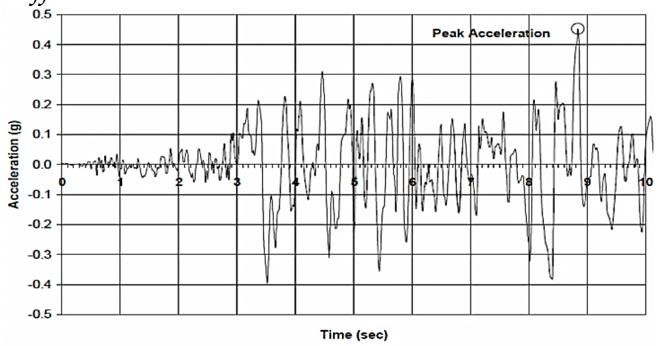

Fig.1. Response spectra curve

Substitute $\omega_o=\sqrt{K/m}$ and $\xi=\frac{c}{2m\omega_o}$ and $\omega_d=\omega_o\sqrt{1-\xi^2}$

where: ω_o : circular frequency; ξ: damping ratio.

Therefore, eq.1 can be written

$$\ddot{x}(t)+2\xi\omega_o\dot{x}(t)+\omega_o^2x(t)=-\ddot{x}_g(t)$$

Using Duhamel's integral, the solution of SDOF system initially at rest is given by (Agrawal and Shrikhande, 2006), [20]

$$x(t)=-\int_0^T\ddot{x}_g(\tau)\frac{e^{-\xi\omega_0(t-\tau)}}{\omega_d}i_{ns}\omega_d(t-\tau)d\tau$$

The maximum displacement of the SDOF system having parameters of ξ and ω_0 and subjected to specified earthquake motion, is expressed by $\ddot{x}_g(t)$.

The relative displacement spectrum of earthquake ground motion is defined as,

$$|x(t)|_{\max}=\left|\int_0^t\ddot{x}_g(\tau)\frac{e^{-\xi w_0(t-\tau)}}{\omega_d}i_{ns}\omega_d(t-\tau)d\tau\right|_{\max}$$

$$s_d(\xi,\omega_o)=|x(t)|_{\max}$$

Similarly, the relative velocity spectrum, S_v and absolute acceleration response spectrum, S_a are expressed as,

$$s_v(\xi,\omega_o)=|\dot{x}(t)|_{\max}$$

$$s_a(\xi,\omega_o)=|\ddot{x}_a(t)|_{\max}=|\ddot{x}(t)+\ddot{x}_g(t)|_{\max}$$

The pseudo velocity response spectrum, S_{pv} for the system is defined as

$$s_d(\xi,\omega_o)=|x(t)|_{\max}$$

Similarly, the pseudo acceleration response, S_{pa} is obtained by multiplying the S_d to ω_0^2 , thus

$$s_{pa}(\xi,\omega_o)=\omega_o^2s_d(\xi,\omega_o) \qquad Eq.(2)$$

$\xi=0$ i.e $\ddot{x}s(t)+\omega_o^2x(t)=-\ddot{x}_g(t)$

Consider a case where

$$s_a=|\ddot{x}(t)+\ddot{x}_g(t)|_{\max}=|-\omega_0^2x(t)|_{\max}=\omega_0^2|x_{\max}|=\omega_0^2s_d=s_{pa}$$

The above equation implies that for an undamped system, $S_a = S_{pa}$.

The quantity S_{pv} is used to calculate the maximum strain energy stored in the structure expressed as

$$E_{\max}=\frac{1}{2}Kx_{\max}^2=\frac{1}{2}m\omega_0^2s_d^2=\frac{1}{2}ms_{pv}^2 \qquad Eq.(3)$$

The quantity S_{pa} is related to the maximum value of base shear as

$$V_{\max}=Kx_{\max}=m\omega_0^2s_d=ms_{pa} \qquad Eq.(4)$$

The relations between different response spectrum quantities is shown in the table (1).

Table (1). Relation between displacement, velocity, and acceleration

Relative displacement, $\lvert x(t)\rvert_{\max}$	$= S_d$	$\simeq \frac{S_v}{\omega_0}$	$\simeq \frac{S_a}{\omega_0^2}$ *	$= \frac{S_{pv}}{\omega_0}$	$= \frac{S_{pa}}{\omega_0^2}$
Relative velocity, $\lvert \dot{x}(t)\rvert_{\max}$	$\simeq \omega_0 S_d$	$= S_v$	$\simeq \frac{S_a}{\omega_0}$	$\simeq S_{pv}$	$\simeq \frac{S_{pa}}{\omega_0}$
Absolute acceleration, $\lvert \ddot{x}_a(t)\rvert_{\max}$	$\simeq \omega_0^2 S_d$ *	$\simeq \omega_0 S_v$	$= S_a$	$\simeq \omega_0 S_{pv}$	$\simeq S_{pa}$ *

(* If $\xi=0$ these relations are exact and the sign $\simeq$ is valid up to $0<\xi<0.2$)

As limiting case consider a rigid system i.e. $\omega_o\to\infty$ or $T_o\to0$, the values of various response spectra are:

$$\lim_{\omega_0\to\infty} S_d \to 0$$

$$\lim_{\omega_0\to\infty} S_v \to 0$$

$$\lim_{\omega_0\to\infty} S_a \to |\ddot{x}_g(t)|_{\max}$$

The three spectra i.e. displacement, pseudo velocity and pseudo acceleration provide the same information on the structural response. However, each one of them provides a physically meaningful quantity and therefore, all three spectra are useful in understanding the nature of an earthquake and its influence on the design. A combined plot showing all three of the spectral quantities is possible because of the relationship that exists between these three quantities. Taking the log of equations (3) and (4)

$$\log S_{pv} = \log S_d + \log\omega_0 \qquad Eq.(5)$$

$$\log S_{pv} = \log S_{pa} - \log\omega_0 \qquad Eq.(6)$$

From the Equations (5) and (6), it is clear that a plot on logarithmic scale with $\log S_{pv}$ as ordinate and $\log\omega_0$ as abscissa, the two equations are straight lines with slopes +45° and -45° for constant values of $\log S_d$ and $\log S_{pa}$, respectively. This implies that the combined spectra of displacement, pseudo velocity and pseudo acceleration can be plotted in a single as in figure2

Multi degree of freedom (MDOF) systems are usually analyzed using Modal Analysis. A typical MDOF system with 'n' degree of freedom is shown in Fig.3. This system when subjected to ground motion undergoes deformations in number of possible ways. These deformed shapes are known as modes of vibration or mode shapes. Each shape is vibrating with a particular natural frequency. Total unique modes for each MDOF system are equal to the possible degree of freedom of system. The equations of motion for MDOF system is given by:

$$[m]\{\ddot{x}(t)\}+[c]\{\dot{x}o(t)\}+[K]\{x(t)\}=-[m]\{r\}\ddot{x}_g(t) \quad Eq.(7)$$

where, [m] = Mass matrix (n × n); [k] = Stiffness matrix (n × n); [c] = Damping matrix (n × n); {r} = Influence coefficient vector (n×1); {x(t)} = relative displacement vector; $\dot{x}(t)$ =relative velocity vector, $\ddot{x}(t)$ =relative acceleration vector, and $\ddot{x}_g(t)$ =earthquake ground acceleration.

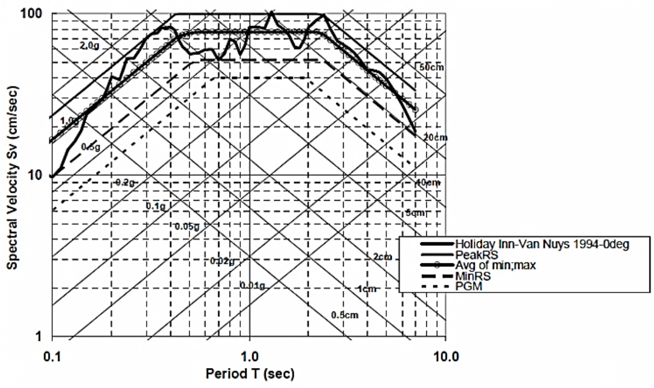

Fig.2. Spectra of displacement, pseudo velocity and pseudo acceleration

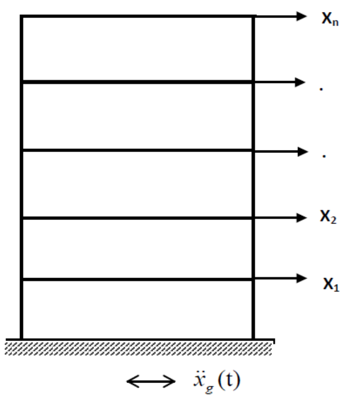

Fig.3. A typical MDOF system with 'n' degree of freedom

The undampedeigen values and eigen vectors of the MDOF system are found form the characteristic equation

$$\{[K]-\omega_i^2[m]\}\phi_i=0 \quad i=1,2,3,\ldots,n \quad Eq.(8)$$

$$\det\left|\{[K]-\omega_i^2[m]\}\right|=0 \quad Eq(9)$$

where, ω_i^2 eigen values of the i_{th} mode; ϕ_i eigen vector or mode shape of the i_{th} mode; ω_i natural frequency in the i_{th} mode.

Let the displacement response of the MDOF system is expressed as

$$\{x(t)\}=[\phi]\{y(t)\} \quad Eq.(10)$$

where {y(t)} represents the modal displacement vector, and [φ] is the mode shape matrix given by

$$[\phi]=[\phi_1,\phi_2,\ldots\ldots\ldots\phi_n]$$

Substituting $x(t)=[\phi]\{y(t)\}$ in eq.7 and pre-multiply by

$$[\phi]^T[m][\phi]\{\ddot{y}(t)\}+[\phi]^T[c][\phi]\{\dot{y}(t)+[\phi]^T[K][\phi]\{y(t)\}=-[\phi]^T[m]\{r\}\ddot{x}_g(t)$$

The above equation reduces to

$$[M_m]\{\ddot{y}(t)\}+[c_d]\{\dot{y}(t)\}+[K_d]\{y(t)\}=-[\phi]^T[m]\{r\}\ddot{x}_g(t) \quad Eq.(11)$$

where:

$[\phi]^T[m][\phi]=[M_m]$= generalized mass matrix;

$[\phi]^T[c][\phi]=[c_d]$=generalized damping matrix;

$[\phi]^T[K][\phi]=[K_d]$=generalized stiffness matrix.

By virtue of the properties of the [φ], the matrices $[M_m]$ and $[K_d]$ are diagonal matrices. However, for the classically damped system (i.e. if the $[C_d]$ is also a diagonal matrix), the Eq.11 reduces to the following equation;

$$\ddot{y}_i(t)+2\xi_i\omega_i\dot{y}_i(t)+\omega_i^2y_i(t)=-\Gamma_i\ddot{x}_g(t)\ (i=1,2,3,\ldots,n) \quad Eq.(12)$$

where,

$y_i(t)$=modal displacement response in the i_{th} mode;

ξ_i=modal damping ration in the i_{th} mode;

Γ_i=modal participation factor for i_{th} mode expressed by

$$\Gamma_i=\frac{\{\phi_i\}^T[m]\{r\}}{\{\phi_i\}^T[m]\{\phi_i\}}$$

eq.12 is of the form of eq.1 representing vibration of SDOF system, the maximum modal displacement response is found from the response spectrum i.e.

$$y_{i,\max}=\left|y_i(t)\right|_{\max}=\Gamma_i s_d(\xi_i,\omega_i) \quad Eq.(13)$$

The maximum displacement response of the structure in the i_{th} mode is

$$x_{i,\max}=\phi_i y_{i,\max}\ (i=1,2,\ldots\ldots..,n) \quad Eq.(14)$$

The maximum acceleration response of the structure in the i_{th} mode is

$$\{\ddot{x}_a\}_{i,\max} = \{\phi_i\}\Gamma_i s_{pa}(\xi_i,\omega_i) \quad (i=1,2,\ldots\ldots..,n) \quad Eq.(15)$$

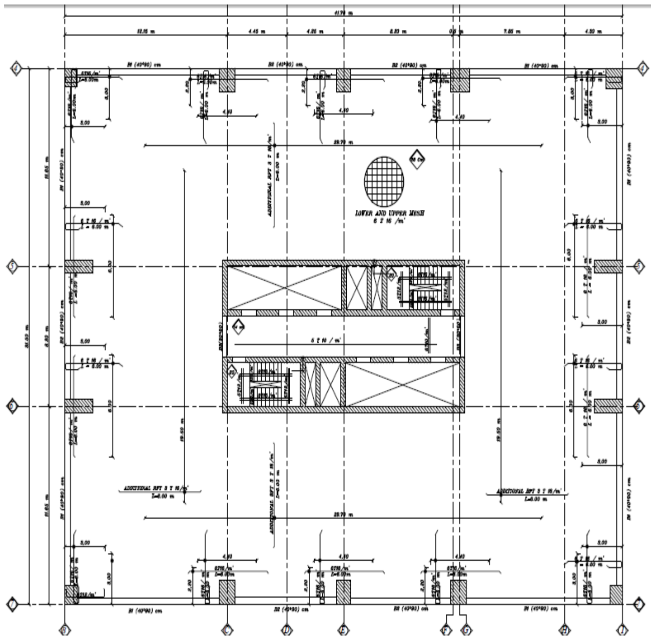

Fig. 3 Flat slab plan system

The required response quantity of interest, r_i i.e. (displacement, shear force, bending moment etc.) of the structure can be obtained in each mode of vibration using the maximum response obtained in eq.14 and eq.15. However, the final maximum response, r_{max} shall be obtained by combining the response in each mode of vibration using the modal combinations rules.

A- Flat slab floor

For the lower range of high-rise flat slab/plate buildings (up to15 stories), the framing action of the slab-columns can provide the necessary stiffness and strength to resist wind and seismic forces. Flat slab/plate -columns subject to lateral loads are analyzed as unbraced two-dimensional equivalent frames using two methodologies; the torsional member method and the effective slab width method. Our Flat slab system consists of a flat plate 28.00 cm resting on five models of columns with marginal beam of 90cm. The slab was checked against deflection, flexural and punching stresses and it was fully safe.

B- Panelled beams floor

Panelled beams slab system consists of thin two way solid slabs 10-12 Cm thickness rested on rigid pannelled beams 30 x 85 Cm sectional area working by grid action where each beam works as an elastic support for the other at the intersection area between them. The paneled beams are supported on external beams 40 x 90 Cm sectional area.

Fig. 4 Panelled beams slab plan system

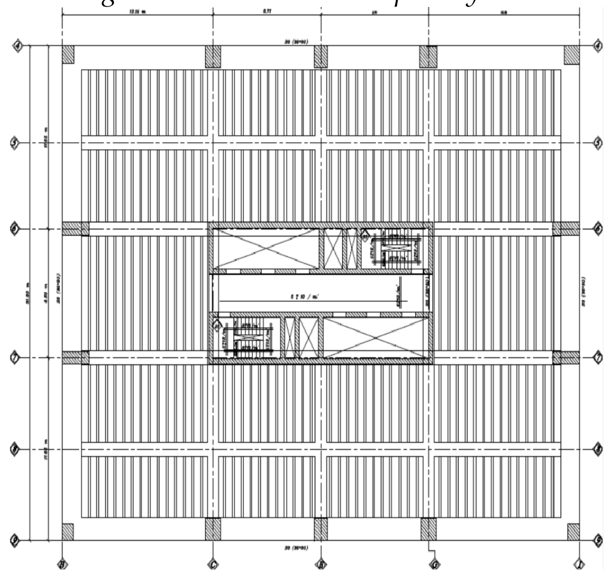

Fig. 5.a Ribbed slab plan system

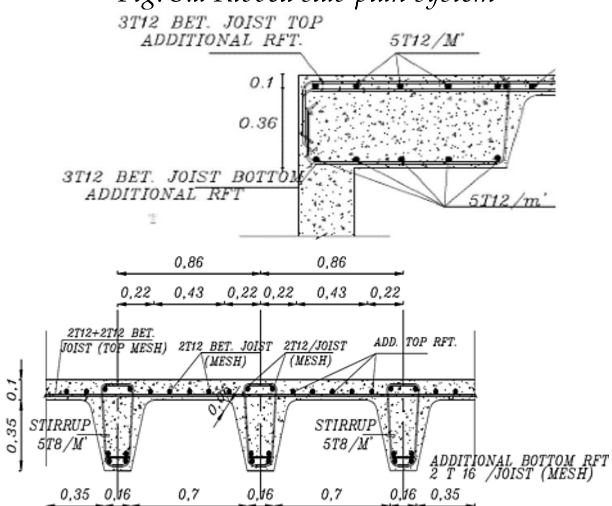

Fig. 5.b Beams & Ribs details for Ribbed slab

3. ANALYSIS PROCEDURE

There are three models of a residential building of 30 stories and total area of 1313.55 m2, the three models (Core system) represent flat slab system, pannelled beams system, ribbed slab system respectively. This systems of slabs were fabricated and analysis by ETABS 9.5 in the current study. All models have the same architecture plan and the same columns sections and also the same area, figure 6 represents the 3D – models from ETABS program.

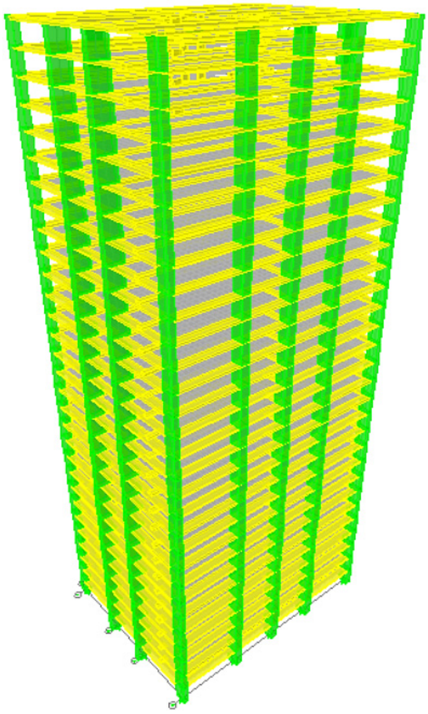

Fig. 6 ETABS 3-D model

Detected Response Parameters from ETABS 9.5 - Detected INTER STORY DRIFT in the three systems

Drift ratio is the ratio between drift and building height in percent, and the inter-story drift ratio is the ratio between the change of drift in the story and the story height.

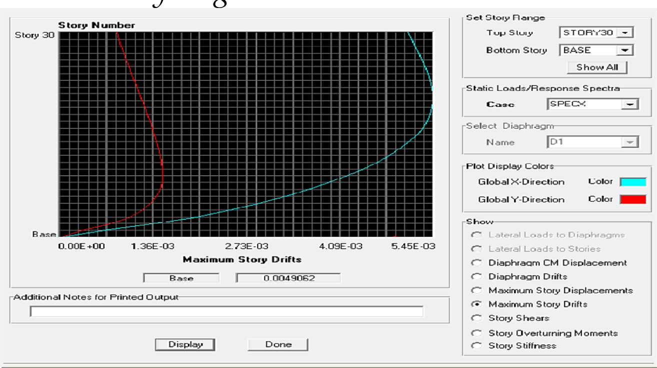

Fig. 7 Inter Story Drift in X-direction for Flat slab system

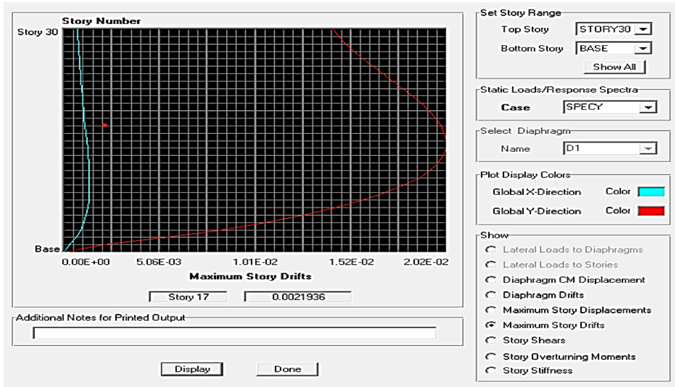

Fig. 8 Inter Story Drift in Y-direction for Flat slab system

B-For Pannelled beams system

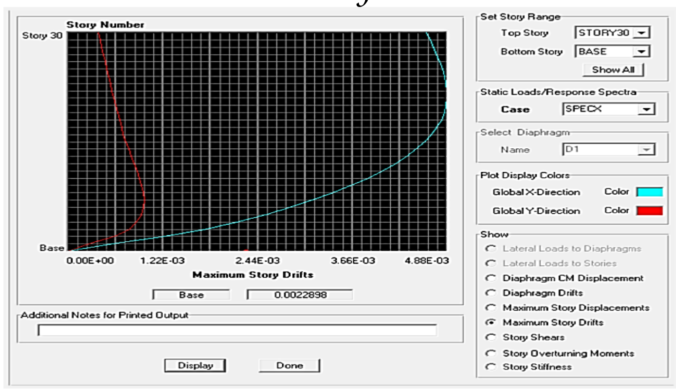

Fig. 9 Inter Story Drift in X-direction for Pannelled beams system

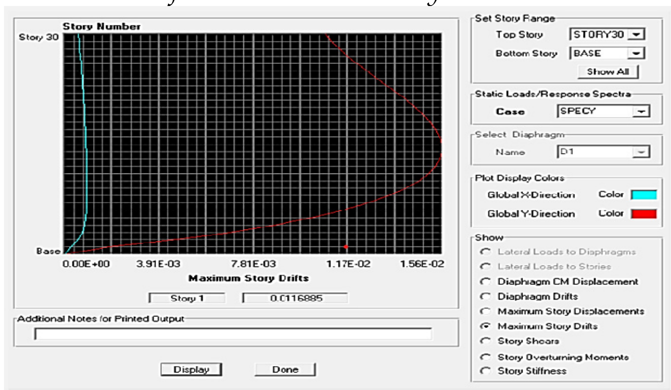

Fig. 10 Inter Story Drift in Y-direction for Pannelled beams system

C-For Ribbed slab system

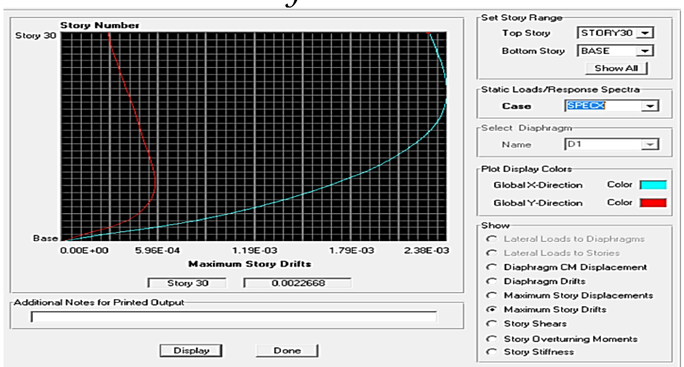

Fig. 11. Inter Story Drift in X-direction for Ribbed slab system

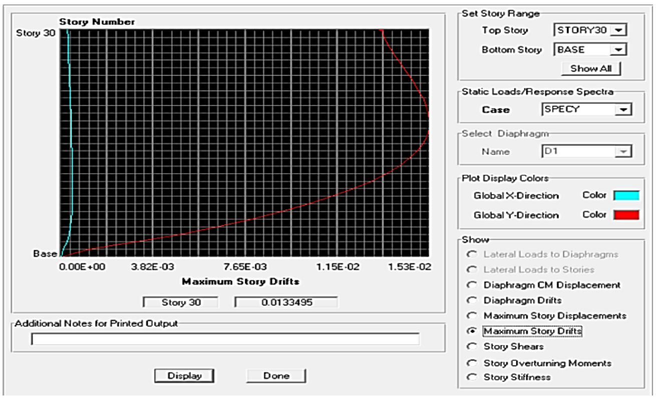

Fig. 12 Inter Story Drift in Y-direction for Ribbed slab system

Detected BASE SHEAR in the three systems

A- For Flat slab system

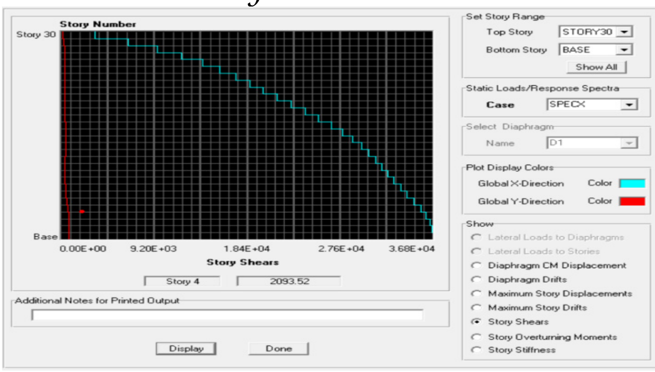

Fig. 13 Base Shear in X-direction for Flat slab system

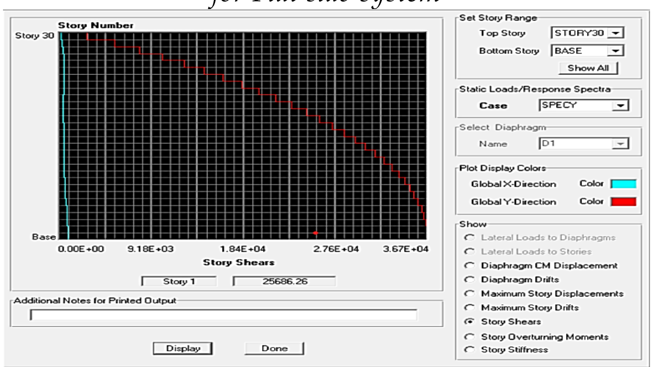

Fig. 14 Base Shear in Y-direction for Flat slab system

B- For Pannelled beams system

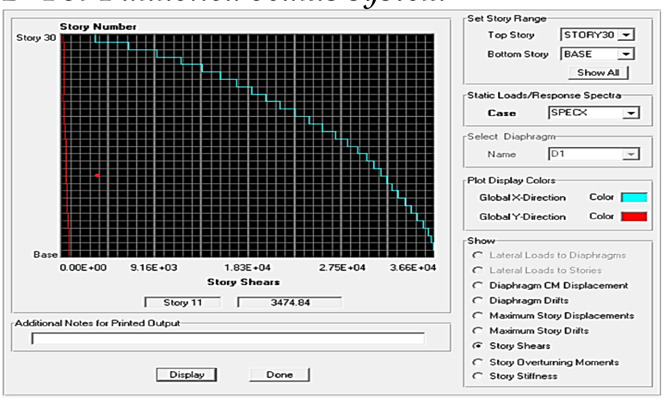

Fig. 15 Base Shear in X-direction for Pannelled beams system

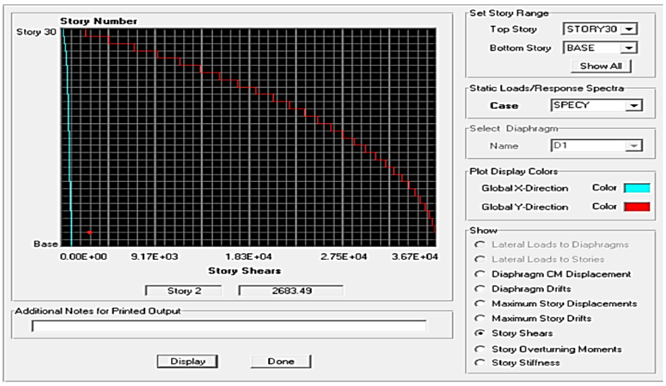

Fig. 16 Base Shear in Y-direction for Pannelled beams system

C-For Ribbed slab system

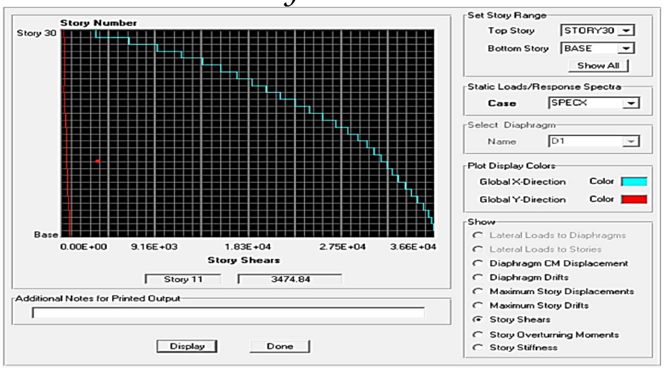

Fig. 17 Base Shear in X-direction for Ribbed slab system

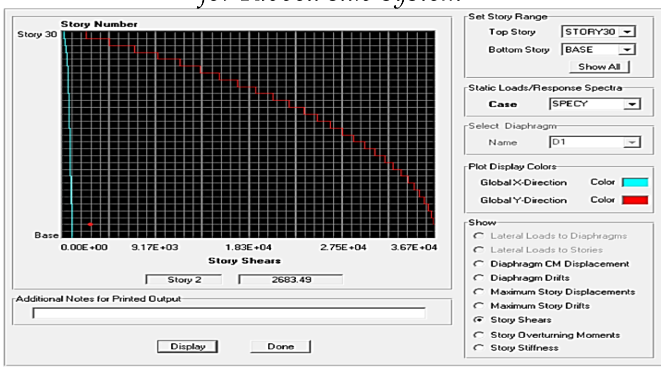

Fig. 18 Base Shear in Y-direction for Ribbed slab system

Detected OVERTURNING MOMENT in the three systems

A-For Flat slab system

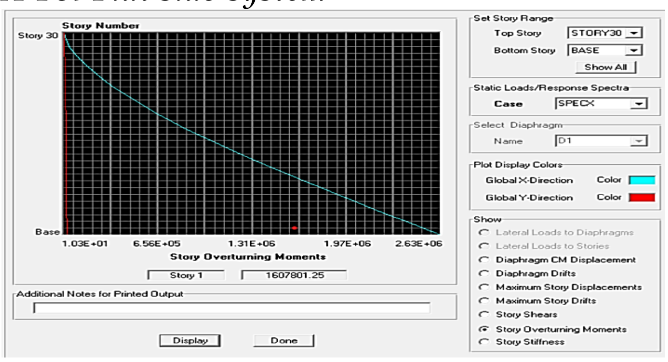

Fig. 19 Overturning Moment in X-direction for Flat slab system

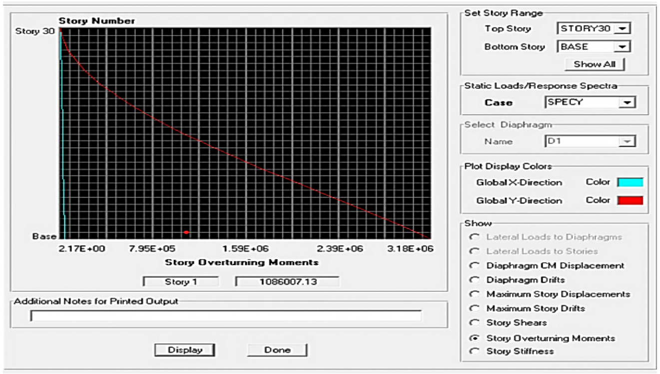

Fig. 20 Overturning Moment in Y-direction for Flat slab system

B- For Pannelled beams system

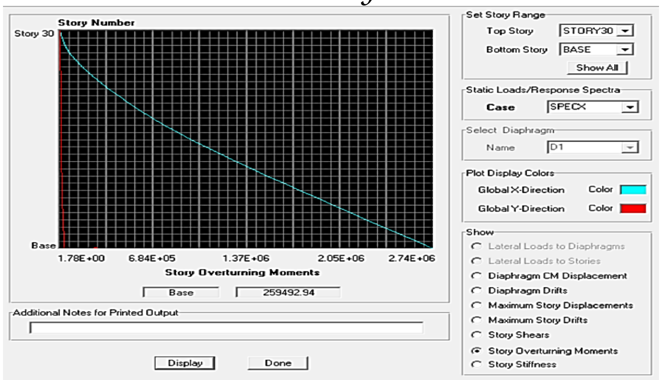

Fig. 21 Overturning Moment in X-direction for Pannelled beams system

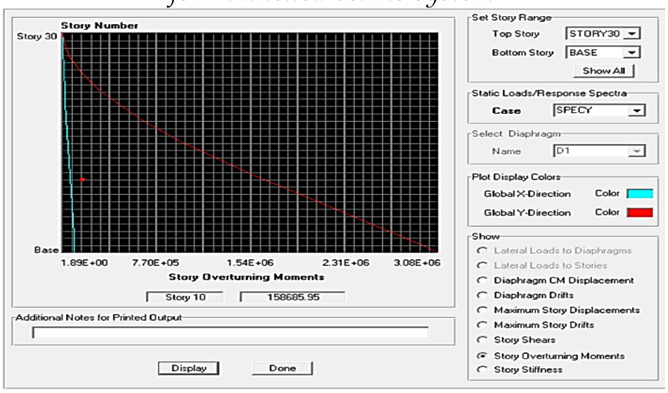

Fig. 22 Overturning Moment in Y-direction for Pannelled beams system

C- For Ribbed slab system

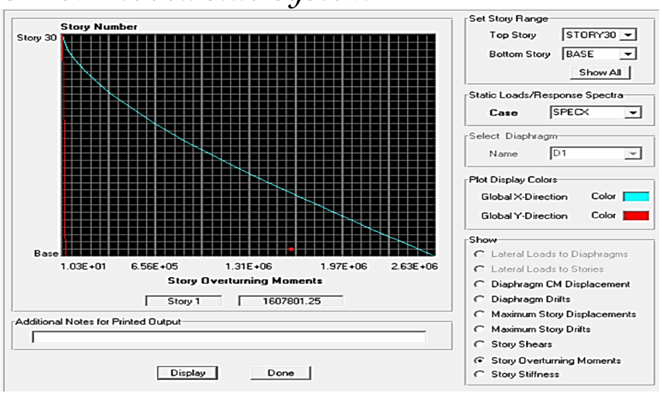

Fig. 23 Overturning Moment in X-direction for Ribbed slab system

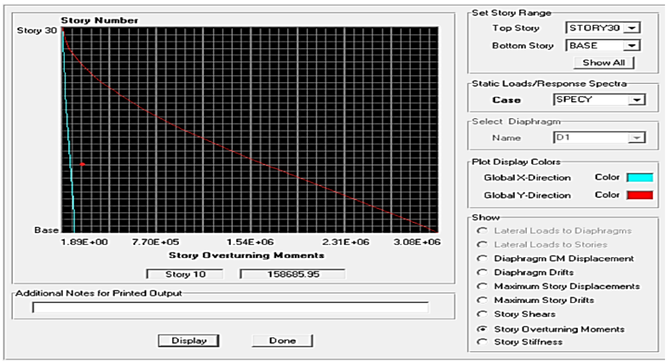

Fig. 24 Overturning Moment in Y-direction for Ribbed slab system

Detected DISPLACEMENT-in the three systems

A-For Flat slab system

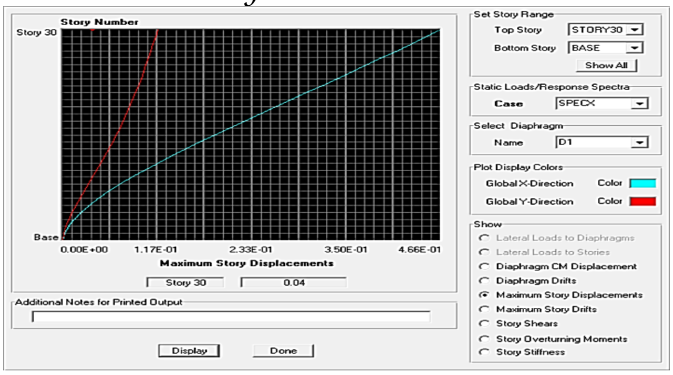

Fig. 25 Displacement in X-direction for Flat slab system

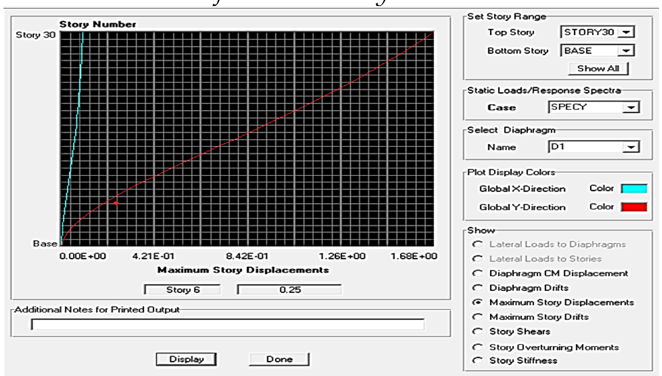

Fig. 26 Displacement in Y-direction for Flat slab system

B-For Pannelled beams system

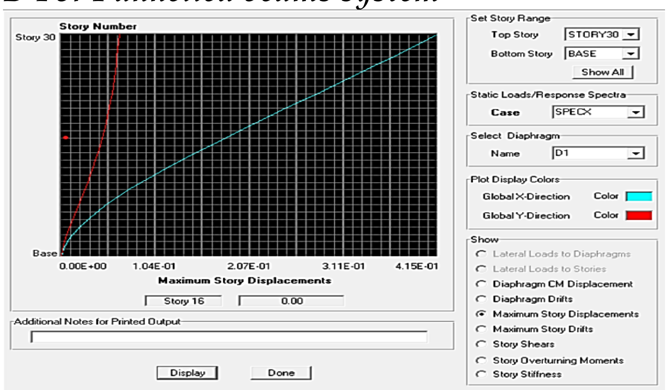

Fig. 27 Displacement in X-direction for Pannelled beams system

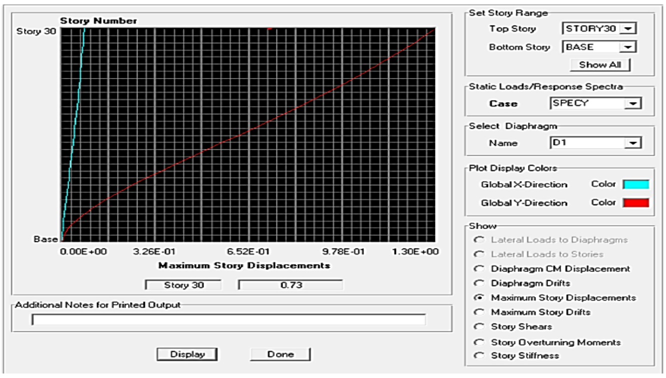

Fig. 28 Displacement in Y-direction for Pannelled beams system

C-For Ribbed slab system

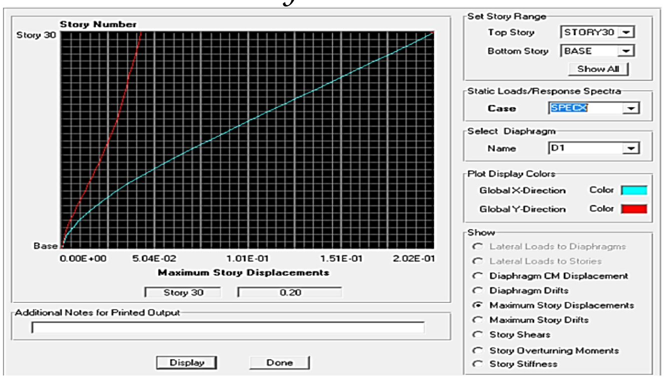

Fig. 29 Displacement in X-direction for Ribbed slab system

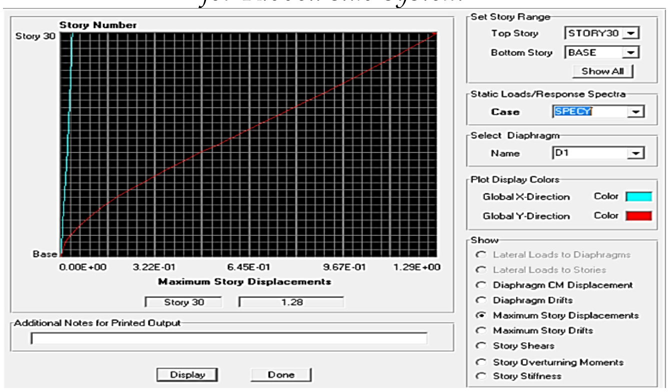

Fig. 30 Displacement in Y-direction for Ribbed slab system

4. ANALYTICAL RESULTS AND DISCUSSION

Results of the analysis three systems of slabs are presented, analyzed and discussed in this section. Topics to be covered include the Inter Story Drift, the Base Shear, Overturning Moment, and Displacement in two directions X and Y of the analysis systems. Tables from 2 to 5 lists the results.

Table (2): Inter Story Drift in X&Y-direction for three systems

Direction	Flat slab	Pannelled beams	Ribbed slab
(m)X	0.00545	0.00488	0.00238
(m)Y	0.0202	0.0156	0.0153

Table (3): Base Shear in X&Y-direction for three systems

Direction	Flat slab	Pannelled beams	Ribbed slab
(KN)X	36800	36600	36600
(KN)Y	36700	36700	36700

Table (4): Overturning Moment in X&Y-direction for three systems

Direction	Flat slab	Pannelled beams	Ribbed slab
YX (KN.m)	2630000	2740000	2630000
(KN.m)	3180000	3080000	3080000

Table (5): Displacement in X&Y-direction for three systems

Direction	Flat slab	Pannelled beams	Ribbed slab
(m)X	0.466	0.415	0.202
(m)Y	1.68	1.3	1.29

The seismic response parameters of buildings are the structure deformations (displacements and rotations), internal forces in structural elements, and ductility demand of members with plastic behavior.

Top story lateral displacement (drift) and the inter-story lateral displacement (story drift) are the seismic response parameter of prime importance for systems of slabs in high rise buildings. Large values of drift could affect the stability and resistance of tall buildings.

The system of Ribbed slab reduced the inter-story drift by 56% than the system of flat slab and by 51% than the system of Pannelled beams in the main direction (X direction). And the system of Ribbed slab reduced the Displacement by 57% than the system of flat slab and by 51% than the system of Pannelled beams in the main direction (X direction).

5. CONCLUSIONS

Based on the results the following conclusions could be drawn:

1. *The choice of the system for slab in the tall building is very important to resist the internal forces and stability.*
2. *The system of Ribbed slab reduced the inter-story drift, and Displacement by grater than 51% for core system.*
3. *The Ribbed slab systems resists the punching shear failures, and increase the ductility capacity.*
4. *The flat slab cases, large inter-story drift which cause brittle punching shear failures, reduces the ductility capacity*

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