Journal of Advanced College of Engineering and Management, Vol. 9, 2024

SEISMIC FRAGILITY ASSESSMENT OF MULTISTORY MASS IRREGULAR BUILDINGS USING INCREMENTAL DYNAMIC ANALYSIS

Urusha Budthapa[1], Aakarsha Khawas*[2], Rajan Suwal[3]

[1] M.Sc.in Structural Engineering, Department of Civil Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University, Nepal

[2]Assistant Professor, Department of Civil Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University, Nepal

[3] Associate Professor, Department of Civil Engineering, Pulchowk Campus Institute of Engineering, Tribhuvan University, Nepal
*Corresponding author: aakarsha.khawas@pcampus.edu.np (Phone number: 9846078585)

Abstract

In rapidly growing urban areas like Kathmandu, the increasing population demands more land, leading to a need for multipurpose buildings that can address multiple global challenges. However, the limited space in urban environments has caused changes in building structures, requiring more functionality within a smaller footprint and resulting in irregularities. An analytical study is conducted to investigate the impact of irregular mass distribution on a symmetrical reinforced concrete frame. This study considered variations in the placement of heavy masses between storey. The study evaluated the structural fragility of buildings with and without mass irregularities under different conditions. The study focused on two reinforced concrete building models, one with 9 storey and the other with 12 storey, both featuring double basements. Shear walls were incorporated into both structures to resist lateral forces, making them dual system structures. A portion of each building was designated as a hotel with a swimming pool on one floor and was subjected to slightly different loading compared to the rest of the building. The structural analysis involved response spectrum analysis and nonlinear time history analysis, with seismic design code NBC 105:2020. The study concluded that the distribution of mass in a structure can significantly impact its performance. While structures with irregular mass distribution at higher levels are more susceptible to earthquake damage in seismic zones, those with mass concentrated in the lower half can show better performance than uniformly distributed (regular) structures. The study emphasized the importance of avoiding structural irregularities whenever possible. However, if they are necessary, they must be designed in compliance with current building regulations, and their effects should be mitigated using appropriate design strategies.

Keywords: *Multistory RC Frame Building, Mass Irregularity, Incremental Dynamic Analysis, Fragility Curve*

1. Introduction

Irregular buildings are often visually striking and unique, making them attractive to architects and developers seeking to create distinctive structures. In densely populated areas where space is limited, irregular designs allow buildings to fit into tight spaces. Nepal's location in a seismic zone makes these irregular high-rise structures particularly vulnerable during earthquakes. Therefore, selecting a structural system capable of withstanding both lateral and gravity loads is crucial. Advances in engineering and construction technology have expanded the possibilities for constructing irregular buildings that were once considered impractical. These buildings can be more profitable than regular ones, commanding higher rents or sale prices due to their unique design and prime locations. However, irregular buildings also present unique challenges, especially regarding seismic safety. They require meticulous planning and engineering to ensure their structural integrity and the safety of occupants during earthquakes. Architects and developers must collaborate closely with seismic experts and engineers to design and construct irregular buildings with seismic safety in mind. Any building is considered irregular if it meets the criteria outlined in clauses 5.5.1 to 5.5.2 of NBC 105:2020.

With advances in computational efficiency, there is growing interest in assessing the seismic performance and vulnerability of buildings. Fragility functions, expressed as fragility curves, are used to assess building vulnerability by estimating the likelihood of exceeding a specified damage threshold across various ground motion intensities. Performance-based earthquake engineering (PBEE) is an emerging approach for analyzing the dynamic response of structures during earthquakes. Incremental Dynamic Analysis (IDA) is a PBEE technique that involves subjecting structures to a series of nonlinear dynamic analyses under scaled ground motion records. When combined with fragility analysis, IDA facilitates probabilistic seismic hazard analysis, which determines the mean annual frequencies of limit state exceedance (Vamvatsikos, 2002). Because of their complicated behavior during earthquakes, mass irregular buildings require a seismic fragility assessment. Comprehending their vulnerability helps in the development of effective retrofitting techniques and enhanced construction regulations to ensure the safety of structures in seismically vulnerable regions (Baral, 2022). Since seismic fragility assessment plays a key role in promoting safety, resilience, and informed decision-making in earthquake-prone regions.

2. Literature Review

Bansal et al. (2012) conducted Response Spectrum Analysis (RSA) and Time History Analysis (THA) on vertically irregular RC building frames with mass irregularity, stiffness irregularity, and vertical geometry irregularity. It was observed that the base shear of mass irregular structures was higher than that of regular structures. Additionally, in the time history analysis, the upper stories of irregular buildings exhibited slightly greater displacement compared to regular buildings.

Agrawal et al. (2020) studied the behavior of swimming pool in different position (i.e. One-Side, Two-Side, Three-Side, Centre) of pool at the terrace floor of the G+9 high rise regular building and concluded that the location of the swimming pool in elevation is significant in the design of the building, and it has been determined that the single side or center position pool qualifies as the best position for the selected structure.

Bhandari et al. (2022) investigated the seismic performance of two high-rise structures with pre-existing torsion irregularities. A shear wall was added to one of the buildings to mitigate torsion effects, and the modified structure was also analyzed. The findings revealed that incorporating shear walls into a structure enhances its performance by reducing torsion. Specifically, at a PGA of 0.35g, the performance of a 10-storied building improved by 35% for life safety, while the performance of a 12-storied building improved by 70% for collapse prevention.

In this study, three-dimensional finite element modeling is done for two buildings of 9 and 12 storey, followed by addition of mass heavy structure in different location of the building. Non- linear time history analysis is carried out by selecting seven pairs of ground motion which are later scaled to match the site requirement. Incremental dynamic analysis performed on these models and the outcome of IDA is used to develop fragility curve.

3. Methodology

3.1. Building Description

The study investigates two reinforced concrete building models, one with 9 storey and the other with 12 storey, both having a double basement. Each building includes shear walls to resist lateral forces, classifying them as dual system structures. The emerging concept of multipurpose buildings, which accommodate various functions like institutional, commercial, and recreational spaces, is considered. In one-third of the structure, which is designated as a hotel with a swimming pool on one floor, the loading differs slightly from the rest of the building.

Figure 1 illustrates the mass irregularity in the 9-storey model, where mass varies across three consecutive storey, resulting in three distinct cases: Bottom Heavy, Middle Heavy, and Top Heavy, based on their vertical location. Similarly, in case of 12 storey model the mass variation is in four consecutive storey with the three cases having four storey each as in figure 2.

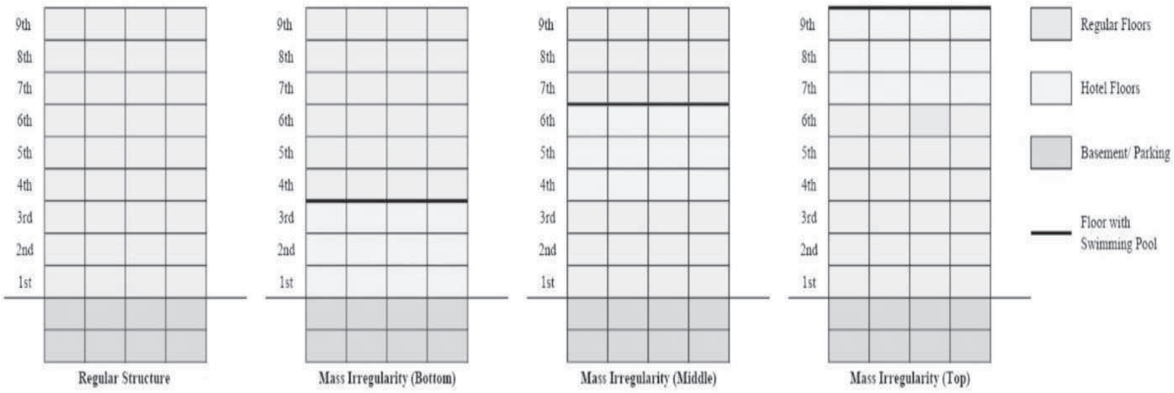


Figure 1: Elevation View of 9 Storey Regular and Mass Irregular Models

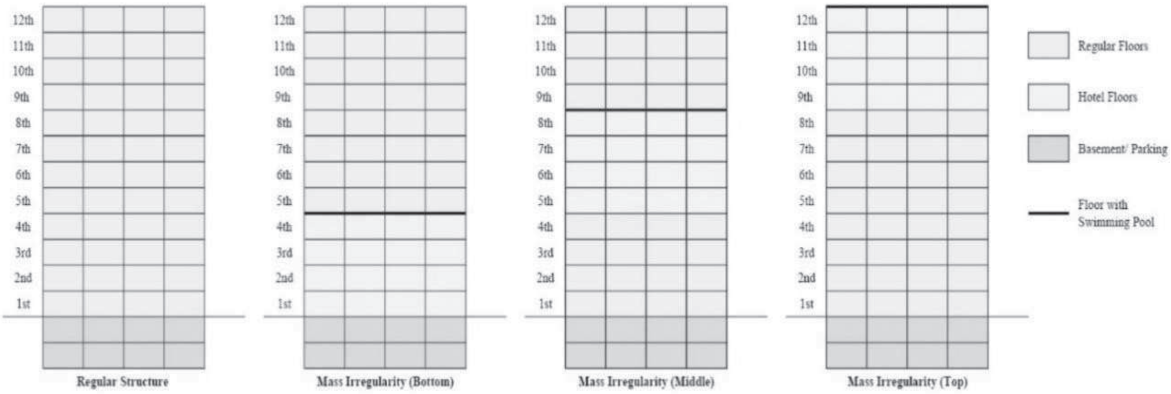


Figure 2: Elevation View of 12 Storey Regular and Mass Irregular Models

The buildings are designed with a 4*4 grid layout and a spacing of 7m. The structural elements, including columns, beams, slabs, and shear walls, are meticulously designed using specific dimensions and material grades to ensure structural integrity and safety. The grade of concrete used for the columns is M35, while that for the beams, slabs, and shear walls is M25. The reinforcement bars used are of grade HYSD 500. The columns are sized at 725mm*725mm for the 9-storey model and 900mm*900mm for the 12-storey model. Beams are sized at 700mm*500mm for the 9-storey model and 800mm*750mm for the 12-storey model. Secondary beams are sized at 400mm*300mm for the 9-storey model and 600mm*400mm for the 12-storey model.

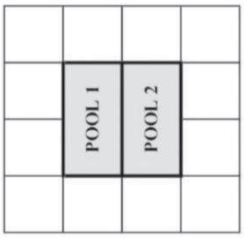


Figure 3: Pool Position (Plan View)

The basement walls are 9 inches thick, and the shear walls are 6 inches thick. The slabs have a uniform thickness of 5 inches across all floors, while the swimming pool features an 8-inch thick slab. The swimming pool is located at the center of the storey and has two sections with different heights: 2.00m for Pool 1 and 1.50m for Pool 2. Geometric non-linearity is considered by applying the P-delta effect. Beams and columns are modeled non-linearly by assigning plastic hinges based on ASCE 41-17 Table 10-7 for beams, and Tables 10-8 and 10-9 for columns. Shear walls are modeled with an auto fiber hinge provided by ETABS. Material non-linearity is accounted for using Manders' stress-strain curve for concrete and Park’s model from ETABS for rebar. Concrete exhibits degrading hysteresis behavior, while rebar exhibits Kinematic hysteresis behavior, as specified by Baral, 2022.

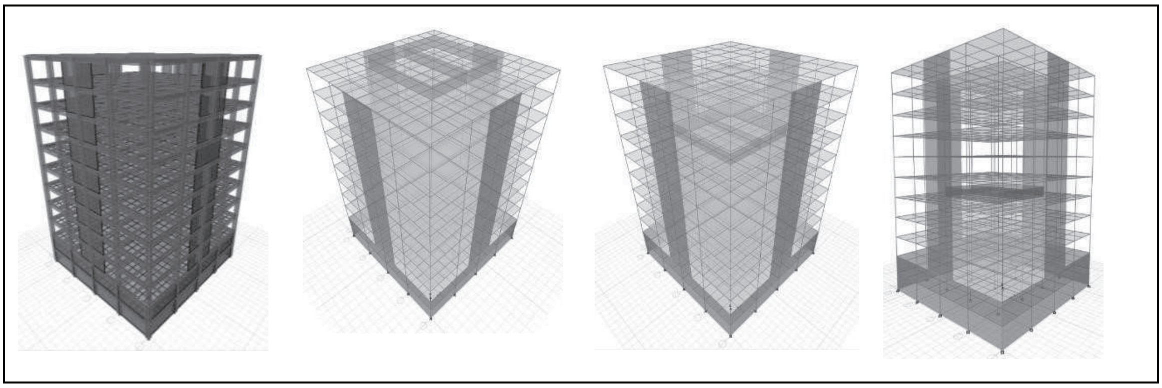


Figure 4(L-R): Regular 9 Storey Building Model followed by Models with Mass Irregularity (Pool) at 9th, 6th and 3rd floor

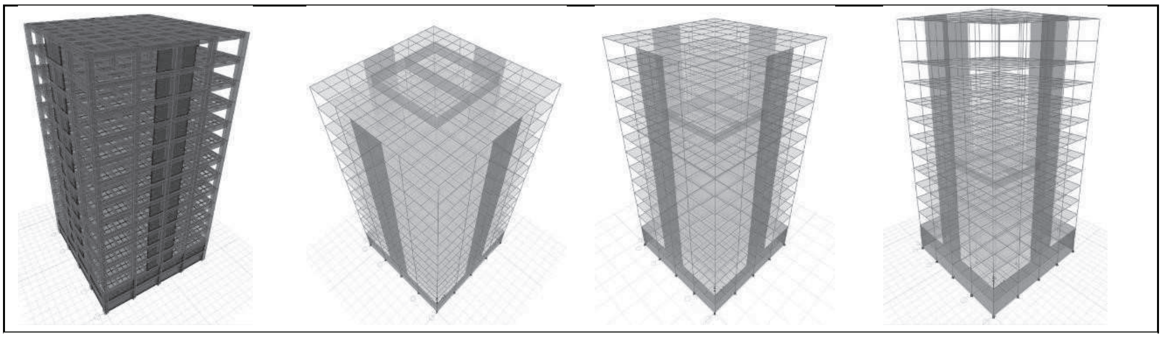


Figure 5(L-R): Regular 12 Storey Building Model followed by Models with Mass Irregularity (Pool) at 12th, 8th and 4th floor

3.2. Incremental Dynamic Analysis (IDA)

Incremental Dynamic Analysis (IDA) is a computational method in earthquake engineering used to comprehensively assess how structures behave under seismic loads. It builds upon the results of probabilistic seismic hazard analysis to estimate a structure's seismic risk. IDA is akin to a dynamic version of static pushover analysis. In IDA, a structural model is subjected to one or more ground motion records, each scaled to various intensity levels, resulting in one or more curves showing ground motion intensity versus structural response parameters. The process of conducting IDA is complex and time consuming. Vamvatsikos et al. (2002) proposed a simplified technique where the intensity measure is incrementally increased from zero until the structure collapses. Prior to analysis, the increment value and stopping criteria must be defined.

The intensity measure reflects the ground motion's effect on the structural response and can be a scalable quantity like peak ground acceleration (PGA), peak ground velocity (PGV), or spectral acceleration (S_a). In this study, PGA is used as the intensity measure. The Damage Measure (DM) is the output of IDA, quantifying the structural damage. DM can be expressed in various forms such as base shear, node rotation, global drift ratio, or inter-story drift ratio (IDR). In this study, IDR is used as the DM. The performance levels specifying the structure's damage limit are derived from the Federal Emergency

Management Agency (Huret, 2017). They include Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) with inter-story drift ratio limits of 0.5%, 1%, and 2%, respectively.

The devastating Mw 7.8 Gorkha (Nepal) earthquake struck on April 25, 2015, approximately 60 kilometers northwest of Kathmandu, the capital of Nepal. It ruptured 150 kilometers of the Main Himalayan Thrust (MHT) beneath the central Nepal Himalaya (Avouac, 2015). For this study, six earthquakes with reverse fault mechanisms and magnitudes ranging from 6.5 to 8, along with a rupture distance greater than 20, were selected from PEER databases. Ground motion data from the Gorkha earthquake were also included. Previous literature on assessing building response to seismic activity in the Trans-Himalayan region (THA) was consulted as a reference for ground motion selection.

S.N.	Ground Motion	Station	Year	Magnitude	Mechanism	Rup (km)
1	Chuetsu-Oki	Joetsu Kita	2007	6.8	Reverse	29.45
2	Tabas Iran	Boshrooyeh	1978	7.35	Reverse	28.79
3	Loma Prieta	Agnews State Hospital	1989	6.93	Reverse Oblique	24.57
4	Northridge	Hollywood-Willoughby Ave	1999	6.69	Reverse	23.07
5	San Fernado	Whittier Narrows Dam	1971	6.61	Reverse	39.45
6	Chi Chi	CHY002	1999	7.62	Reverse Oblique	24.96
7	Gorkha	Patan	2015	7.8	Reverse	60

Initially, the ground motions were downloaded in their original form without scaling from the databases. Seismomatch 2021 (Student Version) with a 0.3 tolerance is employed to align and adjust the ground motion. The selected ground motions are then scaled either up or down to align with the target spectrum specified by NBC 105:2020 for soil type D. Both horizontal directions were accounted for in the selection process to capture variations in response within the recorded data.

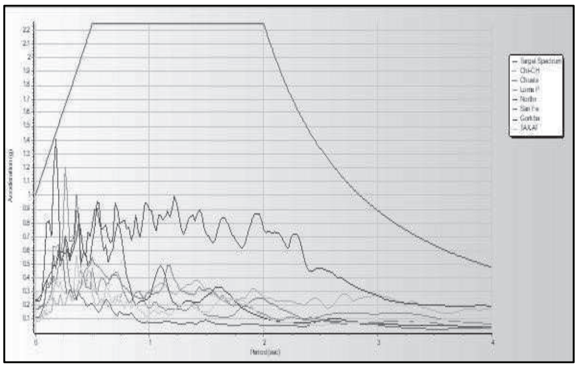


Figure 6: Unmatched Ground Motion Data (X)

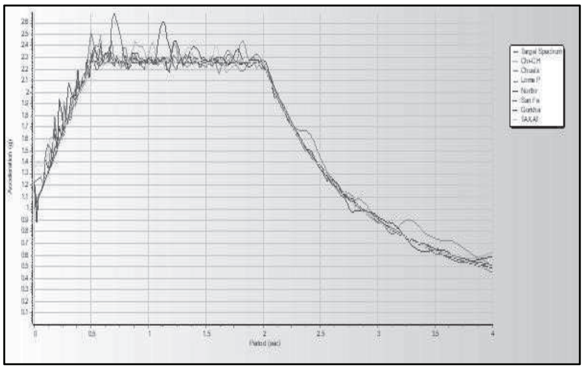


Figure 7: Matched Ground Motion Data (X)

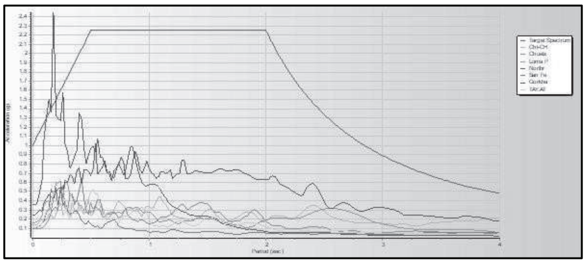


Figure 8: Unmatched Ground Motion Data (Y)

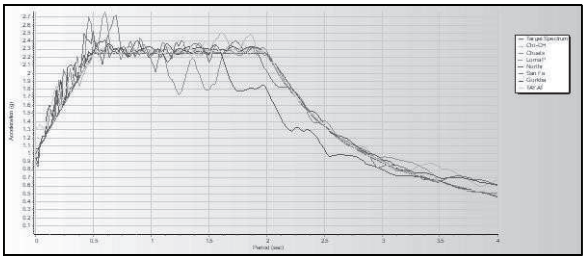
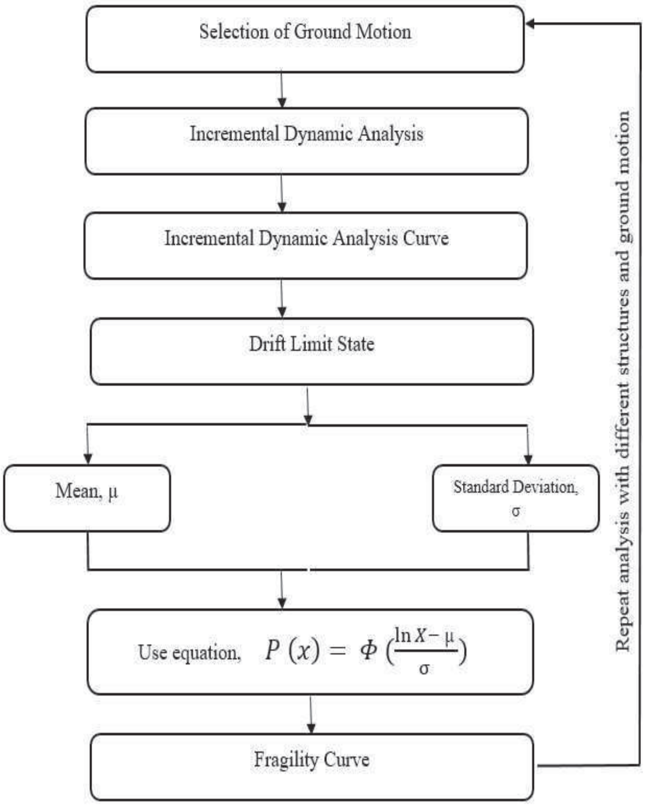


Figure 9: Matched Ground Motion Data (Y)

3.3. Fragility Curve

Fragility curves are valuable tools for predicting the probability of structural system damage under varying ground motion intensities. These curves can be developed using various seismic parameters, including PGA, which is utilized in the IDA. From fragility curves, the mean (μ) and standard deviation (σ) are obtained. The fragility function developed by (Kirçil, 2006) is used to determine the cumulative probability of damage, as expressed in the equation:

$$\boxed{P\ (x) = \Phi\ \left(\frac{\ln X - \mu}{\sigma}\right)}$$



Where,

Φ = standard normal distribution,

X = lognormal distributed peak ground acceleration,

μ and σ = mean and standard deviation of lnX

According to FEMA 356 2000, there are three defined damage states: Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). These states correspond to drift limits of 0.5%, 1%, and 2%, respectively. When using Incremental Dynamic Analysis (IDA) plots, the mean and standard deviations of the logarithms of Peak Ground Accelerations (PGAs) at these various damage states are obtained. The procedure for fragility analysis and curve is shown in the above flow chart.

4. Result and Discussion

4.1. Incremental Dynamic Analysis (IDA)

In the ETABS software, nonlinear time history analysis is conducted by subjecting the building models to bidirectional earthquake excitation. The maximum storey drifts are determined from load cases involving the X component of earthquake in the X direction, the Y component of earthquake in the Y direction, and vice versa (i.e., Y component of earthquake in the X direction and X component of earthquake in the Y direction). The maximum storey drift represents the highest drift observed between the X and Y directions. A higher Peak Ground Acceleration (PGA) value in the earthquake ground motion leads to a greater structural response. The Incremental Dynamic Analysis (IDA) curves plot peak ground acceleration on the y-axis against maximum inter-storey drift ratio on the x-axis.

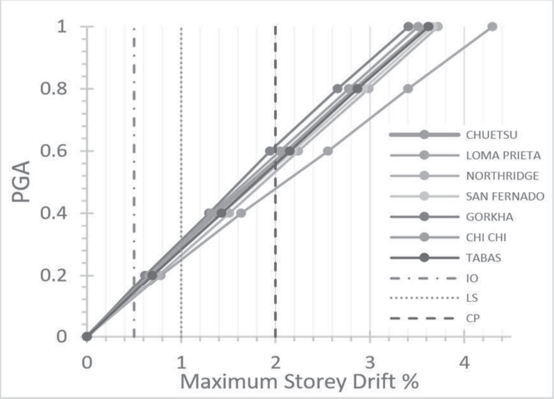


Figure 10: IDA Curve 9 Storey Regular Model

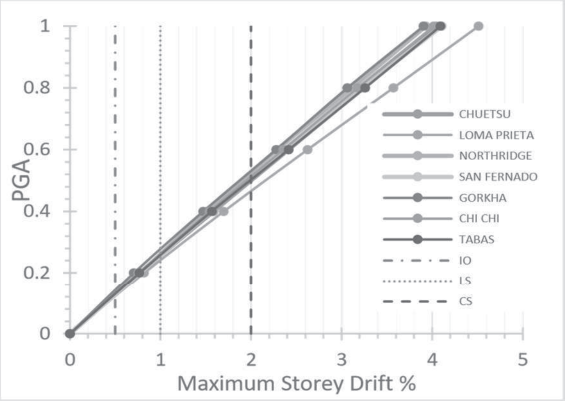


Figure 11: IDA Curve 9 Storey Mass Irregular (Top)

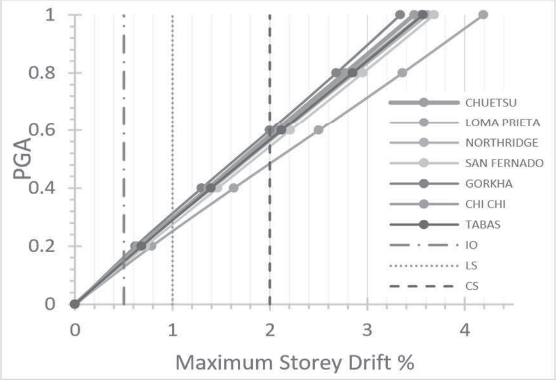


Figure 12: IDA Curve 9 Storey Mass Irregular (Mid)

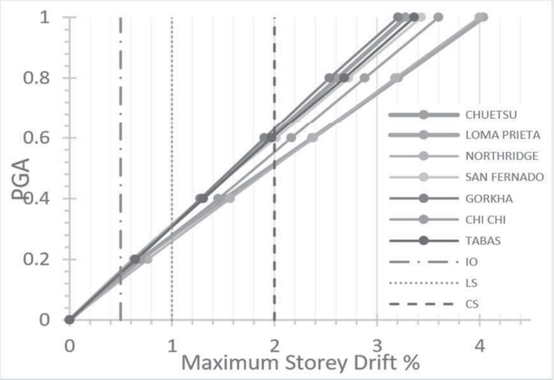


Figure 13: IDA Curve 9 Storey Mass Irregular (Bottom)

The analysis is conducted on 9 storey models of regular and mass irregular structure located at top, mid and bottom of the structure. The top heavy structure showed lower value of PGA at different damage state followed by mid heavy, regular and bottom heavy structure.

The IDA curves show the values of PGAs that exceed the drift limits at damage states. There are seven distinct PGAs values that reach the drift limit for a structure in a damaged state. The fast nonlinear approach of time history analysis only makes little use of nonlinearity. As a result, the IDA curves are nonlinear only to a limited extent. The logarithm of these PGAs values is used to calculate the mean and standard deviation that are tabulated below.

Table 1: Mean and standard Deviation for 9 Storey Models

Damage States	Immediate Occupancy (IO)		Life Safety (LO)		Collapse Prevention (CP)	
	μ	σ	μ	σ	μ	σ
Regular	-1.939	0.083	-1.275	0.077	-0.597	0.076
Top	-2.023	0.040	-1.369	0.043	-0.696	0.046
Middle	-1.935	0.071	-1.268	0.071	-0.587	0.071
Bottom	-1.914	0.075	-1.244	0.083	-0.563	0.089

The analysis is also conducted on 12 storey models of regular and mass irregular structure located at top, mid and bottom of the structure. The top heavy structure showed lower value of PGA at different damage state followed by mid heavy, regular and bottom heavy structure.

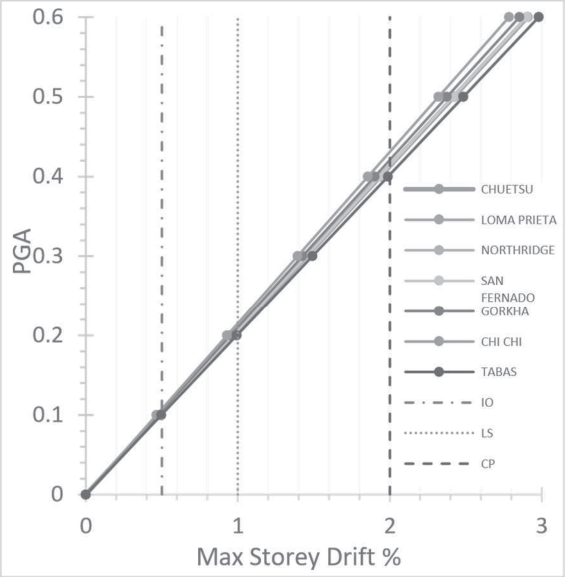


Figure 14: IDA Curve 12 Storey Regular Model

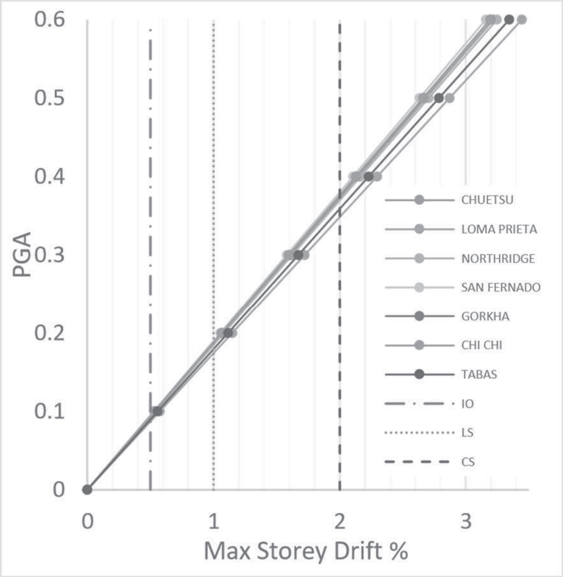


Figure 15: IDA Curve 12 Storey Mass Irregular (Top)

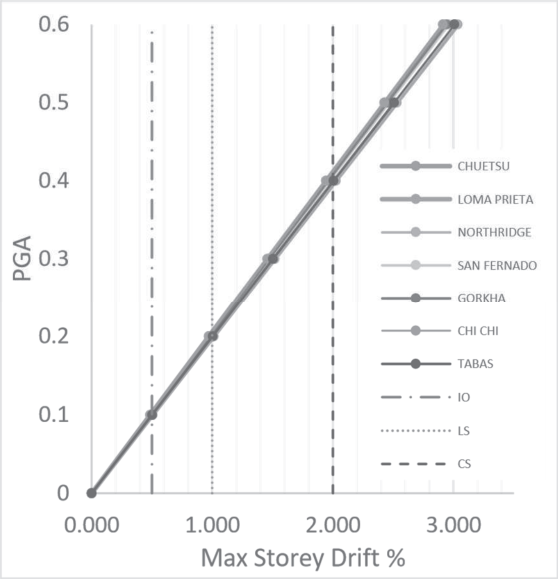


Figure 16: IDA Curve 12 Storey Mass Irregular (Mid)

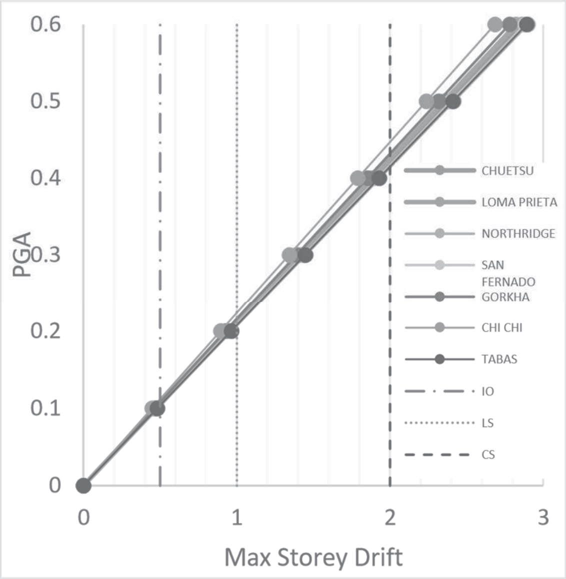


Figure 17: IDA Curve 12 Storey Mass Irregular (Bottom)

The IDA curves show the values of PGAs that exceed the drift limits at damage states. There are seven distinct PGAs values that reach the drift limit for a structure in a damaged state. The fast nonlinear approach of time history analysis only makes little use of nonlinearity. As a result, the IDA curves are nonlinear only to a limited extent. The logarithm of these PGAs values is used to calculate the mean and standard deviation that are tabulated below.

Table 2: Mean and Standard Deviation for 12 Storey Models

Damage States	Immediate Occupancy (IO)		Life Safety (LO)		Collapse Prevention (CP)	
	μ	σ	μ	σ	μ	σ
Regular	-2.269	0.024	-1.576	0.024	-0.883	0.024
Top	-2.384	0.031	-1.691	0.031	-0.998	0.031
Middle	-2.293	0.017	-1.600	0.017	-0.906	0.017
Bottom	-2.244	0.028	-1.551	0.028	-0.858	0.028

4.2. Fragility Curve

The fragility curves demonstrate the probability of exceeding the drift limitations for damage state immediate occupancy, life safety, and collapse prevention at varying PGAS levels. The fragility curve of 9 storey model in different cases and for different performance level is shown in figure 18. According to Nepal Building Code PGA of 0.35g indicates the earthquake with a return duration of 475 years for the specified site.

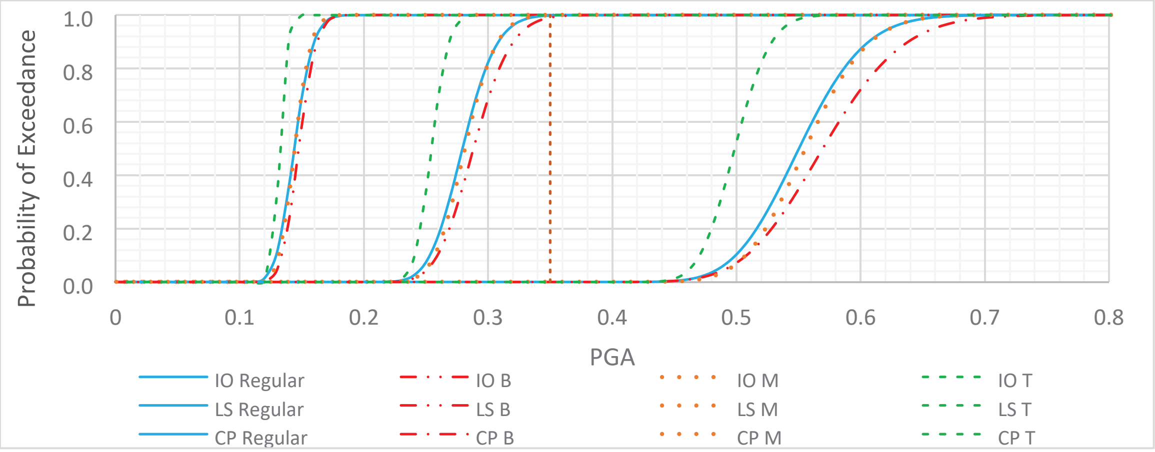


Figure 18: Fragility Curve of 9 Storey Model

From figure 18, it can be seen that probability of exceeding LS is 100% for all cases of 9 storey model at 0.35g PGA. The probability of exceeding LS is 100%, 99.90%, 99.05% and 99.83% for Top Heavy, Mid Heavy, Bottom Heavy and Regular Models respectively at 0.35g PGA. The performance of bottom heavy models is better than other cases in the building. The probability of exceeding CP is about 0% for all cases in the building at 0.35g PGA. However, from the calculation data it can be observed that the performance of bottom heavy models is slightly better than other models. Bottom heavy model displayed the best performance and top heavy was the weakest among the four cases studied. From the figure it can be seen that Top Heavy Model meets initial collapse and final collapse at 0.45g and 0.57g respectively whereas the bottom heavy model has initial and final collapse is shifted to 0.46g and 0.72g respectively.

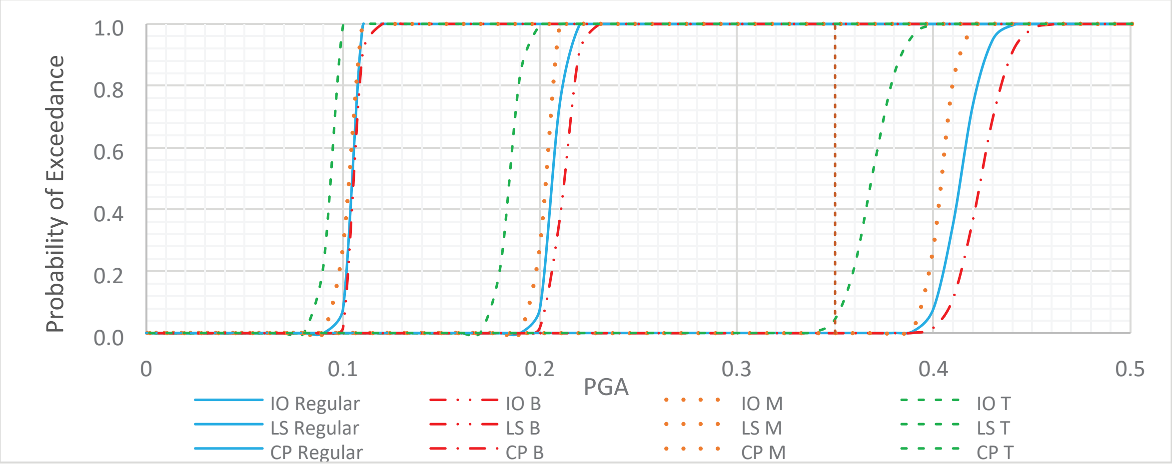


Figure 19: Fragility Curve of 12 Storey Model

The fragility curve of 12 storey model in different cases and for different performance level is shown in figure 19. From the figure, it can be seen that probability of exceeding LS is 100% for all cases of 12 storey building at 0.35g PGA. The probability of exceeding LS and IO is 100% for all Top Heavy, Mid Heavy, Bottom Heavy and Regular Models at 0.35g PGA. The performance of bottom heavy models is better than other cases in the building. The probability of exceeding CP is about 4.5% for Top Heavy and 0% in all other cases in the building at 0.35g PGA. From the calculation data it can be observed that the performance of bottom heavy models is slightly better than other models. Bottom heavy model displayed the best performance and top heavy was the weakest among the four cases studied. From the figure it can be seen that Top Heavy Model meets initial collapse and final collapse at 0.34g and 0.41g respectively whereas the bottom heavy model has initial and final collapse is shifted to 0.39g and 0.47g respectively. The influence of position variation is lesser in 12 Storey model compared to 9 Storey, the reason is 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 9 and 12 storey models, 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.

5. Conclusion and Recommendation

The seismic behavior of 9 and 12-storey RCC buildings was investigated, considering variations in the placement of heavy masses at different storey levels. Incremental Dynamic Analysis is carried out on these eight models using seven pair of ground motion that were scaled to the required intensity. Followed by prepared of fragility curves. The fragility curve illustrates that the top-heavy model experiences initial collapse and final collapse at 0.45g and 0.57g, respectively, in the 9-storey model. In contrast, the bottom-heavy model has initial and final collapse shifted to 0.46g and 0.72g, respectively. Similarly, in the 12-storey model, the top-heavy model encounters initial collapse and final collapse at 0.34g and 0.41g, respectively, while the bottom-heavy model experiences initial and final collapse at 0.39g and 0.47g, respectively. These results indicate that the location of heavy mass significantly influences the structural performance.

It is evident that although a frame with mass irregularity at higher levels is prone to damage in earthquake-prone areas, if placed in the lower half of the structure, these models can exhibit better performance compared to uniformly distributed (regular) structures. While any form of irregularity in a building should be avoided, if such irregularities must be introduced for specific reasons, they should be carefully designed in accordance with prevailing building codes, and their effects should be minimized or balanced using appropriate design techniques. Despite the risk of earthquake damage in complex-shaped buildings, they are gaining preference. Therefore, these buildings should be designed meticulously, taking into account their dynamic behavior, to ensure their structural integrity and safety during seismic events.

Hence the study suggests avoiding irregularities at higher levels wherever possible and recommends further research into mitigation measures for reducing the impact of top-heavy mass irregular structures. Additionally, it notes that the current analysis focuses on RC bare frames with shear walls as per code requirements, but it is suggested to extend the study to include complete infill walls for a more realistic building performance assessment. Furthermore, the study assumes a fixed base for the structure, considering soil-structure interaction for a more accurate representation of structural behavior is recommended. As water in the pool is considered as static load, dynamic behavior of water in swimming pools can be further studied. In this analysis fast nonlinear analysis has been used due to its faster computation. Direct integration method of nonlinear time history analysis can be done with use of faster computing devices. Hence further study can be carried out considering these factors to understand more precise behavior of the structure.

References

1. Agrawal, A. &. (2020). Analysis of Elevated Swimming Pool with Different Positions on the Terrace of RCC Frames using STAAD Pro.
2. Avouac, J. P. (2015). Lower edge of locked Main Himalayan Thrust unzipped by the 2015 Gorkha earthquake. . *Nature Geoscience, 8(9)*, 708-711.
3. Bansal Himanshu, G. (2012, August). Seismic Analysis and Design of Vertically Irregular RC Building Frames. *International Journal of Science and Research (IJSR) Volume 3 Issue 8*.
4. Baral, B. &. (2022, October). Seismic Performance of RC Buildings with Different Positions of Lift Core Wall and Added Shear Walls. (T. U. Institute of Engineering, Ed.) *Proceedings of 12th IOE Graduate Conference, 12,* 505–512.
5. Bhandari, A. &. (2022). Seismic Fragility Assessment of Irregular High Rise Buildings using Incremental Dynamic Analysis. 69-76. 10.3126/aet.v2i01.50446.
6. Huret, R. (2017, November). Federal Emergency Management Agency. Katrina, 163–189. https://doi.org/10.4000/books.editionsehess.939.
7. Kirçil, M. &. (2006). Fragility analysis of mid-rise R/C frame buildings. . *Engineering Structures - ENG STRUCT. 28*, 1335-1345. 10.1016/j.engstruct.2006.01.004.
8. Vamvatsikos, D. a. (2002). Incremental dynamic analysis. *Earthquake Engg.*
9. *Struct. Dyn., 31*, 491-514.