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# Non-Linear Performance of Multi-Storey Flat Slab System with Structural Wall and Perimeter Frames

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***Abstract* – Flat slab system is the most desirable system in the construction of concrete structures due to its added advantages like faster construction, cost effective, clear floor to floor height, larger utilization space by nourishing architectural and MEP intent. Even though the Flat slab system is a proven gravity floor system, it was a most susceptible floor system owing to the nonappearance of lateral load resisting moment frames. Flat slab system in combination with structural wall and perimeter frames offers a stable structural system showing greater response to seismic ground motion. The structural walls often commonly referred as shear wall will possess greater lateral stiffness due to its large in-plane stiffness and strength. In this study a 10 storey commercial building located in Seismic zone – III, comprises of flat slab with a structural wall and perimeter frames are considered for linear analysis and non-linear analysis using FEA software known as ETABS. The model was subjected initially with linear static and dynamic analysis based on the latest provisions practiced by IS 1893:2016 and the structural response like natural time period, base shear, displacement, Lateral drift, storey-drift and slab-column shear capacity will be studied and designed based on Indian codal recommendations. Later the Non-Linear static analysis (NLSA) is performed with respect to the maximum displacement and Non-linear Time-history analysis is performed with Fast Non-Linear Analysis (FNA) method. Corresponding building performance point, structural performance level and the failure behavior of the structural component is observed. From the observation the ultimate performance of the flat-slab structural system is endorsed with respect to the Indian codal provisions.**

***Keywords* – Flat-Slab with Structural wall, Non-Linear, Push-over analysis, Time-History.**

## I. INTRODUCTION

In the evolution of structural engineering, the structural system has been observed a vigorous development in the international progression and in the advancement in repetition of engineering and construction in India. The significant reformations in Structural Engineering in India have taken place during the end of 20th Century due to various factors such as globalization, commercialization and based on the seismological data obtained from the recent earthquakes occurred in India. Three decades earlier the predominant structural system followed in the buildings were moment frame system. Due to the rapid development in infrastructure owes to the growth of vertical expansion in structures is mandatory to ensure the safety and serviceability of human civilization. During this reformation, IS: 456-2000 has transformed from working stress method to limit state method. Whereas the Indian code for earthquake practice has proposed superior guidelines to adopt various lateral resisting structural systems to ensure the structural stability of the structures. Rapid urbanization and development in architectural and aesthetical approach leads to high utilization of spaces during the design phase. Due to this the moment frame system was not found to be the most construction friendly system and becomes uneconomical. So globally proven flat slab system was widely adopted in India during this period. Even though the former available guideline were not sufficient to determine the performance of flat slab system; the earlier codal provision have been interpolated under category of dual system to adopt flat slab in the structural system of buildings. Based on few international developments, Indian code has seen a next major change in the end of 2016. A special clause has been introduced to adopt the flat slab system along with perimeter beams and structural walls. Considering the guidelines provided in IS: 1893-2016 as an introductory data, it is mandatory to perceive the various concert of flat slab system under seismic conditions. Further study and validation of structural performance of flat slab system will contribute to the additional refinement of codal provisions in the future.

In this research a 50 m height 10 storied commercial building is considered for the study. The structure is located in seismic zone III resting on hard rock stratum. The building will have symmetrical structural configuration comprises of flat slab with drop panels with

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central core and scattered core on ends of vertical direction with perimeter frames. All the floors will have commercial occupancy except the fifth floor will have data center which leads to mass irregularity in the structure. The structure is initially subjected to gravity loads, wind loads, static seismic loads and dynamic seismic loads. Analysis is performed under both static and dynamic condition based on the latest provision of prevailing IS: 1893-2016. The structural response like natural period, storey drift, displacement, base shear, punching shear ration is studied. Later the structural elements are designed for the ultimate condition in accordance with latest prevailing Indian standards. Later the structure is subjected to both non-linear static and dynamic analysis. Pushover analysis with displacement coefficient method is adopted for non-linear static analysis. TH analysis with FNA method is adopted for non-linear dynamic analysis. For this study, the columns and beams are assigned with non-linear auto hinges at joints. Structural shear walls are assigned with non-linear fiber hinges. The entire analysis and design are performed using FEA software ETABS. From the non-linear analysis, the performance point of the building, performance level of the structural elements, the maximum
demand capacity of the structural elements and failure point of structural elements are observed.

## II. OBJECTIVE AND SCOPE

The objective of the research are as follows,

1. To assess the Linear performance under static and dynamic condition.
2. To study the structural response like natural time period, displacement, lateral drift, storey drift, base shear and slab column shear capacity.
3. To assess the Non-Linear performance under static condition using displacement coefficient method.
4. To assess the Non-Linear performance under TH dynamic condition using FNA method.
5. Static and Dynamic behavior of the structure under linear condition is obtained and validated against the codal limitations.
6. The building performance level is obtained for Non-Linear structural behaviour under static and dynamic condition.
7. Evaluation and verification of serviceability criteria of buildings located in seismic zone III with flat slab system corresponding to provisions of latest prevailing Indian standards.
8. Identification of critical structural element in the flat slab system beyond the performance level.

## III. MODELING

### 1. Geometric Model

The conceptual structural framing plan of the building for the study is shown in Fig. 1. A 3D FEA model is developed using graphical user interface in FEA software ETABS as shown in Figure. 2. The geometrical and material properties are assigned in the 3D model is tabulated in Table-I and the typical floor storey height is 4m and data center floor storey height is considered as 5m.

Table- I: Geometrical Properties.

| | |
|---|---|
| Concrete grade | M40 |
| Steel grade | Fe500 |
| Number of Storeys | 10 |
| Plan Dimension | 64 mx60 m |
| Typical Floor Height | 4000 mm |
| Data Centre Floor Height | 5000 mm |
| Total Height of building | 50 m |
| Office Floor Flat Slab Thickness | 250 mm |
| Office floor Drop Plan dimension | 4000x4000 mm |
| Office floor Drop Thickness | 500 mm |
| Data Centre floor Flat slab thickness | 300 mm |
| Data Centre floor drop plan dimension | 4000x4000 mm |
| Data Centre floor drop thickness | 600 mm |
| Column Dimension | 1000x1000 mm |
| Periphery Beam | 1000x750 mm |
| Shear Wall thickness | 350 mm |
| Shear Wall Link Beam | 350x750 mm |
| Grade Beam | 600x600 mm |
| Stiffness Modifier for Columns $I_{eff}$ | 0.7 |
| Stiffness Modifier for Beams $I_{eff}$ | 0.35 |

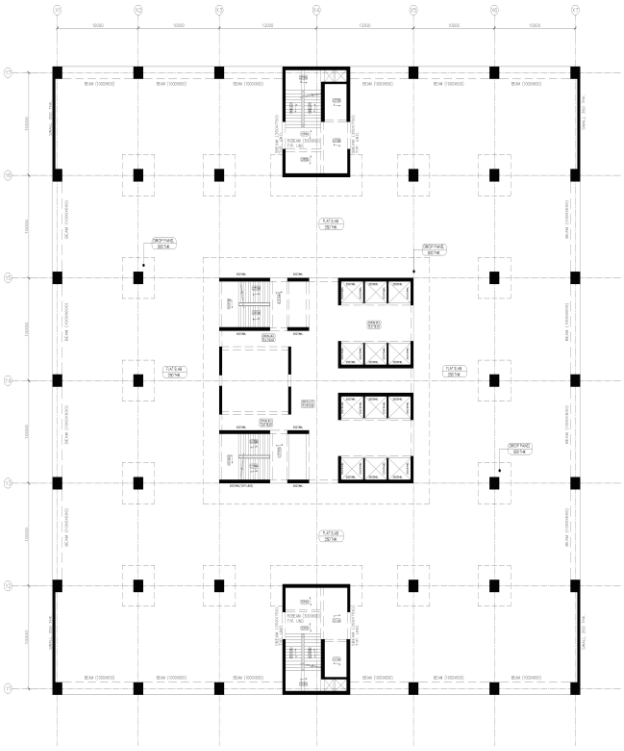

Fig.1.Typical Floor Framing Plan.

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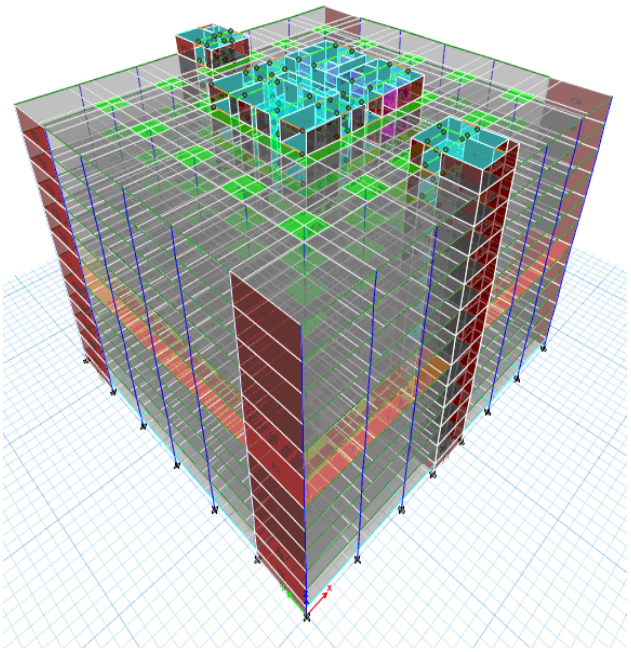

Fig.2.3D FEA Model.

## 2. Gravity Load

Once the geometric 3D model is developed, the gravity loads as described in Table-II is assigned to the model.

Table- II: Gravity Load Parameters

| Description | Load Type | Load Intensity (kN/m$^2$) |
|---|---|---|
| Dead Load (DL) | Self-Weight (DL) | 25 (as per section property) |
| | Super Imposed Load (SDL) | 3.0 |
| | Office Space | 4.0 |
| Live Load (LL) | Data Centre (Non-reducible) | 10.0 |
| | Roof LL (Reducible) | 1.5 |

numerous closely spaced low rise structure. The parameters are k1= 1.0, k2= 1.12, k3=1.0, k4=1.2.

## 3. Equivalent Static Seismic Load

The recent development in IS 1892:2016, the approximate fundamental transitional natural period, Ta for building with RC structural walls is described as below,

$$T_a = \frac{0.075h^{0.75}}{\sqrt{A_w}} \geq \frac{0.09h}{\sqrt{d}} \quad (1)$$

$$A_w = \sum_{i=1}^{N_w}\left[A_{wi}\left\{0.2 + \left(\frac{L_{wi}}{h}\right)^2\right\}\right] \quad (2)$$

The design base shear VB is obtained using equation (3). With respect to the guidelines provided by IS 1893:2016; Z = 0.16, I = 1.2, R = 3.0. and corresponding design acceleration co-efficient for 5% damping is shown in Fig.3.

$$VB = Ah\ W \quad (3)$$

The design horizontal seismic coefficient,

$$A_h = \frac{\left(\frac{Z}{2}\right)\left(\frac{S_a}{g}\right)}{\left(\frac{R}{I}\right)} \quad (4)$$

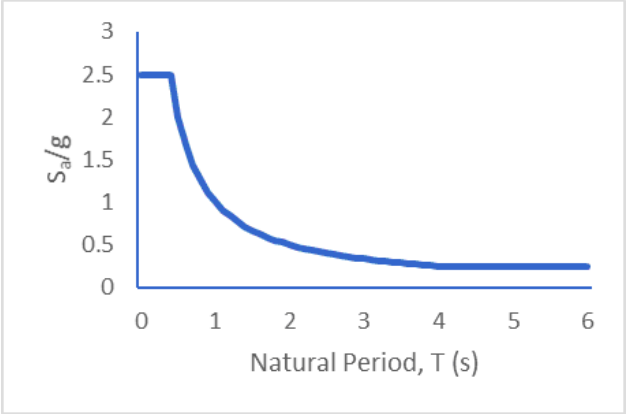


Fig.3. Design Acceleration co-efficient (5% Damping).

## 4. Response Spectrum (RS) function

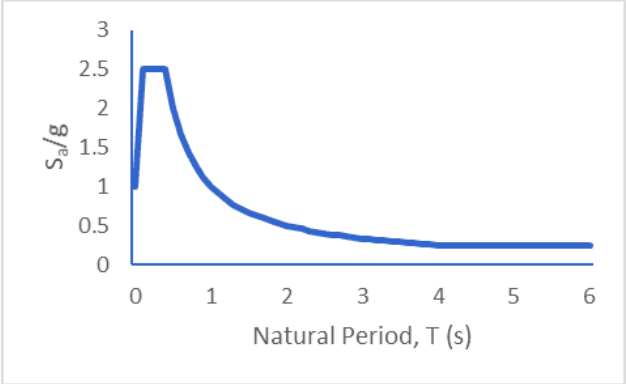


Fig.4. Design Acceleration co-efficient (5% Damping)

The structure is located at zone-III and its height is 50 m. It is mandatory to do dynamic analysis for the structure. Hence RS analysis is performed and the corresponding design acceleration coefficient to be used in RS method is shown in Fig.4.

## 5. Time History (TH) function

TH analysis is done using horizontal ground motion acceleration components. As per the IS 1893:2016 codal guidelines, an appropriate existing earthquake ground motion data is considered as a representative function and to be scaled with the design acceleration RS with 5%

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damping. For this analysis a well know fundamental ground motion data of Elcentro earthquake is considered as a representative TH function. Elcentro earthquake occurred in 1940 at Imperial valley province in the territorial region of U.S and Mexico. The earthquake magnitude of 6.9 in Richter scale and termed as extreme earthquake with intensity as X in Macaulay Intensity scale. This earthquake is measured using strong motion seismograph with maximum perceived intensity and measured next to the fault rupture. Hence Elcentro earthquake ground motion data is considered as a fundamental function and scaled with the design acceleration function as specified in IS 1893:2016 for the analysis. The horizontal ground acceleration motion of Elcentro earthquake along two principal direction is shown in Fig.5 and Fig.6. The scaled ground motion acceleration with respect to design acceleration RS with 5% damping is shown in Fig.7 and Fig.8.

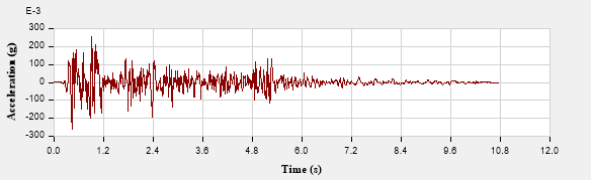

Fig.5. Elcentro N-S component.

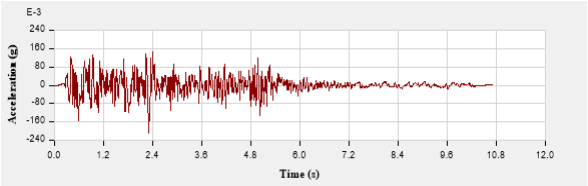

Fig.6. Elcentro E-W component.

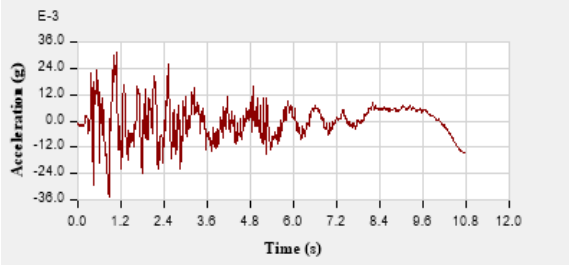

Fig.7. TH X function (Scaled).

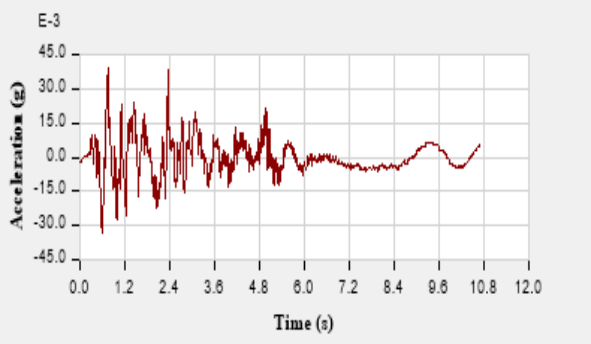

Fig.8. TH Y function (Scaled).

### 6. Push-Over Analysis

It is defined as non-linear static analysis, which was performed by maximum displacement control method. It will be performed for the structures which was designed based on the ultimate load combinations recommended by prevailing Indian standards. Once the structural elements are designed, the auto hinges were assigned for the structural elements and the Non-linear analysis was performed as step by step analysis starting from the results of static gravity analysis and the increment in deflection is measured for each step.

## IV. RESULTS AND DISCUSSION

The above mentioned 10 storey structure is analyzed based on prevailing Indian standards under linear and nonlinear conditions using ETABS software. Under Linear analysis, the structural responses like Base shear, Displacement, Storey-drift, Fundamental Natural period and Slab-Column Shear capacity are discussed.

### 1. Seismic Parameter Observation

The Approximate fundamental natural time period (Ta) and corresponding summary of seismic parameters used from the analysis is listed in Table-III. Further the structural responses are elaborately discussed in the subdivisions henceforth.

Table- III: Seismic Parameter Observation

| | |
|---|---|
| Approximate Fundamental Natural Period (X Dir.), $T_{ax}$ | 0.56 s |
| Approximate Fundamental Natural Period (Y Dir.), $T_{ay}$ | 0.58 s |
| Seismic Weight, W | 725147.3 kN |
| Design Acceleration Coefficient (X and Y Dir.), $S_a/g$ | 1.78, 1.72 |
| Design horizontal seismic coefficient (X and Y Dir.), $A_{hx}$ , $A_{hy}$ | 0.057, 0.055 |
| Design Base Shear (X Dir.), $V_{BX}$ | 41252.83 kN |
| Design Base Shear (Y Dir.), $V_{BY}$ | 39942.7 kN |
| Maximum Displacement (X Dir. – Equi. Static), δeqx | 33.27 mm |
| Maximum Displacement (X Dir. – Resp. Spec.), δspecx | 25.00 mm |
| Maximum Displacement (X Dir. – TH), $\delta_{THX}$ | 30.70 mm |
| Maximum Displacement (Y Dir. – Equi. Static), δeqy | 38.43 mm |
| Maximum Displacement (Y Dir. – Resp. Spec.), δspecy | 28.55 mm |
| Maximum Displacement (Y Dir. – TH), $\delta_{THY}$ | 36.09 mm |
| Maximum Storey Drift (X Dir. – Equi. Static), Deqx | 0.0819% |
| Maximum Storey Drift (X Dir. – Resp. Spec.), Dspecx | 0.0617% |

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| | |
|---|---|
| Maximum Storey Drift (X Dir. – TH), $D_{THX}$ | 0.0759% |
| Maximum Storey Drift (Y Dir. – Equi. Static), Deqy | 0.0981% |
| Maximum Storey Drift (Y Dir. – Resp. Spec.), Dspecy | 0.0768% |
| Maximum Storey Drift (Y Dir. – TH), $D_{THY}$ | 0.0923% |

## 2. Natural Time Period

The Approximate fundamental natural time period (Ta) and natural time period in mode of oscillation (Tk) along both principle direction is shown in Figure.9. From the figure it is observed that the Natural time period in first mode of oscillation along X-direction (Tkx) and Y-direction (Tky) is 0.403s and 0.469s higher than Approximate fundamental Time Period along X-direction (Tax) and Y-direction (Tay) respectively.

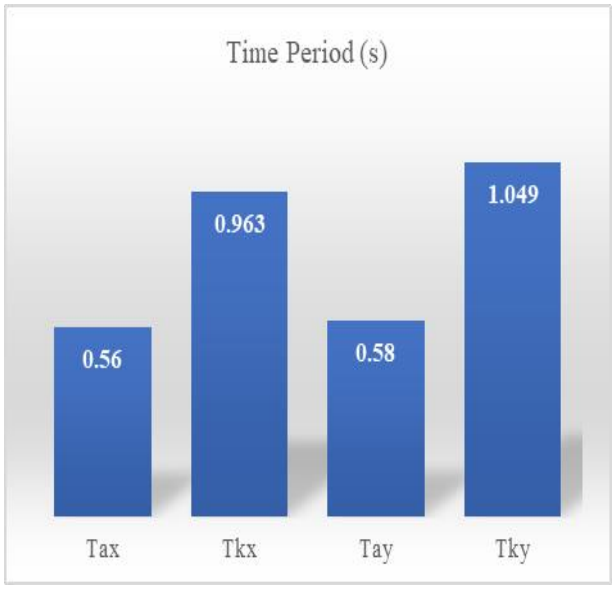


Fig.9. Natural time period.

## 3. Modal Participation Mass Ratio

The modal participation mass ratios for 10 modes have been listed in Table-IV. The first two modes are contributed along Y-direction and X-direction by 66% and 67% respectively and the third mode is contributed by torsion. Also, the natural time period between first two modes is differed by 8%. Thus, the codal recommendation is satisfied and there is no irregularity in modes of oscillation in the two-principal direction.

Table- IV: Modal Participation Mass Ratio

| Mode | Period (s) | X-dir. (%) | Y-dir (%) | Tor (%) |
|---|---|---|---|---|
| 1 | 1.049 | 0.00 | 0.66 | 0.01 |
| 2 | 0.963 | 0.67 | 0.00 | 0.00 |
| 3 | 0.911 | 0.00 | 0.01 | 0.65 |
| 4 | 0.26 | 0.00 | 0.18 | 0.00 |
| 5 | 0.239 | 0.18 | 0.00 | 0.00 |
| 6 | 0.116 | 0.00 | 0.05 | 0.01 |
| 7 | 0.107 | 0.06 | 0.00 | 0.00 |
| 8 | 0.068 | 0.04 | 0.00 | 0.00 |
| 9 | 0.061 | 0.00 | 0.08 | 0.02 |
| 10 | 0.04 | 0.05 | 0.00 | 0.00 |

## 4. Base Shear

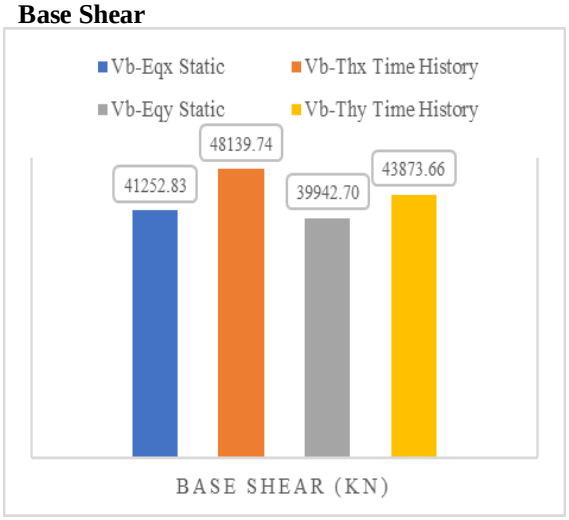


Fig.10. Base Shear VB (kN).

The Base shear for equivalent static seismic analysis and TH analysis along two principal directions is shown in Figure.10. From the graph it is expressed that the Base shear for TH analysis is greater by 16% along X-direction and 9% along Y-direction than the Equivalent static analysis respectively.

## 5. Storey Shear

The storey shear in both directions for Equivalent static analysis and TH analysis as shown in Fig. 11 and Fig.12 respectively. The storey shear of TH analysis shows a lesser profile between 5th floor to 9th floor along X direction. In Y direction, the TH analysis shows a lesser profile between 7th floor to 1st floor.

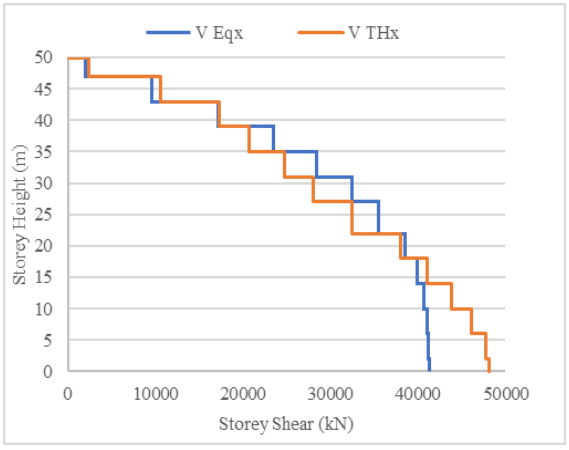


Fig.11. X direction- Storey Shear

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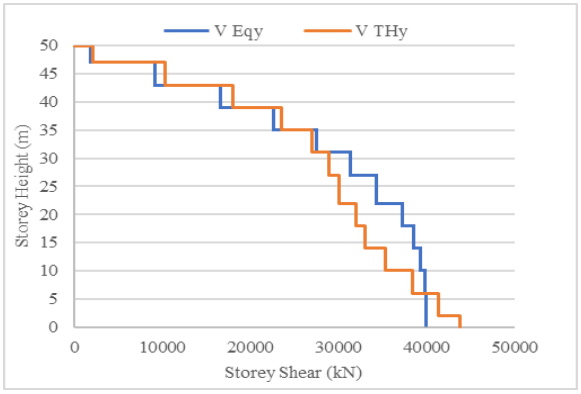


Fig.12. Y direction- Storey Shear

## 6. Displacement

The displacement of the building along two principal directions for three variants (Equivalent static, RS and TH) of linear analysis were shown in Fig.13 and Fig.14. From the figure it was perceived that the maximum displacement at top storey along X direction due to RS analysis and TH analysis is 24.8% and 7.7% lesser than Equivalent static analysis respectively. Similarly, the maximum displacement at top storey along Y direction due to RS analysis and TH analysis is 25.7% and 6.1% lesser than Equivalent static analysis respectively.

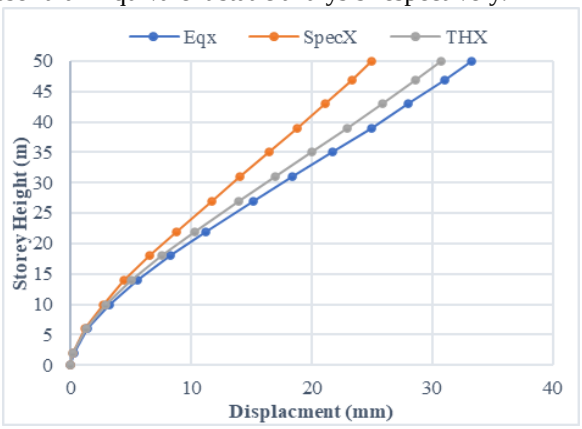


Fig.13. X direction- Displacement.

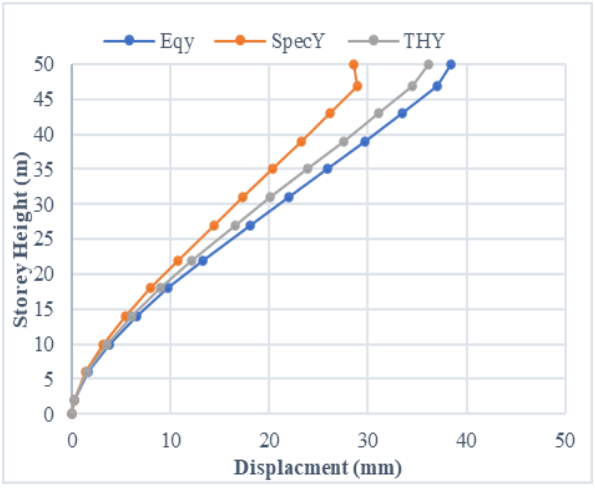


Fig.14. Y direction- Displacement.

## 7. Storey Drift

The Storey drift of the building along two principal directions for three variants of linear analysis were shown in Fig.15 and Fig.16. From the figure it was observed that the maximum storey drift is observed between 7th and 8th floor. The storey drift along X direction due to RS analysis and TH analysis is 24.6% and 7.3% lesser than Equivalent static analysis respectively. Similarly, the storey drift along Y direction due to RS analysis and TH analysis is 21.7% and 5.9% lesser than Equivalent static analysis respectively.

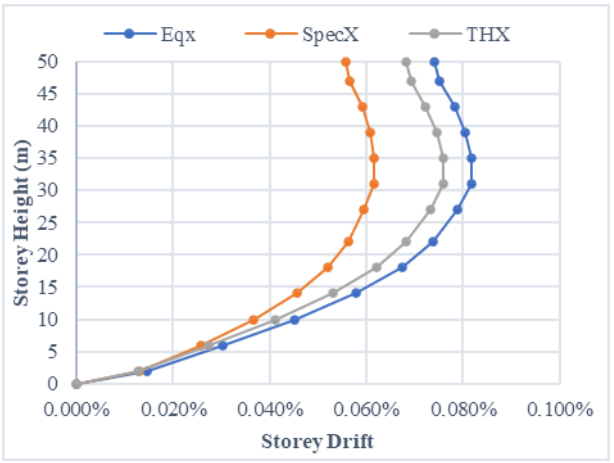


Fig.15. X direction- Storey Drift.

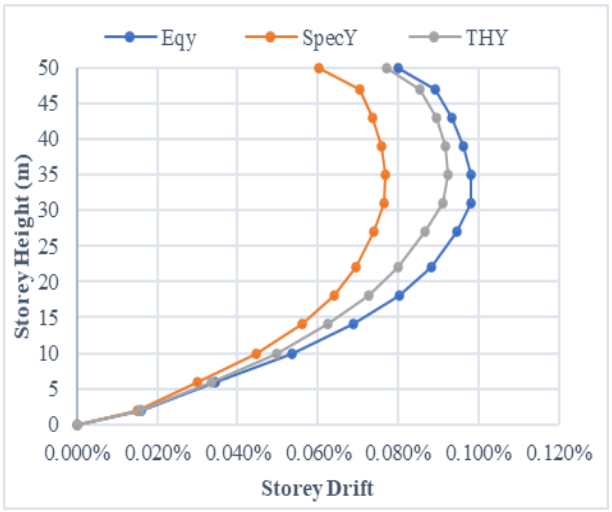


Fig.16. Y direction- Storey Drift.

## 8. Non-Linear Time History Analysis (NLTH)

NLTH analysis was executed in both orthogonal direction of the structure using scaled TH ground motion in reference with El-Centro earthquake record and results. Fig.17 shows the graphical representation of Base shear Vs Time, whereas the maximum shear force of -48,934kN was observed in 3.9 sec along X-direction and maximum shear force of 42,949 kN was observed in 2.8 sec along Y-direction.

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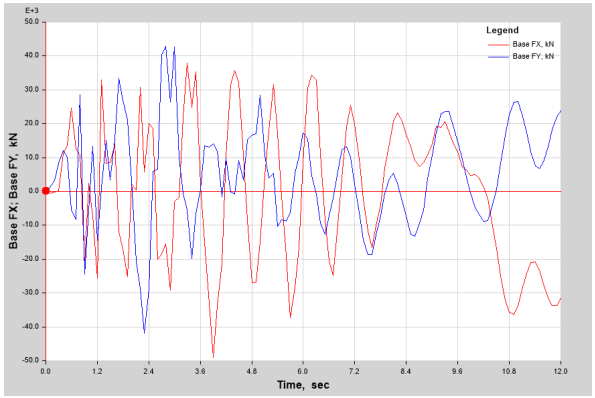


Fig.17. Time Vs Base Shear.

The Time Vs Displacement graph shown in Fig.18 details about the maximum displacement of 31.54 mm occurred at 4.4 sec along X- direction and maximum displacement of -34.86 mm occurred at 2.8 sec along Y- direction.

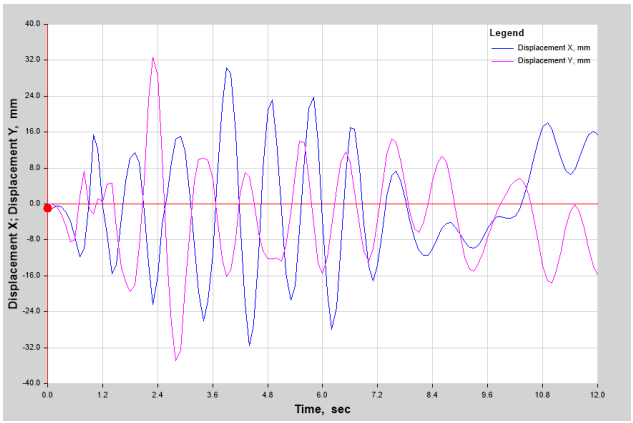


Fig.18. Time Vs Displacement.

In Time Vs Acceleration graph as shown in Fig. 19 describes the maximum acceleration of -2.416 m/sec2 recorded at 1.0 sec in X-direction and -1.883 m/sec2 recorded at 0.8 sec in Y-direction.

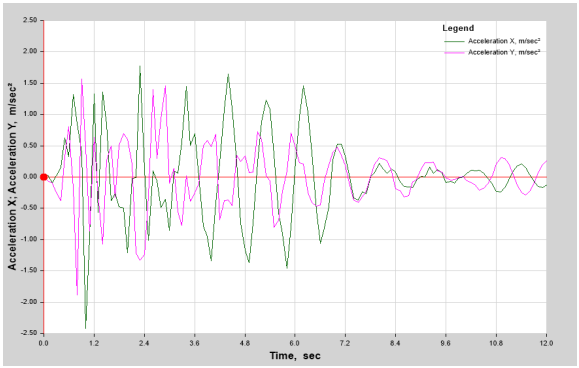


Fig.19. Time Vs Acceleration.

Similarly, Time Vs Velocity graph was shown in Fig.20, it has been perceived that the maximum velocity of -200.73 mm/sec obtained at 4.2 sec and –233.12 mm/sec obtained at 2.5 sec along X and Y directions respectively.

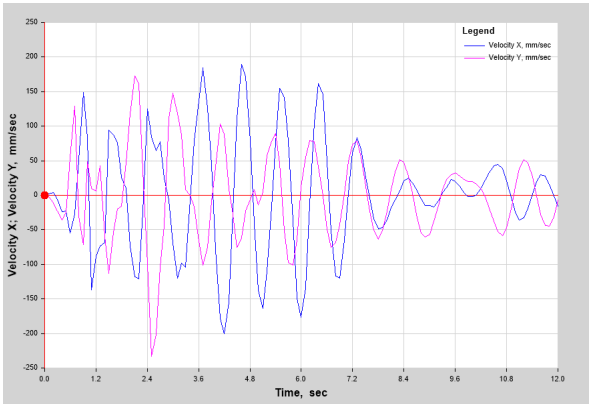


Fig.20. Time Vs Velocity.

## 9. Push-Over Analysis

The non-linear static analysis is carried out in X and Y direction of the structure with displacement co-efficient method. Along both directions base shear and displacements are recorded for various steps and the elements performance levels are listed in Table-V and Table-VI. The base shear and displacement as shown in Figure.21 and Figour.22 respectively. The building performance point is shown for X and Y direction in Fig.23 and Fig.24 respectively.

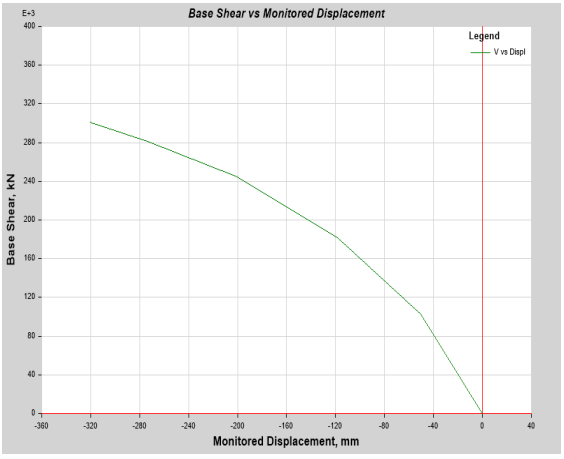


Fig.21. Push-X : Displacement Vs Base Shear.

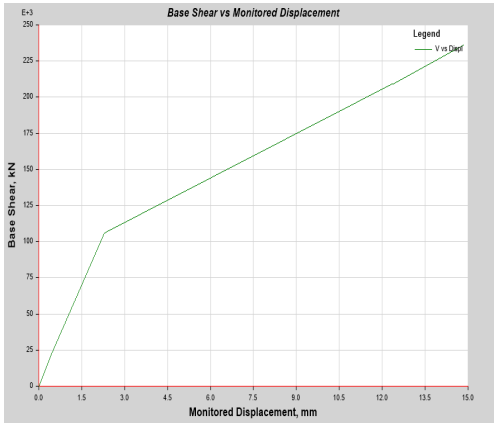


Fig.22. Push-Y : Displacement Vs Base Shear.

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Table- V: PUSH X: Observed Displacement Vs Base Shear.

| Step | Observed Displ. (mm) | Base Force (kN) | 1 - 2 | 2 - 3 | 3 - 4 | 4 - 5 | >5 | I-IO* | IO*-LS* | LS*-CP* | >CP* | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 6110 | 0 | 0 | 0 | 0 | 6110 | 0 | 0 | 0 | 6110 |
| 1 | -50.391 | 102526.5727 | 6106 | 4 | 0 | 0 | 0 | 6110 | 0 | 0 | 0 | 6110 |
| 2 | -117.759 | 180954.424 | 5774 | 336 | 0 | 0 | 0 | 6110 | 0 | 0 | 0 | 6110 |
| 3 | -119.745 | 182209.1004 | 5764 | 346 | 0 | 0 | 0 | 6110 | 0 | 0 | 0 | 6110 |
| 4 | -200.205 | 244569.6328 | 5532 | 576 | 0 | 0 | 2 | 6102 | 8 | 0 | 0 | 6110 |
| 5 | -273.561 | 281305.6923 | 5233 | 851 | 2 | 0 | 24 | 6060 | 26 | 2 | 22 | 6110 |
| 6 | -317.311 | 299602.2488 | 5132 | 886 | 8 | 0 | 84 | 5970 | 44 | 10 | 86 | 6110 |
| 7 | -317.623 | 299616.9618 | 5132 | 886 | 8 | 0 | 84 | 5970 | 44 | 10 | 86 | 6110 |
| 8 | -320.409 | 300950.125 | 5130 | 886 | 10 | 0 | 84 | 5960 | 54 | 10 | 86 | 6110 |

Table- VI: PUSH Y: Observed Displacement Vs Base Shear.

| Step | Observed Displ.(mm) | Base Force (kN) | 1 - 2 | 2 - 3 | 3 - 4 | 4 - 5 | >5 | I-IO* | IO*-LS* | LS*-CP* | >CP* | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 6110 | 0 | 0 | 0 | 0 | 6110 | 0 | 0 | 0 | 6110 |
| 1 | 0.391 | 20099.5732 | 6108 | 2 | 0 | 0 | 0 | 6110 | 0 | 0 | 0 | 6110 |
| 2 | 2.287 | 105631.1012 | 6052 | 58 | 0 | 0 | 0 | 6110 | 0 | 0 | 0 | 6110 |
| 3 | 2.338 | 106734.2603 | 6046 | 64 | 0 | 0 | 0 | 6110 | 0 | 0 | 0 | 6110 |
| 4 | 12.338 | 208966.3823 | 5439 | 670 | 0 | 0 | 1 | 6109 | 0 | 0 | 1 | 6110 |
| 5 | 12.377 | 208952.839 | 5439 | 670 | 0 | 0 | 1 | 6109 | 0 | 0 | 1 | 6110 |
| 6 | 14.846 | 236015.3724 | 5314 | 795 | 0 | 0 | 1 | 6107 | 0 | 0 | 3 | 6110 |

1 - Initial Point, 2 - Effective Yield Point, 3- Peak Strength Point, 4 - Residual Strength Point, 5 - Ultimate Deformation Point.

IO* - Immediate Occupancy Level, LS* - Life Safety Level, CP* - Collapse Prevention Level.

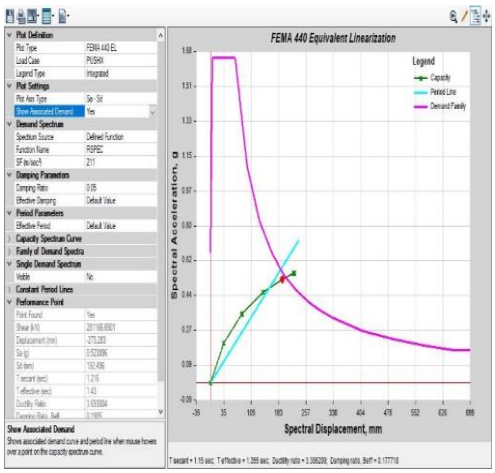


Fig.23. Push-X : Performance Point.

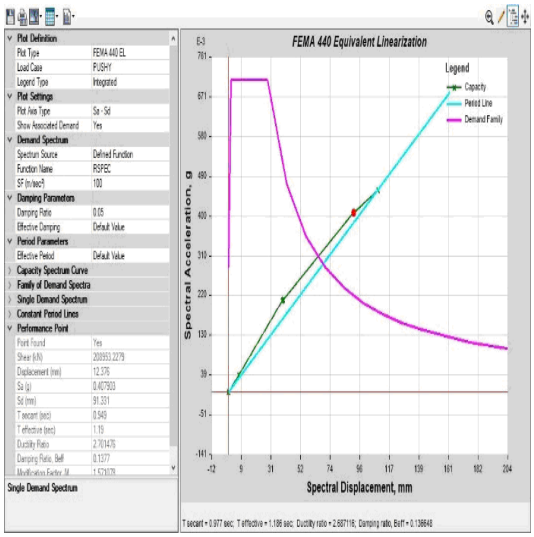


Fig.24. Push-Y : Performance Point.

## V. CONCLUSION

The Fundamental approximate time period is 72% and 80% lesser than the modal oscillation time period in X and Y direction respectively. We know that the stiffness is indirectly proportional to the time period. Hence the actual modal stiffness is comparatively lesser than the fundamental code recommended stiffness parameters. This shows the dynamic analysis is compulsory for flat slab structural systems irrespective of the building height and seismic zones. The considered building doesn't have any irregularity in modes of oscillation, this was due to the position of the structural walls.

The Base shear due to TH function is relatively higher when compared to Equivalent static whereas the storey

shear shows a varying profile between the floors, this shows the stiffness between floors are non-uniform during the TH analysis. Hence it was recommended to perform TH analysis when adopting flat slab structural system. Even though the base shear in TH analysis is greater than the equivalent static seismic analysis, the lateral displacement of each storey is relatively lesser than the equivalent static analysis and higher than the RS analysis, hence it is evident that performing TH analysis will be necessary while adopting flat slab structural system. The storey drift shows a same profile compared to the displacement, hence the code specified storey drift recommendation of 0.1% is sufficient for the serviceability criteria.

In Non-linear analysis, the structural response is entirely different than the linear analysis, the maximum base shear and maximum displacement are occurring in different time period along X direction, but the maximum base shear and maximum displacement are occurred in the same time period along Y direction. The maximum acceleration is occurred nearer to the natural period of modal oscillation in both X and Y direction, whereas the

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maximum velocity coincides nearer to the time period where maximum displacement is observed.

In Push over analysis along X direction, all the structural elements are under IO level up to step-3. In step-4, 8 structural elements are under IO-LS level. Whereas in step-5, 22 structural elements are beyond CP level. Hence, building performance point is observed at this stage. This shows few structural elements are failing without showing any mode of warning before failure. Especially the shear beams connecting shear walls are in these criteria. Hence, during design and detailing of these shear beams special attention is required to avoid this failure condition. In push over analysis along Y direction, all the structural elements are under IO level up to step-3. Here the building performance point is reached at step-4. But in step-4, a corner column is beyond CP level. This column failure occurs without showing any signs of warning before failure. Here the situation happens for the corner column which is adjacent to the shear wall. This corner column fails at the ground level. Further investigation is required to investigate on the behavior of the columns adjacent to structural shear walls with different structural arrangements to understand the failure behavior of those elements. Even though the Punching shear capacity are limited, some mode of failure is observed in slab-column connection in few levels. Hence, further shear capacity study of slab-column connection is necessary under linear and non-linear seismic conditions to avoid such failure.

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