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Seismic Performance of RC Multistory Building with Vertical Mass Irregularity

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Abstract
Rapid population growth is a widespread issue in urban settings such as Kathmandu. The surge of population needs a large amount of land. The concept of multipurpose buildings may play a key role in addressing numerous global issues. Utilization of space in urban cities has caused many changes in the structure of building, more functionality is needed in less space which makes the building structure irregular. As Nepal is in a seismically active zone, these uneven high-rise structures suffer tremendously during earthquakes. Thus it is very crucial to select a structural system capable of withstanding these lateral forces, including gravity loading. An analytical analysis is conducted to find the influence heavy mass leading to irregularity on a symmetrical RC frame with inter storey heavy mass location variation along with central as well as eccentric positioning of the mass. For the study, two reinforced concrete building models of 9 and 12 storey with double basement are studied. Shear wall is provided in both the structure to resist the lateral force exerted in the structure. One third of the structure is subjected to a slightly different set of loading compared to rest of the building. The portion is considered as a hotel with a swimming pool on one of its floor. Equivalent static analysis and model response spectrum analysis is carried in the buildings using ETABS version 18 . Seismic design code NBC 105:2020 is used for analysis. Maximum storey displacements, storey drift, base shear and model time period are taken as the parameter for analysis. It is concluded that proper distribution of mass in a structure can have significant influence on its performance. While the frame with mass irregularity on higher levels is vulnerable to damage, but if kept in the lower half of the structure can perform better than uniformly mass distributed (regular) structure.

Keywords
Multistorey RC Frame Building, Mass Irregularity, Response Spectrum Analysis

1. Introduction

Earthquake resistant design of reinforced concrete building is continuing area of research because structures have been prone to earthquake since the first structure was built. Buildings with asymmetry and various types of irregularity are determined to be a major factor in structural failures, property damage, and earthquake-related fatalities. From earlier earthquakes that struck Kern County in 1954 to two more recent earthquakes in Nepal in 2015 and Imphal (India) in 2016, the vulnerability accompanied with these structures cannot be ignored [1]. Although significant amount of work has been done on asymmetric buildings, well-accepted guidelines for multistory asymmetric structures is still lacking.

For architects and developers looking for remarkable buildings that stand out from the crowd, irregular buildings can be very appealing [2]. In densely populated areas, available land for construction is often limited, forcing architects and developers to design irregular buildings that can fit into tight spaces. Advances in engineering and construction technology have made it possible to construct irregular buildings that were previously not feasible. Though irregular buildings can be more profitable than regular buildings these buildings come with unique challenges, particularly in terms of seismic safety. These buildings require careful planning and engineering to ensure their structural integrity and the safety of their occupants during an earthquake. As a result, it's essential that architects and developers work closely with seismic experts and engineers to ensure that their irregular buildings are designed and constructed with seismic safety in mind [3].

As per Nepal Nepal Building Code 105:2020, structure complying with any of the clauses. 5.5.1 to 5.5.2 is considered irregular. A difference of more than 50% between the effective masses of two consecutive stories is considered as mass irregularity. Light roofs, penthouse, and mezzanine floors need not be considered [4].

Darshan D. et al. (2016) [5] analyzed five models about the influence of irregular mass in a G+12 structure where the regular model performed better than all other models in terms of lateral load resistance in comparison to mass irregularity in alternate storey, bottom storey, middle storey, and top storey, and it was concluded that a structure with equal mass distribution across all storey will perform better. Satheesh, A.J. et al. (2019) [6] studied the seismic response of vertically irregular 15 storey RC buildings with different location of masses along the height including in-plan eccentricity. The study concluded that seismic response of the structure showed lesser influence of mass irregularity when placed at lower portion of the frame. Kumar, Nilesh et al. (2022) [7] studied G+14 storey building with mass and vertical geometrical irregularity using static and dynamic methods in ETABS. As per the study, mass irregular structure had the highest storey shear, story displacement, and story drift in comparison to regular and vertical geometrically uneven buildings.

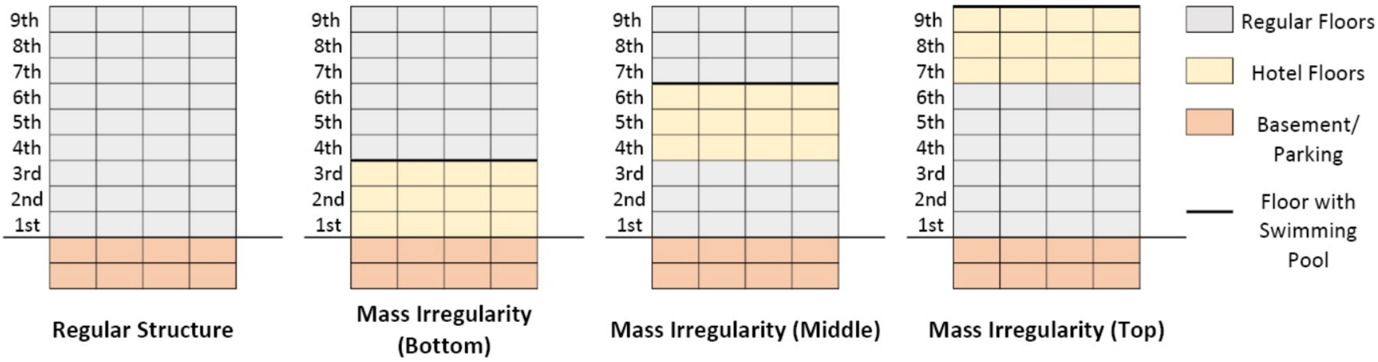

Figure 1: Elevation View 9 Storey Models

The objective of this study is to evaluate the seismic performance of multistory RC Buildings varying the position of mass leading to irregularity in the structure.

2. Building Description

For the study, two reinforced concrete building models of 9 and 12 storey with double basement are studied. Shear wall is provided in both the structure to resist the lateral force. The concept of multipurpose building is emerging where a single building serves several facilities such as institutional, commercial, recreational, etc. In this case, one third of the structure is subjected to a slightly different set of loading compared to rest of the building. The portion is considered as a hotel with a swimming pool on one of its floor.

Figure 1 shows mass irregular model of 9 storey model has mass variation of in three consecutive storey and three cases has been generated. The swimming pool is located in 3^{rd}, 6^{th} and 9^{th} storey for bottom heavy, middle heavy and top heavy models respectively.

Figure 2 shows mass irregular model of 9 storey model has mass variation of in top three consecutive storey and three cases has been generated. The swimming pool is located in 9^{th} storey for top heavy models.

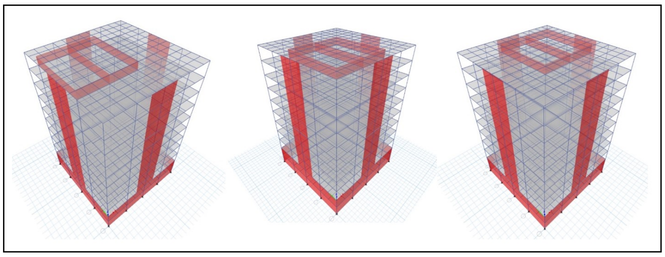

Figure 2: Top Mass Irregular Position A, B and C (9 Storey)

Figure 3 shows mass irregular model of 9 storey model has mass variation of in mid three consecutive storey and three cases has been generated. The swimming pool is located in 6^{th} storey for mid heavy models.

Figure 4 shows mass irregular model of 9 storey model has mass variation of in bottom three consecutive storey and three cases has been generated. The swimming pool is located in 3^{rd} storey for bottom heavy models.

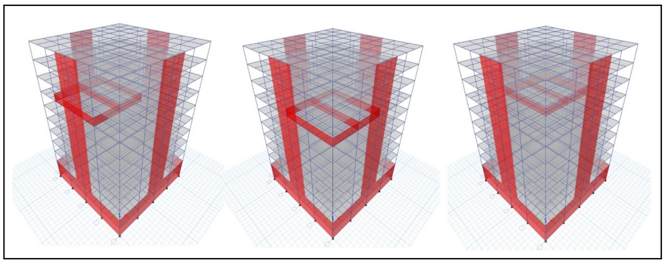

Figure 3: Mid Mass Irregular Position A, B and C (9 Storey)

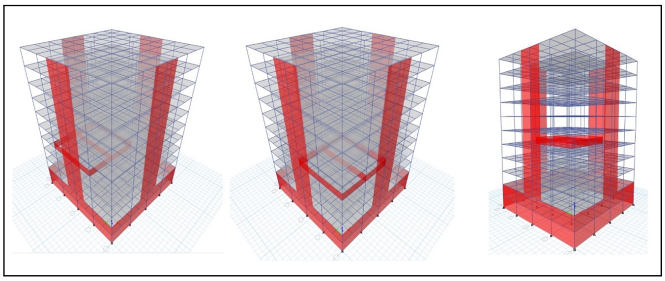

Figure 4: Bottom Mass Irregular Position A, B and C (9 Storey)

Figure 5 shows regular model having equal mass distribution in its every floor of 9 and 12 Storey.

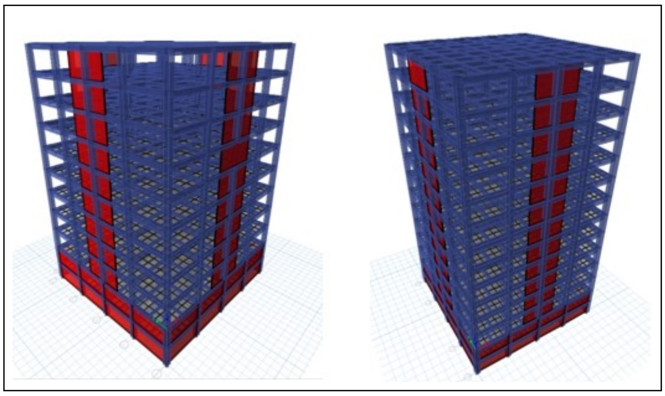

Figure 5: Regular Model of 9 Storey (left) and 12 Storey (right)

Figure 6 shows mass irregular model of 12 storey model has mass variation of in three consecutive storey and three cases has been generated. The swimming pool is located in 4^{th}, 8^{th} and 12^{th} storey for bottom heavy, middle heavy and top heavy models respectively.

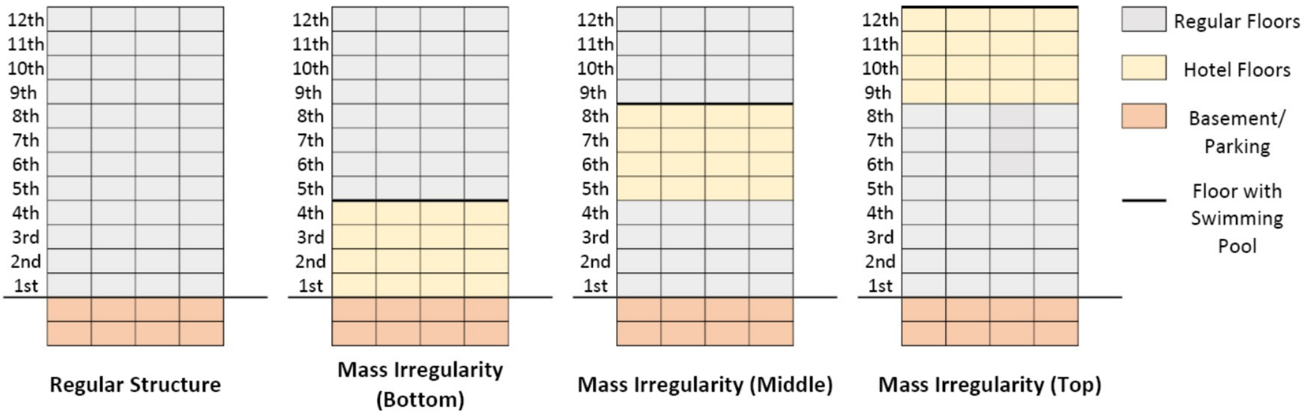

Figure 6: Elevation View 12 Storey Models

Figure 7 shows mass irregular model of 12 storey model has mass variation of in top four consecutive storey and three cases has been generated. The swimming pool is located in 12^{th} storey for top heavy models.Similarly, figure 8 shows mass irregular model of 12 storey model has mass variation of in mid four consecutive storey and three cases has been generated. The swimming pool is located in 8^{th} storey for mid heavy models. Figure 9 shows mass irregular model of 12 storey model has mass variation of in bottom four consecutive storey and three cases has been generated. The swimming pool is located in 4^{th} storey for bottom heavy models.

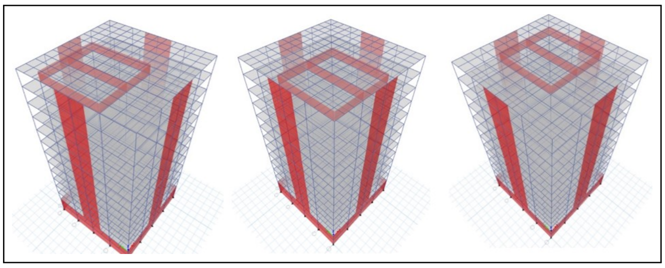

Figure 7: Top Mass Irregular Position A, B and C (12 Storey)

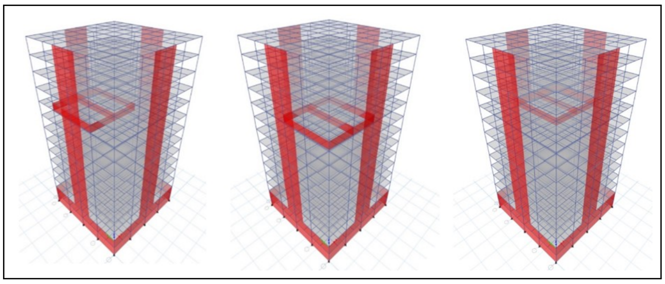

Figure 8: Mid Mass Irregular Position A, B and C (12 Storey)

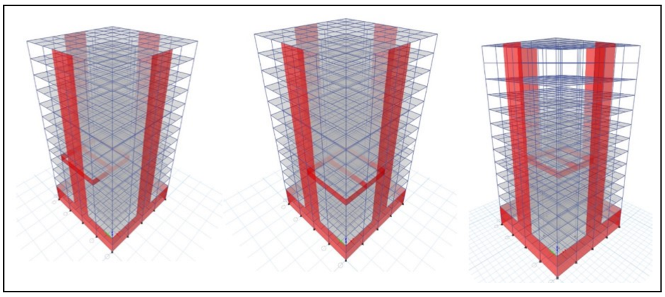

Figure 9: Bottom Mass Irregular Position A, B and C (12 Storey)

The influence of eccentric loading of mass irregularity within the storey is also studied. The figure 10 shows the plan view of the storey with different position of the water body.

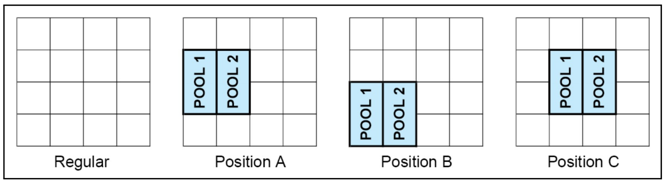

Figure 10: Plan Layout of the Pool in Different Positions

Hence 10 building models, i.e. Regular, Top Heavy (A,B,C), Middle Heavy (A,B,C) and Bottom Heavy (A,B,C) of each 9 and 12 storey is analysed.

To facilitate comprehension, the variation of mass in terms of vertical plane (storey) is referred as location of mass irregularity and the variation of mass in terms of horizontal plane (plan) is referred as position of mass irregularity in this literature.

Dimension of the Models

For the analysis, NBC 105: 2020 is followed.

No. of Bay :	4*4 (Along X and Y direction)
Grid Spacing:	7m
Grade of Rebar:	HYSD 500
Grade of Concrete:	M35 (Column)
	M25 (Beam, Slab and Shear Wall)

9 Storey Model

- Column Size : 725mm*725mm
- Beam Size : 700mm*500mm
- Secondary Beam Size : 400mm*300mm

12 Storey Model

- Column Size : 900mm*900mm
- Beam Size : 800mm *750mm
- Secondary Beam Size : 600mm*400 mm

Basement Wall : 9”

Shear Wall Size : 6”

Slab Thickness : 5” (All Floors) and 8” Swimming Pool

Pool Height : 2.00m (Pool 1) and 1.50m (Pool 2)

3. Methodology

The models are analysed by equivalent static method and model response spectrum method using ETABS Version 18.

3.1 CODAL Data

Seismic Zone Factor, Z (Kathmandu, Cl. 4.1.4) = 0.35

Importance Factor, I (Cl 4.1.5) = 1.25

Storey Height, h = 4.00 m

No. of Storey, N = 9 and 12

Height of Building, H = 36.00 m and 48.00m

Soil Type = D

Period of Vibration

For All other Structural Systems, $K_t = 0.050$

Approximate Time Period (Cl 5.1.2),

$$T = Kt * H^{0.75}$$

- For 9 Storey = 0.735 sec and
- For 12 Storey = 0.912 sec

Amplified Time Period, (Cl 5.1.3)

$$T1 = 1.25 * T$$

- For 9 Storey = 0.919 sec and
- For 12 Storey = 1.140 sec

Ta = 0.500 and Tc = 2.000

Peak Spectral Acceleration normalized by PGA,

$$\alpha = 2.250$$

Coefficient controlling descending spectrum branch,

$$\text{K} = 0.800$$

Calculation of Spectral Shape Factor, Ch(T)

Since $Ta \leq T \leq Tc$,

$$Ch(T) = \alpha = 2.250$$

Elastic Site Spectra (Cl 4.1.1),

$$C(T) = Ch(T) \times Z \times I = 0.984$$

Elastic Site Spectra for Serviceability Limit State,

$$Cs(T)(Cl4.2) = 0.2 \times C(T) = 0.197$$

Calculation of Spectral Shape Factor, Ch(T)

Ducitility Factor for ULS State (Cl. 5.3.1, Table 5.2),

$$R_\mu = 3.500$$

Over-strength Factor for ULS State (Cl. 5.4.1),

$$\Omega_u = 1.400$$

Over-strength Factor for SLS State,

$$\Omega_s\text{‘} = 1.200$$

Horizontal Base Shear Coefficient

ULS State (Cl. 6.1.1) = 0.201

SLS State = 0.164

Exponent related to Structural Period,

- For 9 Storey, k = 1.209 and
- For 12 Storey, k = 1.320

3.2 Applied Load

Soil Pressure on Basement Walls

Characteristic strength of concrete (fck) = 25 N/mm^2

Characteristic strength of steel (fy) = 500 N/mm^2

Clear height between the floor (h) = 3.92 m

Length of the wall (Lw) = 28 m

Unit weight of the soil (γ) = 18 KN/m^3

Angle of internal friction of the soil(θ) = 30 Degree

Surcharge produced by vehicular movement (Ws) = 0 KN/m^2

Safe bearing capacity of the soil (qs) = 130 KN/m^2

Moment Calculations

$K_a = 0.333$

Lateral load due to soil pressure (Pa) = 21 KN/m

Lateral load due to surcharge load (Ps) = 0 KN/m

Pressure Coefficient (P=Ax+By+Cz+D) used in Etabs

$$\text{C} = -6 \text{ and D} = 42$$

Live Load

Underground Basement (Parking/ Live Storage) = 4 kN/m^2

Regular Storey = 3 kN/m^2

Hotel Floors = 2 kN/m^2

Roof Live = 1.5 kN/m^2

Floor Finish

Roof and Parking Floors = 1.25 kN/m^2

Regular Floors = 1.50 kN/m^2

Floors with Swimming Pool = 1.75 kN/m^2

Wall Load

Wall Load on Frame = 9.6 kN/m

Water Pressure (Swimming Pool)

a. Gravity Load

Pool 1 = 20kN/m^2

Pool 2 = 15 kN/m^2

b. Lateral Load on Walls

Unit Weight of Water = 10 kN/m^3

Pool 1 (Height 2.00m),

C = -10 and D = 20

Pool 2 (Height 1.50m),

C = -10 and D = 15

3.3 Seismic Weight of Structure

As per NBC 105:2020, the seismic weight is taken as the sum of the dead loads and the factored seismic live loads between the mid-heights of adjacent stories.

Table 1: Live Load Category and Factor

Live Load Category	Factor
Storage	0.6
For Other Purpose	0.3
Roof	Nil

4. Result and Discussion

Buildings are modeled complying the criteria of NBC 105:2020. Firstly the buildings are analyzed using equivalent static method obtaining the necessary information from the above mentioned code. After that these buildings are analyzed using response spectrum method.

At first the base shear from the both cases are calculated. Since the base shear obtained from response spectrum method is found to be less than that of equivalent static method, the base shear for response spectrum method is scaled up to be equal to that obtained from equivalent static method.

4.1 Base Shear

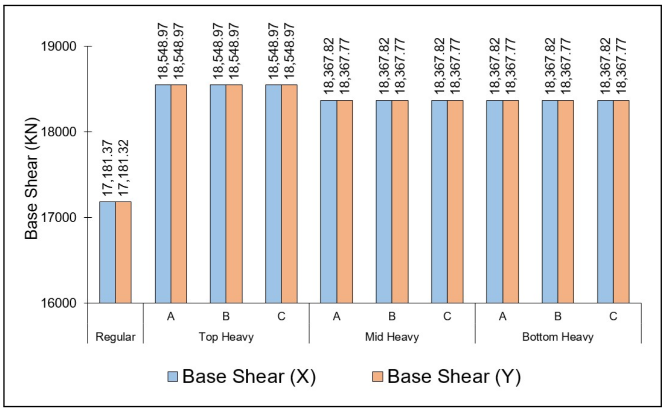

Figure 11: Base Shear (9 Storey)

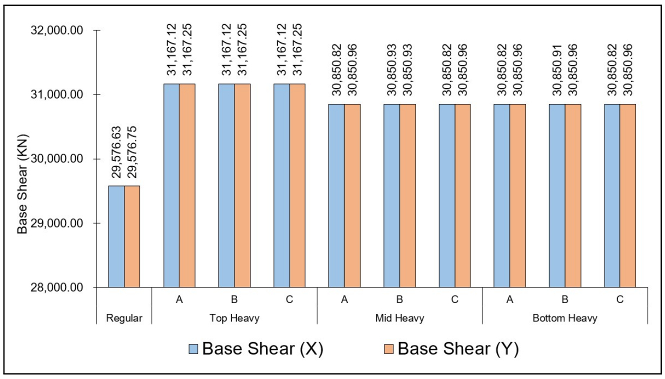

Figure 12: Base Shear (12 Storey)

In comparison to the regular models, the value of base shear in 9 storey models is more than 7.96% and 6.91% in top heavy and mid-bottom heavy models respectively as seen in figure 11. In similar pattern, figure 12 shows the 12 storey models has base shear value more than 6.59% and 6.30% in top heavy and mid-bottom heavy models respectively in comparison to their regular model.

The value of base shear remains equal in mid heavy and bottom heavy model for both 9 and 12 storey cases. The reason might be due to the same mass being located at different location with the overall seismic weight of the structure staying constant. The same could not be applicable in case of top heavy models as all the other models had roof live load of 1.5 KN/m^2 on their roofs which resulted in these models having less overall seismic weight than models with mass irregularity at the top. Hence resulting in slightly less value of base shear.

4.2 Time Period

The time period of first mode showed a bit similar results in all the three locations of A and C. The bottom heavy model (position B) had the least time period among all the 10 models of 9 storey. The lesser time period in bottom heavy models indicates that these models typically experience lesser displacements but greater accelerations. In case of buildings with higher natural periods and lower natural frequencies, the displacements is larger and smaller accelerations. Table 2 shows the values of time period at different mode of 10 models of 9 storey.

Table 2: Time Period 9 Storey Model

	Mode 1	Mode 2	Mode 3
REGULAR	1.192	1.192	0.834
TOP HEAVY			
A	1.306	1.295	0.884
B	1.298	1.298	0.892
C	1.306	1.305	0.876
MID HEAVY			
A	1.200	1.173	0.826
B	1.183	1.175	0.824
C	1.202	1.191	0.838
BOTTOM HEAVY			
A	1.136	1.095	0.786
B	1.113	1.099	0.777
C	1.14	1.123	0.819

Similar to the 9 storey model, in this building model as well we can observe bottom heavy model (position B) had the least time period among all the 10 models and A and C showed similar output. In dynamic events, a building with a longer time period is generally considered to be more flexible and will experience larger lateral displacements, on the other hand structure with a shorter time period is stiffer and will experience smaller displacements. Table 3 shows the values of time period at different mode of 10 models of 12 storey.

Table 3: Time Period 12 Storey Model

	Mode 1	Mode 2	Mode 3
REGULAR	1.715	1.715	1.194
TOP HEAVY			
A	1.828	1.819	1.252
B	1.823	1.82	1.259
C	1.829	1.828	1.245
MID HEAVY			
A	1.734	1.702	1.184
B	1.703	1.696	1.175
C	1.749	1.744	1.206
BOTTOM HEAVY			
A	1.672	1.61	1.131
B	1.62	1.607	1.114
C	1.697	1.689	1.188

4.3 Storey Displacement

The displacement of regular and several cases of mass irregular building in response spectrum cases for X and Y direction shown in Table 4.

Although the plan of the structure is symmetric, variation in deflection in two directions is due to pool 1 and pool 2 of different depth and secondly due to eccentric positioning at position A and position B as well as different depth of pool 1 and pool 2.

Table 4: Maximum Displacement of 9 and 12 Storey models in X and Y direction

	9 Storey		12 Storey	
	X	Y	X	Y
REGULAR	127.576	127.576	276.235	276.237
TOP HEAVY				
A	150.50	148.65	290.30	291.62
B	150.83	151.37	294.45	293.50
C	149.12	148.4	290.02	290.42
MID HEAVY				
A	122.43	123.93	271.82	276.27
B	124.10	122.64	272.762	269.76
C	123.20	120.18	279.405	277.33
BOTTOM HEAVY				
A	119.10	128.75	266.47	285.12
B	126.31	125.55	276.74	273.90
C	119.91	116.60	274.18	271.95

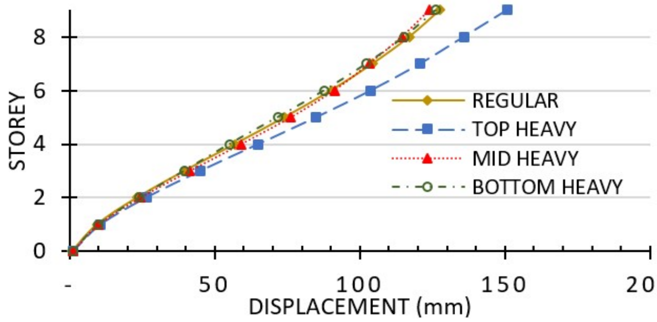

Figure 13: Maximum Storey Deflection of 9 Storey Position B Model of ULS (X direction)

Figure 13 shows the heavy mass located at the top has 17.96%, 18.23% and 16.89% more top displacement in Position A, B and C respectively compared to its regular model in X direction.

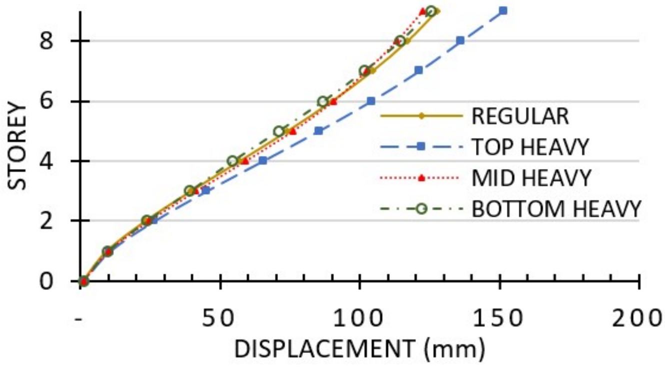

Figure 14: Maximum Storey Deflection of 9 Storey Position B Model of ULS (Y direction)

Similarly, in Y direction as well the values are somewhat similar, 16.51%, 18.65% and 16.39% for position A, B and C respectively as displayed in figure 14.

It can be observed that position B is found to exhibit higher value of displacement followed by position A and position C is the safest option with mass located at the center.

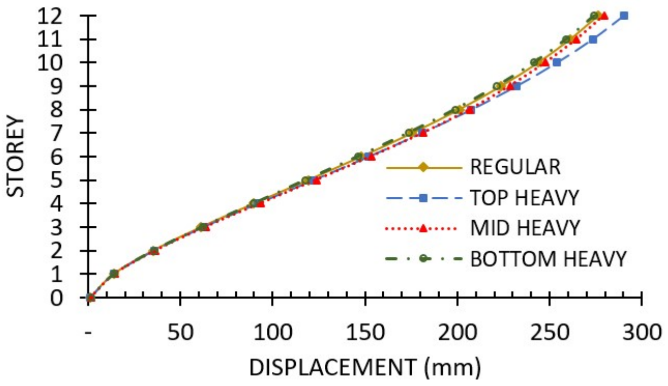

Figure 15: Maximum Storey Deflection of 12 Storey Position B Model of ULS (X direction)

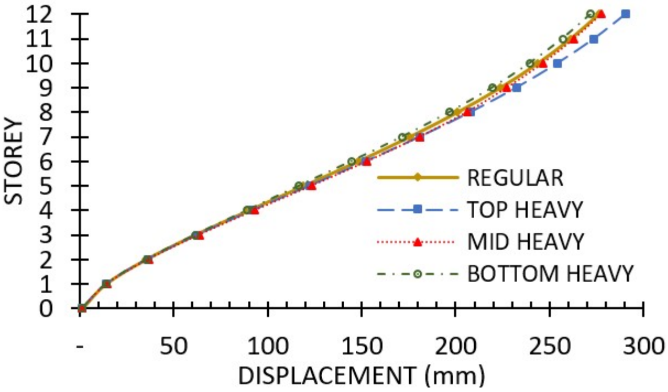

Figure 16: Maximum Storey Deflection of 12 Storey Position B Model of ULS (Y direction)

Similar to the previous 9 Storey models, in the 12 Storey Model as well the heavy mass located at the top has 5.09%, 6.59% and 4.99% more top displacement in position A, B and C respectively compared to its regular model in X direction (figure 15) .

Figure 16 shows the graph of Y direction where the somewhat similar, 5.57%, 6.25% and 5.13% for position A, B and C respectively. It can be observed that position B shows higher value of displacement followed by position A and position C is the safest option with mass located at the center.

The difference in percentage is lesser in 12 storey model compared to 9 storey, the reason might be due to increase in dead load of the structure as the size of member section has increased with the increase in number of storey. As the weight of water is constant in both Building I and II, increased dead load reduced the influence of the water weight on the overall seismic weight of the second model resulting in lesser variation compared to the first one.

4.4 Inter Storey Drift

The value of drift of building in regular state and with mass irregularity at various location and position in the structure is studied.

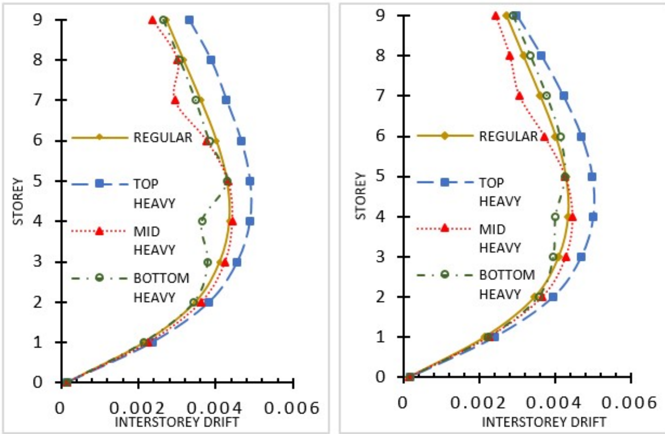

Figure 17: Inter storey Drift of 9 Storey Position A Mode in ULS (X and Y direction)

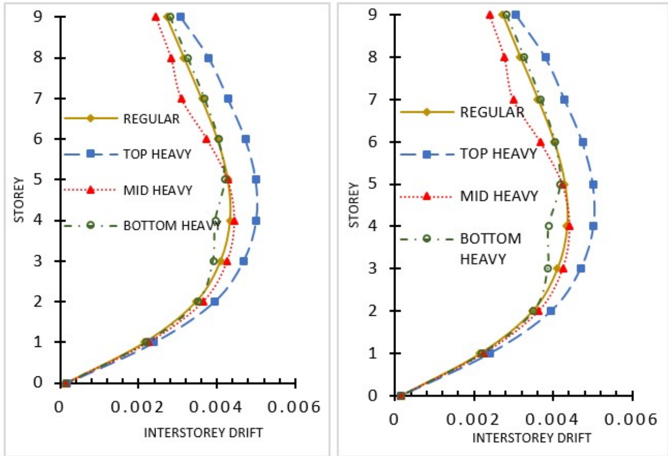

Figure 18: Inter storey Drift of 9 Storey Position B Mode in ULS (X and Y direction)

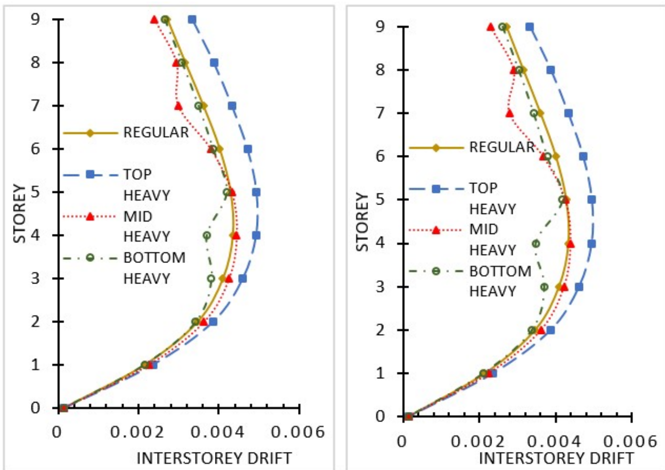

Figure 19: Inter storey Drift of 9 Storey Position C Mode in ULS (X and Y direction)

As seen in maximum displacement, the heavy mass located at the top has 12.34%, 15.33% and 13.74% more value of maximum inter storey drift in position A, B and C respectively compared to its regular model in X direction. Similarly, in Y direction as well the values are somewhat similar, 15.37%, 15.74% and 13.99% for position A, B and C respectively.

It can be observed that position B is found to exhibit higher value of inter storey drift in both the direction (figure 18). The second most value is displayed by position C in X direction (figure 19) and position A in Y direction (figure 17). The variation may be resulted due to non-uniform water bodies i.e. pool 1 and pool 2 of different depth.

In 12 storey model as well the heavy mass located at the top has 2.98%, 4.81% and 3.46% more value of maximum inter storey drift in position A, B and C respectively compared to its regular model in X direction. Similarly, in Y direction as well the values are somewhat similar, 5.04%, 5.28% and 3.21% for position A, B and C respectively.

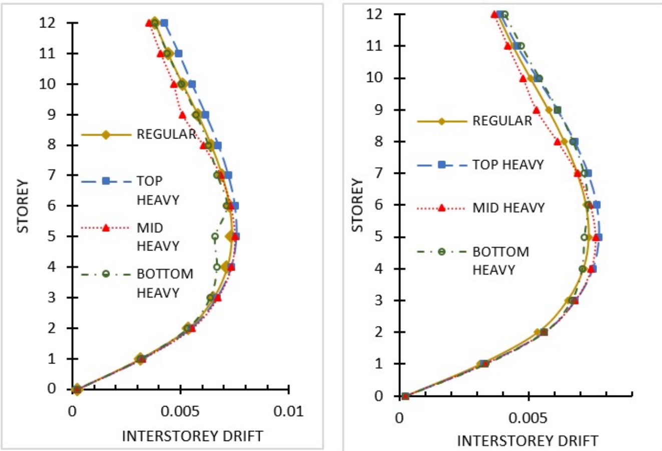

Figure 20: Inter storey Drift of 12 Storey Position A Mode in ULS (X and Y direction)

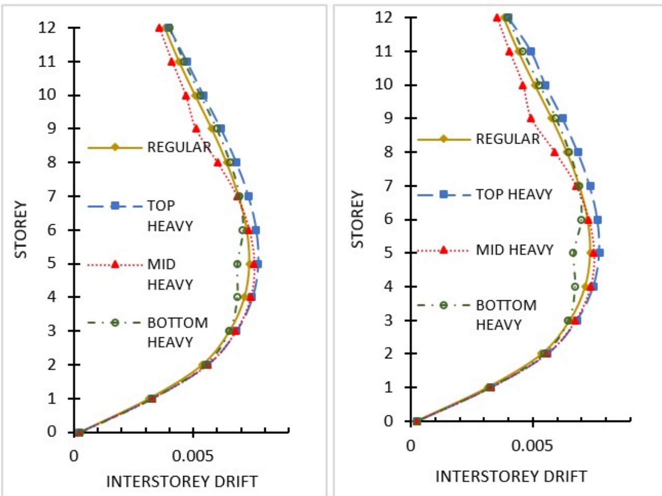

Figure 21: Inter storey Drift of 12 Storey Position B Mode in ULS (X and Y direction)

Complying with the previous building model, it can be observed that position B is found to exhibit higher value of inter storey drift in both the direction. The second highest value is displayed by position C in X direction and position A in Y direction. As stated previously, this variation may be resulted due to non-uniform water bodies i.e. pool 1 and pool 2 of different depth.

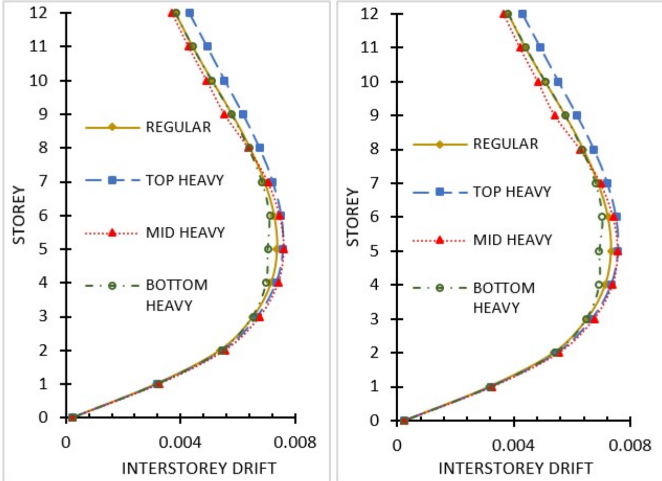

Figure 22: Maximum Storey Deflection of 12 Storey Position C Model of ULS (X and Y direction)

Maximum value of inter storey drift is higher in Y direction compared to X direction for all cases. Regular and top heavy structure showed smooth curve compared to mid heavy and bottom heavy structure that displayed slight inconsistency in the area of concentration of heavy mass. All building model satisfy the value of inter drift ratio specified by Nepal Building code. The maximum value of inter story drift ratio is 0.025 for ultimate limit state and 0.006 for serviceability limit state [4].

5. Conclusion

The seismic response of 9 and 12 storey RC building models having variation in position of heavy mass in different storey level as well as within the same storey is studied. Equivalent static analysis and modal response spectrum analysis is performed in all 20 models. The conclusion drawn from the analysis are as follows:

- The value of maximum displacement in the structure for bottom Heavy is up to 6.64% less and 18.65% more in top heavy model compared to uniformly mass distributed regular model in 9 Storey. For 12 storey model, the values are 3.53% less in bottom heavy and 6.59% more in top heavy model.
- The value of base shear in regular models is 7.96% and 6.91% less than that of top heavy and mid-bottom heavy model in 9 storey and 5.38% and 4.31% less than that of top heavy and mid-bottom heavy model in 12 storey models. The value of base shear remained equal in mid heavy and bottom heavy model for both 9 and 12 storey cases, the reason might be these models have overall equal seismic weight only certain mass is being located at different location. Thus the base shear in structure with equal seismic weight and geometry might remain the same in different in spite of variation in position and location of mass if all other parameters are kept unaltered.
- Maximum value of inter storey drift is higher in Y direction compared to X direction for all cases. The load is uniformly distributed in Y direction in comparison to X direction. Regular and top heavy structure showed

smooth curve compared to mid heavy and bottom heavy structure that displayed slight inconsistency in the area of concentration of heavy mass. The value of maximum drift in the structure for bottom heavy is up to 3.94% less and 15.74% more in top heavy model compared to uniformly mass distributed regular model in 9 Storey. For 12 storey model, the values are 5.01% less in bottom heavy and 5.28% more in top heavy model.

From this it can be understood that frame having mass irregularity on higher level show weak seismic performance but if kept in the lower half of the structure can perform better than uniformly mass distributed (regular) structure. Any form of irregularities in a building must be avoided but if irregularities have to be introduced for any reason, they must be designed properly following the conditions of prevailing building codes and the effect must be minimized or balanced utilizing suitable design techniques. Even though complex shaped building has a risk of sustaining damages during earthquakes but are getting more preference. Hence, such buildings should be designed properly taking care of their dynamic behavior.

6. Recommendation

This study has been focused in mass irregularity of a symmetric RC frame building having heavy mass in different location variation along with central as well as eccentric positioning of the mass. Soil structures interaction has not been included in the study. Hence the recommendation for future works are as follows:

- The present study is limited to equivalent static and modal response spectrum analysis hence non linear analysis can be performed on these models.
- The study is carried for RC bare frame and can be further extended including infill wall to capture the realistic performance of buildings.
- The base of structure is assumed to be fixed. Soil structure interaction can be considered for realistic behavior of structure.
- Water in the swimming pool is considered as static dead load, dynamic behavior of water can be taken into consideration.
- The study focuses on two buildings, one with 9 Stories and another with 12 Stories but its applicability can be extended to buildings with different numbers of stories.

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