Linear Time History Analysis of Asymmetric Flat Slab buildings having Unequal Orthogonal Lengths

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Abstract—*Recent earthquakes have shown that the irregular distribution of mass, stiffness and Strengths may cause serious damage in structural systems. The present study is aimed at understanding the effects of earthquake forces on buildings that are irregular in plan i.e. L-shaped. The effect of wing lengths and their aspect ratios on performance of the structure is studied. Unequal orthogonal lengths are taken to study its effects on response of the building. Buildings are modelled with Flat Slab with and without shear walls and their results compared to determine which shear wall configuration gives the best resistance to seismic forces. Seismic analysis is done using Linear Time History Analysis method. The analytical results show that maximum amount of base shear, roof displacement, drifts occur in models that have equal wing lengths. As the length of one wing is shortened the values of the said parameters also come down i.e., base shear variation is19% and 34% in x and y direction respectively. Roof displacement also reduces by 19% as orthogonal length ratio is reduced. Story drift values also show a reduction of 18%. The presence of shear walls and their positioning impacts the performance of the structure and also the presence of torsion in the buildings.*

Keywords—Linear Time History Analysis, Flat Slab, Asymmetric, Orthogonal Projections.

I. INTRODUCTION

Earthquakes are one of the most devastating natural hazards that cause great loss of life and livelihood. They are caused due to sudden release of energy from earth's crust resulting due to actions of tectonic plates. This energy, released in the form of seismic waves can do high damage or in worst case destroy major structures.

Buildings with structural systems that have irregular distribution of mass, stiffness and strengths are prone to serious damage. Building configuration therefore is an important factor affecting the performance of the structures. Configuration can be broadly defined as the size and shape of the building, the size and location of structural and non-structural elements. Good configuration results in simple and economical design and better performance.

Seismic codes distinguish between regular and irregular configurations, irregular configurations occur when the building deviates from simple regular, symmetrical form in plan, section and elevation which creates two kinds of problems namely: torsion and stress concentration. Torsional problems are most typically associated with plan irregularity or geometries, where the size and location of vertical elements produce eccentricity between the centres of mass and resistance. Torsional forces create great uncertainty in analysing the building's resistance. Stress concentration occurs when an undue proportion of seismic force is concentrated at one or a few locations in the building. For irregular buildings shaped as L in plan the dominant problematic factors are torsion and stress concentration. The presence of torsion and its impact on structure's performance is the aim of this study. This is caused because the centre of mass and the centre of rigidity in this form cannot geometrically coincide for all possible earthquake directions. The resulting rotation tends to distort the buildings in ways that will vary in nature and magnitude depending on characteristics of ground motion. The magnitude of forces and seriousness of the problem will depend on various factors like: the mass of the building, structural system employed, the length of wings and their aspect ratios and the height of wings and their height/depth ratios.

Research has been done on this topic earlier, (Khante.S.N. & Lavkesh.R.Wankhade, 2010)**[1]**Conducted an analytical study on seismic behaviour of symmetric and asymmetric building with mass asymmetry. They studied the effect of torsion in asymmetric building having fixed base and isolated base using response spectrum and linear time history analysis and concluded that base isolation is an effective technique in mass eccentric models. (Kumar, Gornale, & Mubashir, 2012)**[2]** did a study on seismic performance evaluation of RC framed buildings (torsionally asymmetric buildings). Structures were modelled with and without infill walls and analysis done in finite element software SAP using pushover analysis method and concluded that performance of models is better when stiffness of infill walls is considered. (Abdel-Basset, 2012)[3]Did an analytical study on modelling of flat plate RC buildings. The objective was to identify an appropriate finite element model to study its dynamic behaviour. He concluded that modelling of walls and slabs using block (solid) elements is the most appropriate representation of these buildings as it provides accurate results compared to modelling with frame or shell elements. (Alavi & Rao, 2013)**[4]**Did an analytical study to realise seismic response of structures for various shear wall locations on RC buildings having re-entrant corners in high seismic zone on five storey high building with 6 different locations of shear walls. Observations proved that structures are more vulnerable when they are irregular and also eccentricities between centre of mass and centre of resistance are more significant to the torsional behaviour of building. (Khante & B.P.Nirwan, 2013)[**5**]did research on mitigation of response of asymmetric building using tuned mass dampers using software SAP2000 and performing Non-linear time history analysis using El Centro ground motion data. They concluded that TMD is reliable and practical alternative to enhance the earthquake resistance of existing and new structures and efficient in decreasing the torsional response.

The works discussed studied the performance of asymmetric buildings and the presence of torsion. They show primarily effects of earthquake forces on flat slab buildings that are symmetrical and regular moment resistant frame buildings in case of asymmetrical models. The present work focuses on L-shaped asymmetric flat slab building configurations with unequal wing lengths, different ratios of orthogonal projections are taken to study the effect on structural response using linear time history analysis technique.

The objective of present work is to study:

1. Effect of earthquake forces on asymmetric RC flat slab buildings using linear time history analysis.
2. Effect of different orthogonal ratios on behaviour of structure.
3. Degree of torsion present and its mitigation using different shear wall configurations.

II. MODELLING AND ANALYSIS

A total of 16 structural models representing RC multi-storey Flat slab buildings have been considered in this study. All the models considered are asymmetric in plan with respect to both the axes thus the L shape and the orthogonal projections are kept unequal. There are 3 cases of unequal lengths for each model. Additionally shear walls were also included in the models for mitigation and control of structural response. Three different configurations of shear walls at different strategic locations have been employed. The models were subjected to earthquake motion by using El Centro ground motion record. Finite element software ETABS v13 was used to carry out the linear time history analysis.

Table 2.1 General Model Data

Variable	Data
Length of span in x &y directions	6m
Height of floors	3m
No. of floors	10
Thickness of slab	200mm
Size of columns	0.8m x 0.8m
Size of drops	2m x 2m
Depth of drops	100mm
Size of perimeter beam	300mm x 500mm
Thickness of shear walls	200mm
Grade of concrete	M30
Grade of steel	Fe 415
Ground Motion Data	El Centro

Table 2.2 Different Shear Wall Configurations Adopted

Model Type	Shear Wall Configuration
Model – A	Shear wall concentrated near Centre of Mass (Box Type)
Model – B	Shear walls along the edges
Model - C	Shear walls at corners

Table 2.3 Different ratios of Orthogonal Projections

Model Type	Orthogonal Projection in x-direction (b_1) m	Orthogonal projection in y-direction (b_2) m	Ratio (b_2/b_1)
Model 1	24	24	1
Model 2	24	18	0.75
Model 3	24	12	0.5
Model 4	24	6	0.25

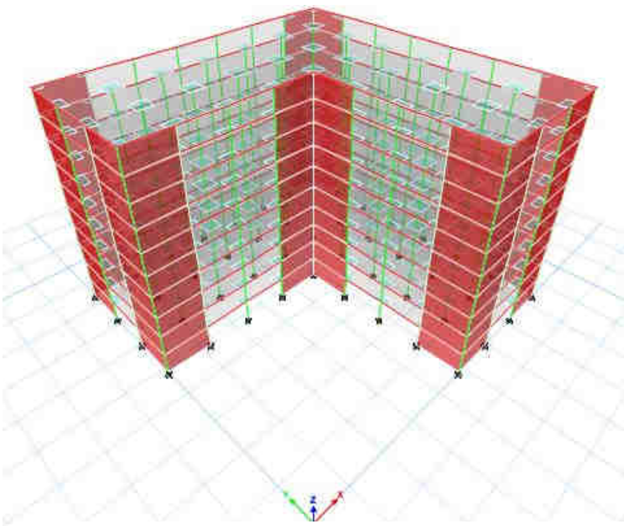

Figure 2.3 3-D model of L-shaped building having SW configuration A

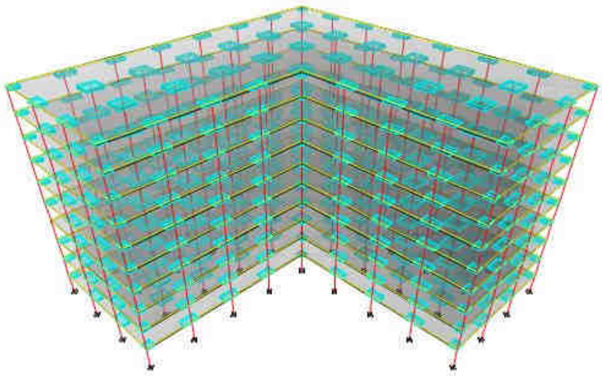

Figure 2.1 3-D model of L shaped building having equal orthogonal projections

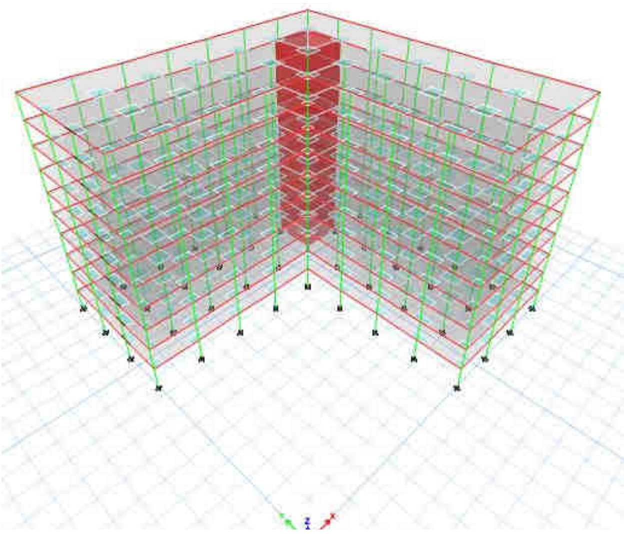

Figure 2.2 3-D model of L-shaped building having SW configuration A

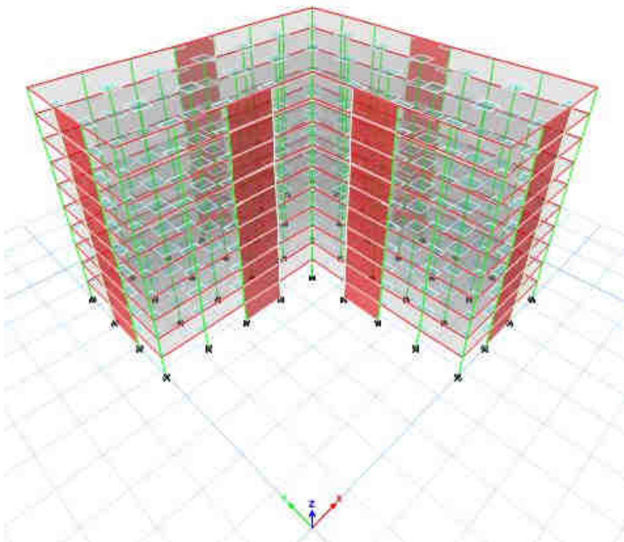

Figure 2.4 3-D model of L-shaped building having SW configuration C

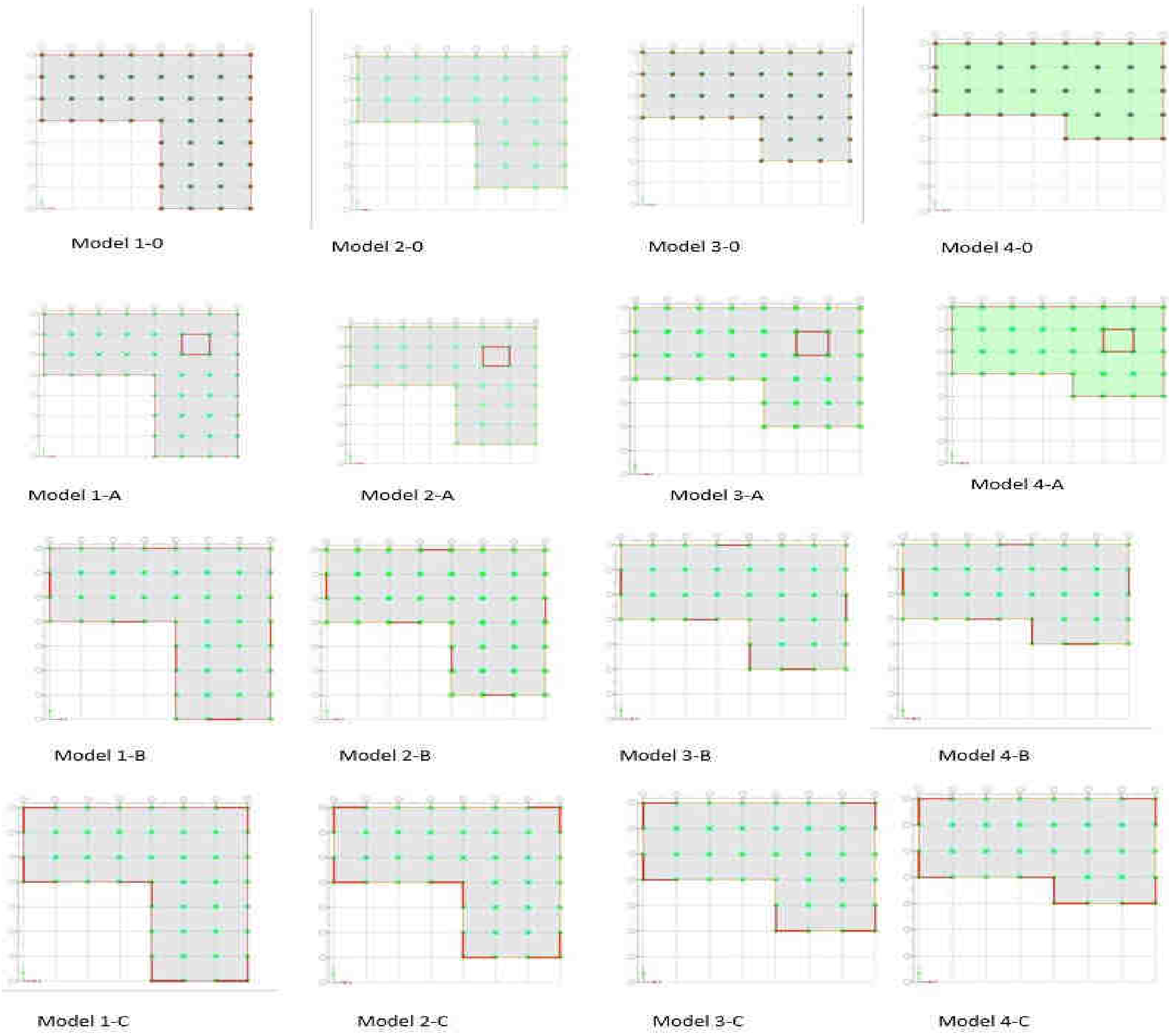

Fig 2.1 2-D plan view of all the models analyses

All the models have an L-shaped plan of varying dimensions due to varying orthogonal lengths. The figures show the plan views models that were used in the analysis. 3 different configurations of shear walls are employed placed at strategic locations.

III. RESEARCH METHODOLOGY

The seismic analysis is done using linear time history method. Static procedures are suitable for short regular buildings. For tall buildings, buildings with torsional irregularities, or non-orthogonal systems dynamic procedure is required. A linear time history analysis overcomes all the disadvantages of response spectrum analysis when non-linearity is not involved. However the method is time consuming and requires greater computational efforts for calculating the response at specified time intervals.

Time history analysis is performed using ground motion records of earthquakes that have occurred previously that is recorded using accelerometers. This data is in the form of time and acceleration values. The ground motion data is given as input to the software which then calculates the response of the structure such as displacement, velocity, base shear etc. at discrete time intervals. The ground motion is applied in the form of acceleration loads and not as regular loads that are applied for static analysis. Thus it is as if an earthquake is acting on the structure which helps in understanding the precise response of a structure in case of earthquake.

Time history analysis in itself involves different methods, they can be described as

Linear Direct Integration Method:

A direct-integration time-history method employs numerical techniques such as Newmark's, Wilson's etc. which solves equations for the entire structure at each time step, as compared to modal time-history load method, which uses the method of mode superposition.

Linear Modal Method:

A modal time-history analysis uses the method of mode superposition, compared to direct-integration time-history, which solves equations for the whole structure at each time step.

Non-Linear Direct Integration Method:

A direct-integration time-history solves equations for the entire structure at each time step, additionally non linearity is considered. The nonlinear property of a structure is defined usually by the way of assigning hinges to its members.

Non-Linear Modal Method:

As described earlier modal time-history analysis uses the method of mode superposition same like in linear method with the critical difference being the structure is assigned with nonlinear properties in the model.

Linear direct integration method is used for analysis in this study.

As per the basic principle of structural dynamics the general equation of motion can be written as:

$$m\ddot{x} + c\dot{x} + kx = F_{ext} \quad (3.1)$$

Or

$$m\frac{d^2x}{dt^2} + c\frac{dx}{dt} + kx = F_{ext} \quad (3.2)$$

Shown above is a second order differential equation where m=mass of the structure, c=viscous damping, k=stiffness of the structure which can be solved analytically or numerically. For time history analysis numerical methods are required. In this case newmark's method is used, it is a step-by-step numerical time integration scheme. It is a set of solution methods with different physical interpretations for different values of. The total simulation time is divided into a number of intervals (usually of equal duration Δt) and the unknown displacement (as well as velocity and acceleration) is solved at each instant of time. The method solves the dynamic equation of motion in the (i + 1) th time step based on the results of the ith step.

The equation of motion for the (i +1)th time step is:

$$m\ddot{x}_{i+1} + c\dot{x}_{i+1} + kx_{i+1} = f_{i+1} (3.3)$$

Here $\ddot{x}$ stands for acceleration, $\dot{x}$ stands for velocity and x stands for displacement.

To solve for the displacement or acceleration at the (i + 1)th time step, the following equations are assumed for the velocity and displacement at the (i + 1)th step in terms of the values at the ith step:

$$\dot{x}_{i+1} = \dot{x}_i + (1-\alpha)\ddot{x}_i\Delta t + \ddot{x}_{i+1}\alpha\Delta t$$
(3.4)

$$x_{i+1} = x_i + \dot{x}_i\Delta t + (0.5-\beta)\Delta t^2\ddot{x}_i + \beta\Delta t^2\ddot{x}_{i+1} (3.5)$$

By putting the value of velocity($\dot{x}_{i+1}$) and displacement (x_{i+1}) the only unknown variable acceleration can be found. In the solution set suggested by the Newmark-β method, the Constant Average Acceleration (CAA) method is the most popular because of the stability of its solutions. This method assumes the acceleration to remain constant during each small time interval Δt, and this constant is assumed to be the average of the accelerations at the two instants of time t_i and t_{i+1}. The CAA is a special case of Newmark-β method where α=0.50 and β=0.25.

Thus in CAA method the equations for velocity and displacement become:

$$\dot{x}_{i+1} = \dot{x}_i + \frac{(\ddot{x}_i + \ddot{x}_{i+1})\Delta t}{2} \quad (3.6)$$

$$x_{i+1} = x_i + \dot{x}_i\Delta t + \frac{(\ddot{x}_i + \ddot{x}_{i+1})\Delta t^2}{4} \quad (3.7)$$

Inserting these values in (3.3) and rearranging the coefficients we get

$$\left(m + \frac{c\Delta t}{2} + \frac{k\Delta t^2}{4}\right)\ddot{x}_{i+1} = f_{i+1} - kx_i - (c + k\Delta t) - \left(\frac{c\Delta t}{2} + \frac{k\Delta t^2}{4}\right)\ddot{x}_{i+1}$$
(3.8)

To obtain the acceleration $\ddot{x}_{i+1}$ at an instant of time t_{i+1} using Eq. (3.8), the values of x_i, $\dot{x}_i$ and $\ddot{x}_i$ at the previous instant t_i have to be known (or calculated) before. Once $\ddot{x}_{i+1}$ is obtained, Eqs. (3.6) and (3.7) can be used to calculate the velocity $\dot{x}_{i+1}$ and displacement x_{i+1} at timet_{i+1}. All these values can be used to obtain the results at time t_{i+2}. The method can be used for subsequent time-steps.

IV. RESULTS AND DISCUSSION

4.1 Base Shear

Seismic force at the base of the building is known as base shear. It is the maximum lateral force that will occur due to seismic ground motion at the base of the structure.

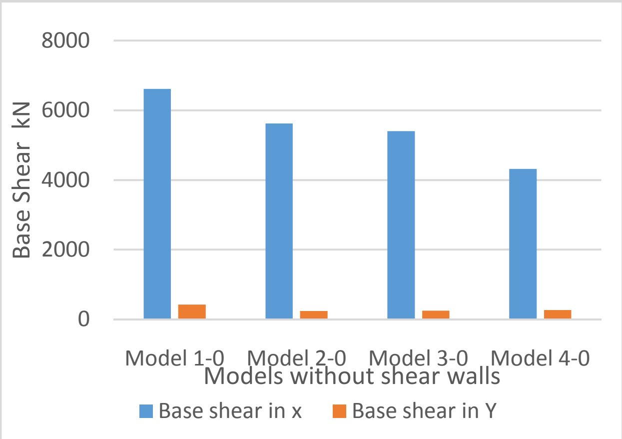

Fig 4.1.1 base shear variation when ground motion in x- direction in models without shear walls

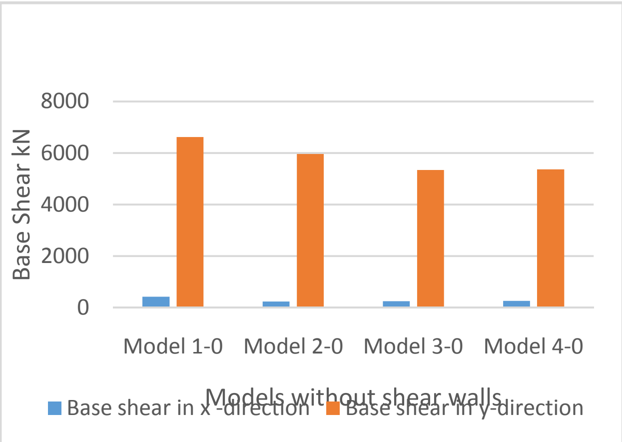

Figure 4.1.2 base shear variation when ground motion in y-direction in models without shear walls

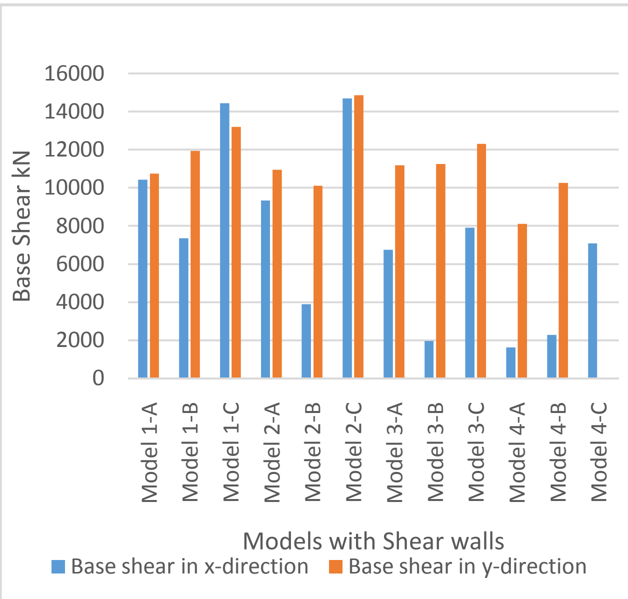

Figure 4.1.3 base shear variation when ground motion in x-direction in models with shear walls

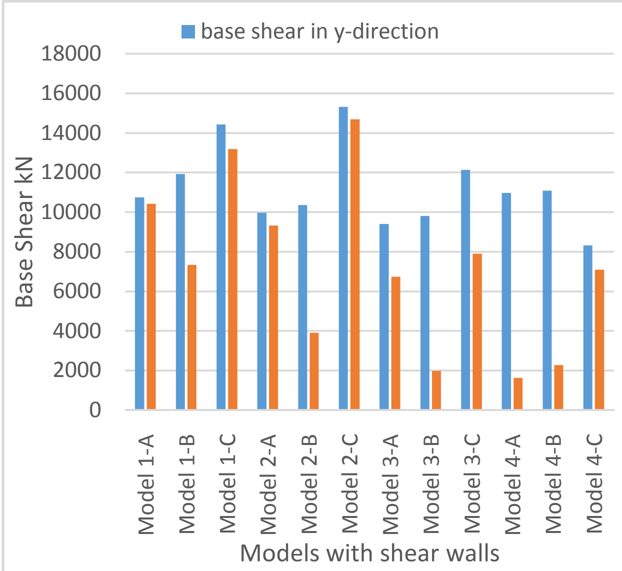

Figure 4.1.4 3 base shear variation when ground motion in x-direction in models with shear walls

- Based on the graphs of base shears it can be observed that for models without shear walls as one of the orthogonal length decreases so does base shear. Highest is observed when both orthogonal lengths are of equal lengths (6623kN in y direction and 6615 in x direction for respective ground motion direction) and decreases as the ratio of orthogonal length decreases (5364kN in y direction and 4320kN in x direction).
- For ground motion in x-direction base shear in x-direction comes down from model 1 to model 4 by 34%, similarly for ground motion in y-direction base shear comes down by 19%.
- Amongst each models High amounts of base shear is observed in models having shear wall configuration “C” (14695 kN Model 2-C in x-direction, 15316 kN Model 2-C in y-direction) and lowest in models containing shear wall configuration “A”.
- For models with equal orthogonal lengths and shear walls base shear is varying (increasing) from SW configuration A to SW c by 27.75%, for orthogonal length ratio 0.75 it varies by 34%, for ratio 0.5 its 24% and for ratio 0.25 its 60% for ground motion applied in x-direction similar trend is observed for ground motion in y-direction.

4.2 Story Displacements

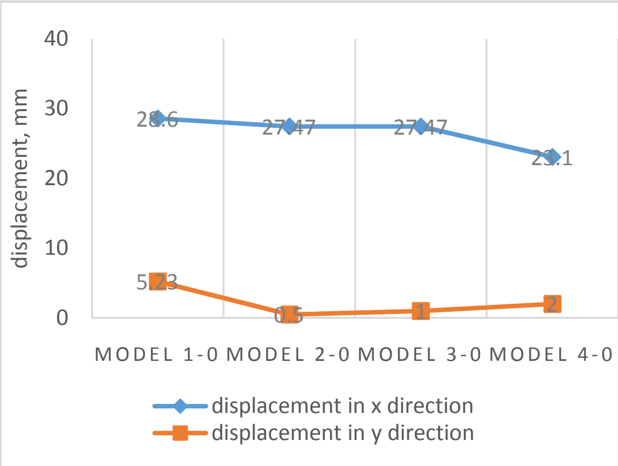

Figure 4.2.1 variation of roof displacement due to ground motion in x-direction in models without shear walls.

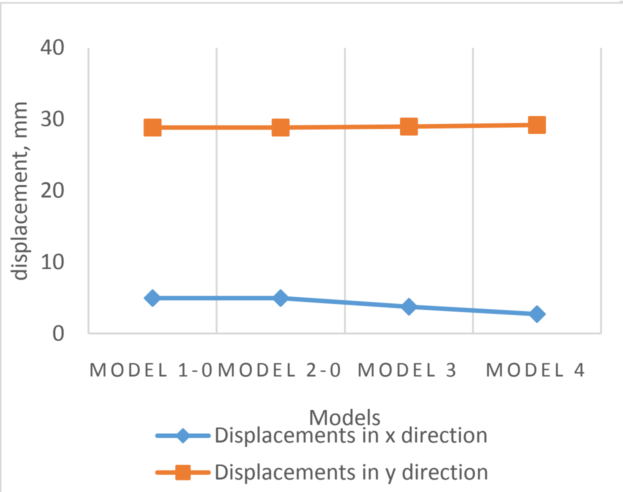

Figure 4.2.2 variation of roof displacement due to ground motion in y-direction in models without shear walls

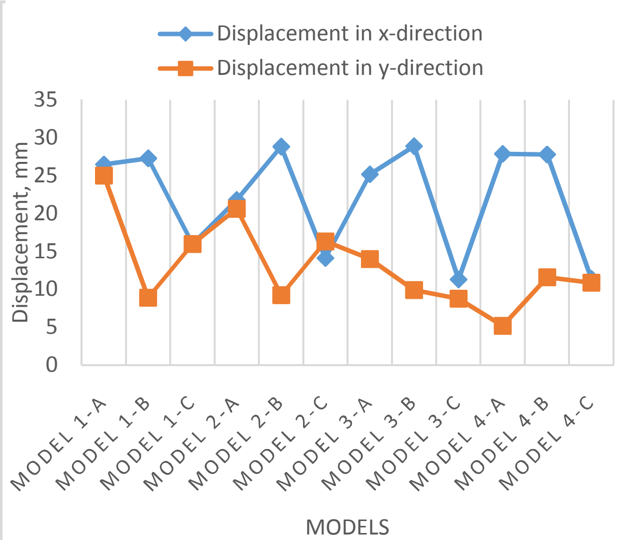

Figure 4.2.3 variation of roof displacement due to ground motion in x-direction in models with shear walls

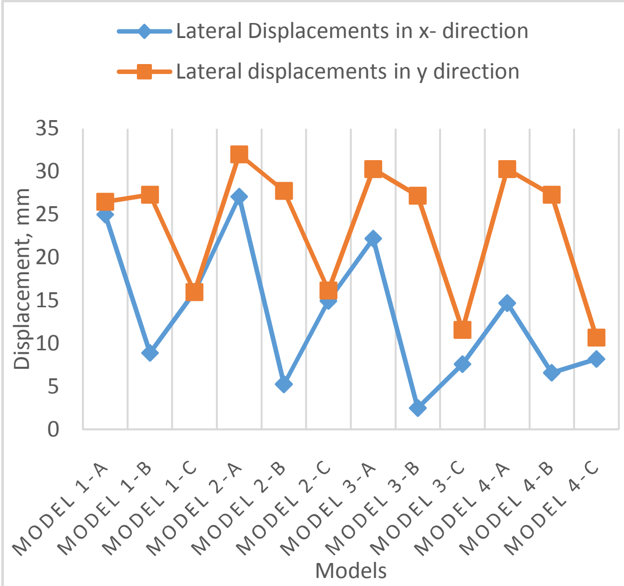

Figure 4.2.4 variation of roof displacement due to ground motion in y-direction in models with shear walls

- In models without shear walls the displacement value comes down from model 1 to model 4 by 19% the maximum displacement is in Model 1 -0 and minimum in Model4-0 (both x & y ground motion.
- In models with shear walls and excitation along x-direction max displacement occurs in Model 3-B (28.9mm) and least in Model 4-C (10.9mm). The difference between max and min displacement in all the models is almost 62.2% Though the excitation is along x-direction significant displacements are observed in y-direction also maximum being in Model 1-A (25mm). Models 1-C, 2-C, 3-C and 4-C (least orthogonal length ratio) the lateral displacements long both the transverse axes are equal.
- Similarly For excitation along y-direction max lateral displacement is observed in Model-2A (30mm) and least in 4-C (10mm) difference being almost 66%. Significant displacement are also observed in x-direction maximum being 20.1mm in Model 2-A. similarly in Models 1-C, 2-C, 3-C and 4-C the displacements along both the transverse axes are equal.

4.3 Story Drift

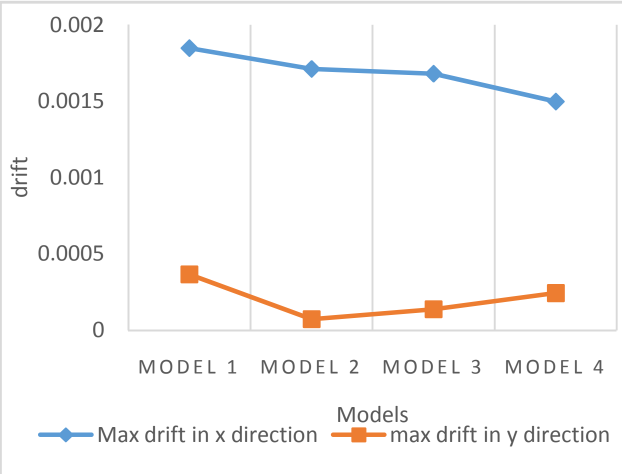

Figure 4.3.1 story drift in models without shear walls when ground motion in x-direction

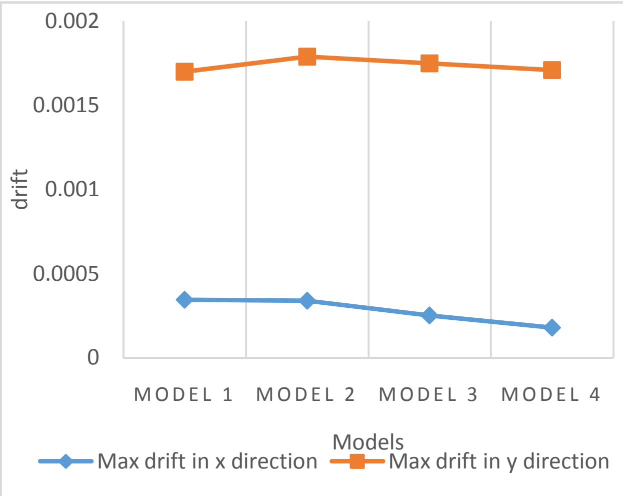

Figure 4.3.2 story drift in models without shear walls when ground motion in y-direction

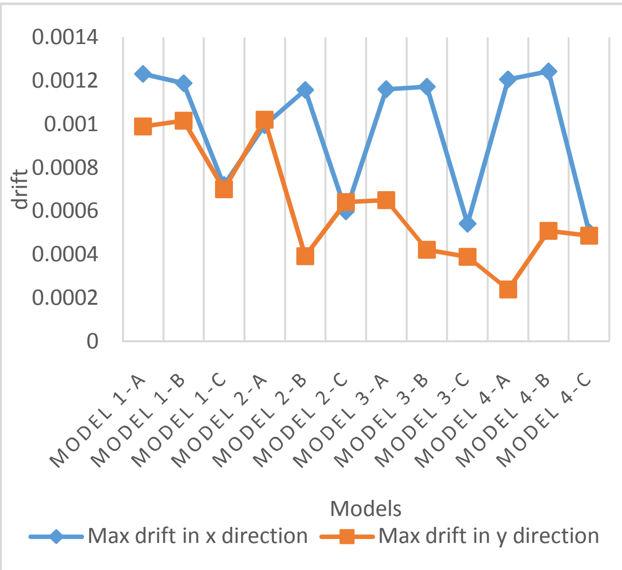

Figure 4.3.3 story drift in models with shear walls when ground motion in x-direction

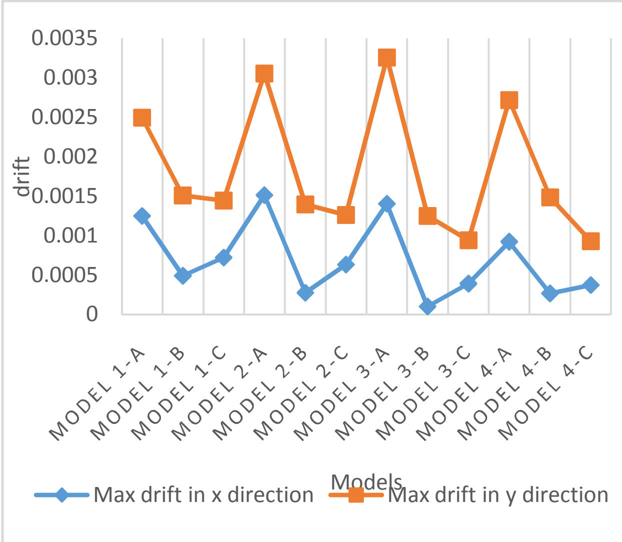

Figure 4.3.4 story drift in models with shear walls when ground motion in y-direction

- The drifts exhibited by the analytical models are found to be well within permissible limits. The maximum is observed in Model 1-0 and Model 3-0 in y-direction. The variation in drifts (decrease) from Model1-0 to Model 4-0 19% in x-direction and 5% in y-direction.
- In x direction as the ratio of orthogonal lengths decreases the drift increases in that direction albeit by a smaller percentage. In y-direction as the ratio of orthogonal length decreases the drift increases by a small amount.
- With the introduction of shear walls the drift values in all the 4 models come down. Each of the 4 models has 3 different shear wall configurations A, B and C. Maximum drift is observed in models having configuration B (walls on edges), comparatively other configuration exhibit lesser drifts in for ground motion in x-direction. For ground motion applied in y-direction max drifts are observed in models having SW configuration A. The minimum drifts within all of the subsets of the 4 models is observed in the configuration C (walls on the corners).
- In models with shear walls highest drift occurs in Model 1-A (0.001232) and the lowest in Model 4-C (0.000488) when ground motion is in x-direction. Greater values of drift also occur in y-direction though the excitation is only along x-axis compared to models without shear walls. Similarly for excitation along y-axis max drift Occurs in Model 3-A (0.001855) and minimum

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in Model 4-C (0.000338). Greater values of drifts also occur in x-direction in models with shear walls compared to their counterparts without shear walls.

- The variation of drifts from highest to lowest for models of different orthogonal lengths is observed as : for equal orthogonal lengths 43.1%, for orthogonal length ratio 0.75 it is 48%, for ratio 0.5 its observed as 53.70% and for ratio 0.25 it is 60%.In y-direction the values are 42%% for equal lengths, 60% when ratio is 0.75, 70%when ratio is 0.5, 71% for orthogonal length ratio 0.25.

4.4 Determination of Torsional Irregularity

As per IS 1893 (part 1)-2002 [10] Torsional irregularity to be considered to exist when the maximum storey drift, computed with design eccentricity, at one end of the structures transverse to an axis is more than 1.2 times the average of the storey drifts at the two ends of the structure.

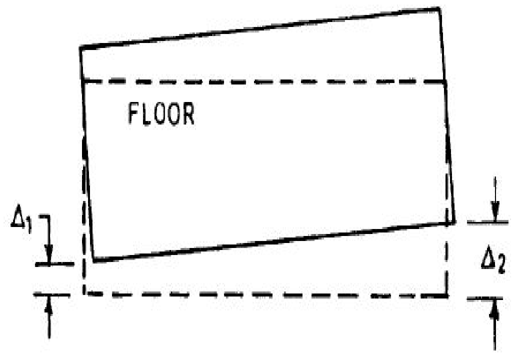

Figure 4.4.1 torsional irregularity as demonstrated by IS code

- Torsion irregularity as per the code definition is not found in the models without shear walls. However when shear walls are introduced torsion irregularity is found to be developed depending on the shear wall positions.
- Torsion irregularity is predominant in models with SW configuration 'B' i.e. when shear walls are kept along the edges. Configurations 'A' and 'C' don't show any torsional irregularity..

Table 4.4.1 Torsional irregularity in x-direction

Model	δ_1 (max)	δ_2 (min)	1.2 x δ_{avg}	Remarks
Model 1	28	23.5	30.9	no torsion irregularity
Model 2	26.5	26.3	31.68	no torsion irregularity
Model 3	27.5	27.1	32.76	no torsion irregularity
Model 4	23.1	22.8	27.54	no torsion irregularity
Model 1-A	26.5	22.2	29.22	no torsion irregularity
Model 1-B	27.3	16.8	26.46	torsion irregularity exists
Model 1-C	16	14.4	18.24	no torsion irregularity
Model 2-A	21.9	21.1	25.8	no torsion irregularity
Model 2-B	28.8	16	26.88	torsion irregularity exists
Model 2-C	0.6	0.4	0.6	no torsion irregularity
Model 3-A	22.8	20.7	26.1	no torsion irregularity
Model 3-B	28.9	17	27.54	torsion irregularity exists
Model 3-C	11.3	10.2	12.9	no torsion irregularity
Model 4-A	24.5	24.2	29.22	no torsion irregularity
Model 4-B	27.8	18.5	27.78	torsion irregularity exists
Model 4-C	11.4	8.1	11.7	no torsion irregularity

Table 4.4.2 Torsional irregularity in y-direction

Model	δ_1 (max)	δ_2 (min)	1.2 x δ_{avg}	Remarks
Model 1	5.2	3.8	5.4	no torsion irregularity
Model 2	0.5	0.5	0.6	no torsion irregularity
Model 3	1	0.9	1.14	no torsion irregularity
Model 4	2	1.9	2.34	no torsion irregularity
Model 1-A	25	20.4	27.24	no torsion irregularity
Model 1-B	8.9	6.3	9.12	no torsion irregularity
Model 1-C	16	15.7	19.02	no torsion irregularity
Model 2-A	20.6	17.8	23.04	no torsion irregularity
Model 2-B	9.3	6.4	9.42	no torsion irregularity
Model 2-C	0.7	0.4	0.66	torsion irregularity exists
Model 3-A	12.6	9.6	13.32	no torsion irregularity
Model 3-B	9.9	7.3	10.32	no torsion irregularity
Model 3-C	8.8	6.6	9.24	no torsion irregularity
Model 4-A	5.2	4.5	5.82	no torsion irregularity
Model 4-B	11.6	9	12.36	no torsion irregularity
Model 4-C	10.9	7.8	11.22	no torsion irregularity

V. CONCLUSIONS

- The analysis results show that as the ratio of orthogonal length b1/b2 decreases the base shear also decreases by 19% and 34.36% in x and y respectively from models 1 to 4. In models with shear walls highest base shear is found in models having shear wall configuration "C" as it has maximum weight.
- Similarly with the decreasing ratio lateral displacements also are found to decrease. Highest lateral displacement is observed when the orthogonal projections are of equal length i.e. Model 1 and least in Model 4. The difference between maximum and minimum is observed to be19%. With the introduction of shear walls displacements in each model are found to decrease significant one being in shear wall configuration "C". This holds good for ground motion applied in both the directions.
- Furthermore it is observed that there is significant lateral displacement along an axis though the ground motion is applied transverse to it.
- As the ratio b1/b2 decreases the drifts are found to decrease marginally from Model 1 to Model 4 marginally when ground motion is in x-direction. The drift values from model 1 to model 4 come down by 18.94% and also increase marginally when ground motion is in y-direction.
- Amongst each individual model, comparison with different shear wall configuration reveals that with the use of shear walls drifts decrease. Amongst models with shear walls highest drift is found in models having shear wall configuration "B".
- Introduction of shear walls helps in reducing the drifts and roof displacements but it is observed that placing of shear walls influences the torsion produced in the structure. Examination of torsion irregularity as per the code standards shows that torsion irregularity can be said to exist predominantly in models with SW configuration 'B' in the considered analytical models Consequently high amount of roof displacements and storey drifts are observed inModels in which torsional irregularity is found to exist (x-direction).

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