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Seismic Fragility Assessment of Irregular High Rise Buildings using Incremental Dynamic Analysis

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Abstract

The construction of high rise buildings is common in city areas. These buildings may be irregular because of aesthetics or other requirements. As Nepal lies in a seismically active region these irregular high rise buildings may not perform well during earthquakes. Two existing irregular high rise buildings are taken as case study buildings that had pre-existing torsion. Shear walls are added to the building at the required location to minimize torsion in the buildings. The objective of the study is to determine the performance of building with and without torsional irregularity. The seismic performance of all the buildings is carried out by taking seven pairs of ground motions using nonlinear time history analysis. These ground motions are scaled to the required intensity to develop incremental dynamic analysis (IDA) curve. These IDA curves are used to develop fragility curves to access the performance in the buildings. The result from the analysis showed that performance in one building improved by 35% and in another by 70% at the peak ground acceleration (PGA) of 0.35g.

Keywords: high rise, irregularity, IDA, seismic performance

1. Introduction

Nepal lies in the Himalayan seismic belt and has faced several minor and major earthquakes in the past. These Himalayas are the youngest chain of the mountain and are believed to be evolving causing unstable geological and geomorphological conditions [1]. This Himalayan region has a long history of strong ground motion and has experienced some earthquakes with a magnitude exceeding 7.5 since 1255 A.D. [2]. The construction of high rise structures is common in city areas to meet the demand of the growing population. Due to the requirement of an aesthetic and unique solution by architects, irregular structures are constructed which may cause unfavorable behavior of the entire structure or structural components. When the distribution of mass and stiffness in a multi-story concrete building is uneven, it leads to torsional sensitivity in the structure under seismic activity or wind. The torsional sensitivity of the structure can be reduced by changing the orientation of columns or adding shear walls to the structure. [3]. Torsional irregularity also exists in a building if the natural period corresponding to the fundamental torsional mode is more than the first two translational modes [4].

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Making structure with fundamental mode as translational, a major requirement in the structure is bending which results in optimal plastic mechanism, with the capacity of dissipating earthquake-induced energy due to post elastic incursion of structures [3].

Kassem et al. [5]respectively. Non-linear time history analysis (NL-THA carried out a study to evaluate buildings before and after carrying out retrofitting using shear walls and steel bracing. Non-linear time history analysis was carried out to develop Incremental Dynamic Analysis (IDA) curve. The conclusion from the study was that the performance of structures with shear wall was improved much and is the best method for carrying out retrofitting for structures. Irfan et al. [6] developed fragility curves based on incremental dynamic analysis curves using the ground motion of the Aceh earthquake. The fragility curve was used to assess the seismic performance of building structures. Desai et al. [7] carried performance evaluation using fragility analysis of reinforced concrete frame-wall structures. Fragility analysis is carried out using the lognormal distribution of cloud of response obtained using incremental dynamic analysis for high rise buildings. Limit states were obtained from FEMA 356.

In this study, seismic performance evaluation of two irregular high-rise irregular buildings is carried out which had preexisting torsion. Shear walls are added to the building to remove torsion in the building and the modified building is also analyzed. Three-dimensional finite element modeling is done for buildings. Non-linear time history analysis is done by taking seven pairs of ground motion scaled up according to requirement. Incremental dynamic analysis is carried out and the result is used to develop a fragility curve.

2. Methodology

2.1 Building description

Two irregular high rise buildings are taken as case study buildings. The first building is named building 'A' and the second building is known as building 'B'. Building A is ten stories with total height of 30m. Building B is twelve stories with a total height of 38.405m. Shear walls are added to both buildings to make the first two modes translational. The buildings are named A1 and B1 after the addition of shear walls. These buildings are shown in figure 1 and 2. The thickness of the added shear wall is 200mm in both buildings. The size of the columns are 400*400, 400*600, 400*700, 400*800 mm, and the beam is 400*550 mm in building A. The size of columns are 1000*400, 400*600, 500*700, 600*600, 700*700, and the size of beams are 400*250, 450*300, 550*350, 650*400mm in building B. 25MPa concrete and 500MPa rebar are used in building A. 30MPa concrete for columns and 25MPa for other members and 500MPa rebar is used in building B. Dead and live loads are assigned in the building according to Indian Standard Codes. The nonlinearity in beams and column is represented by the plastic hinge provided in Etabs. P-M3, fiber hinges are used for shear walls. Nonlinear time history analysis was carried out using the Takeda model which is available in Etabs.

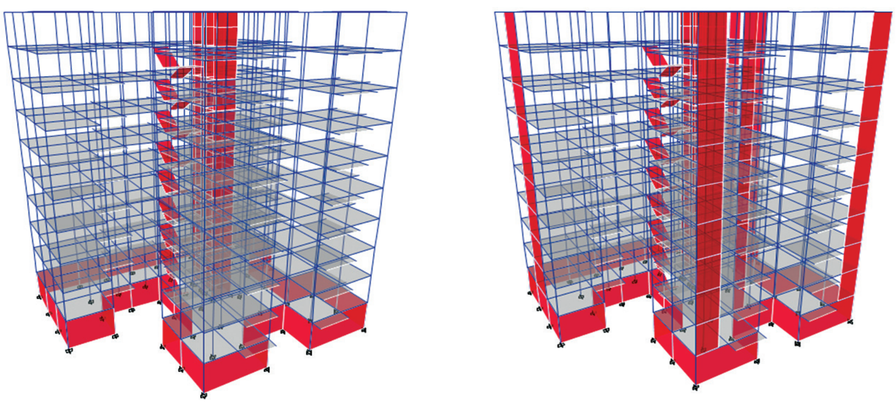

Figure 1: 3D model of building 'A' (left) and building 'A1' (right)

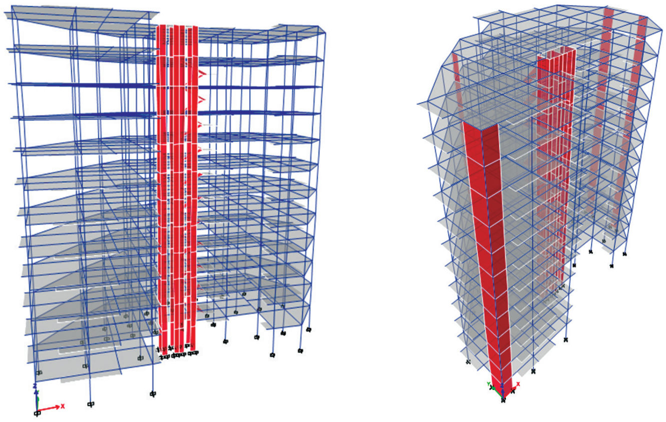

Figure 2: 3D model of building 'B' (left) and building 'B1' (right)

2.2 Incremental Dynamic Analysis (IDA)

IDA is the powerful tool to access the seismic performance of structures subjected to earthquake motion. The result can be obtained in the form of ground motion intensity vs structural response parameter. IDA can be used for capturing non-linear material behavior, geometric non-linearity, pounding buildings, high rise buildings using nonlinear dynamic procedures. The actual process of performing Incremental Dynamic Analysis is very repetitive and resource intensive. The method developed by Vamvatsikos & Cornell [8]interpret the results and apply them to performance-based earthquake engineering. IDA is an emerging analysis method that offers thorough seismic demand and capacity prediction capability by using a series of nonlinear dynamic analyses under a multiply scaled suite of ground motion records. Realization of its opportunities requires several steps and the use of innovative techniques at each one of them. Using a nine-story steel moment-resisting frame with fracturing connections as a test bed, the reader is guided through each step of IDA: (1 gives a simple algorithm of increasing Intensity measure by constant increment from zero until the structure is collapsed. This algorithm requires predefined increments and rules to determine when to stop the analysis.

Intensity measure quantifies the value of ground motion that affects the structural response. Scalable quantities like peak ground acceleration (PGA), peak ground velocity (PGV), spectral acceleration (Sa), etc. can be used as intensity measures. PGA is used as an intensity measure in this study. The output of the IDA is damage measure (DM). DM is a measurable quantity that can be obtained from non-linear dynamic analysis. DM can be represented in various forms like base shear, node rotation, global drift ratio, inter story drift ratio (IDR), etc. IDR is used as DM in this study.

Seven pairs of ground motion are taken for study. The earthquake data are selected based on magnitude ranging from 6.5-8, source mechanism as reverse or oblique, and fault distance greater than 20km. The selected ground motions are matched to the spectra of the Nepal Building Code for soil type D [9] using Seismomatch. The matched spectra are shown in figure 3. The performance level that specifies the damage level in the structure is taken from Federal Emergency Management Agency (FEMA) [10]. They are summarized as immediate occupancy (IO), life safety (LS) and collapse prevention (CP) with the inter story drift ratio limit of 0.5%, 1% and 2% respectively.

Table 1: List of selected ground motions

SN	Earthquake name	Year	Station name
1	Tabas_ Iran	1978	Boshrooyeh
2	Loma Prieta	1989	Agnews State Hospital
3	Northridge-01	1994	Hollywood -Willoughby Ave
4	Chi-Chi_ Taiwan	1999	CHY002

5	San Fernando	1971	Whittier Narrows Dam
6	Chuetsu-oki_ Japan	2007	Joetsu Kita
7	Gorkha	2015	Patan

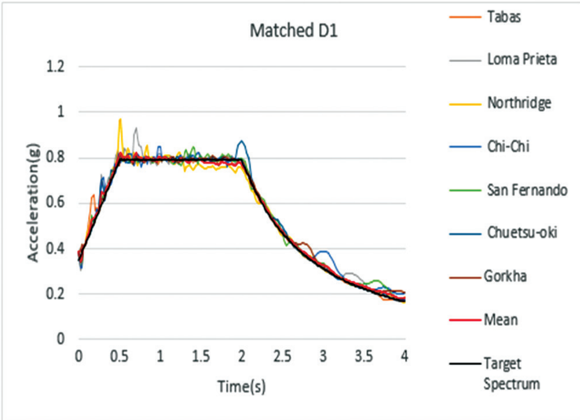

Figure 3: Matched response spectra of ground motion

2.3 Fragility Curve

Fragility curves are useful tools to predict the probability of damage in the structural system under various intensities of ground motion. Various seismic parameters can be used to develop a fragility curve. Since PGA is used to develop IDA, it is also used in the fragility curve. The two main parameters to develop a fragility curve are mean (μ) and standard deviation (σ). The assumption used by M. Serdar [11]which have been designed according to the 1975 version of the Turkish seismic design code, based on numerical simulation with respect to the number of stories of the buildings. Sample 3, 5 and 7 story buildings were designed according to the Turkish seismic design code. Incremental dynamic analyses were performed for those sample buildings using twelve artificial ground motions to determine the yielding and collapse capacity of each sample building. Based on those capacities, fragility curves were developed in terms of elastic pseudo spectral acceleration, peak ground acceleration (PGA to develop the fragility function is used to determine the cumulative probability of damage, which is given in equation (i) as:

$$P(x)=\emptyset\left(\frac{\ln X-\mu}{\sigma}\right) \quad \text{................(i)}$$

Where ∅ is standard normal distribution, X is lognormal distributed ground motion index (PGA), μ and σ are mean and standard deviation of lnX. The flowchart for developing the fragility curve is shown in figure 4.

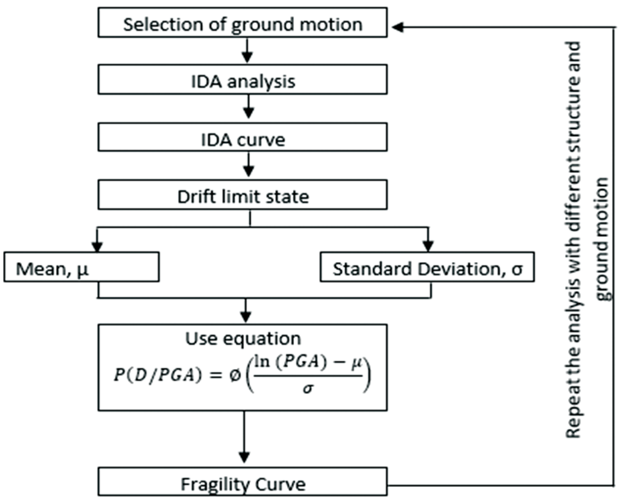

Figure 4: Flow chart for developing fragility curves

3. Result and Discussion

3.1 Modal Analysis

From the result of the modal analysis, it is seen that building A has higher mass participation in the torsional mode in the first mode and building B has higher mass participation in the torsional mode in the second mode. So these buildings are torsionally irregular. After the addition of shear walls torsion is removed from both buildings. This result can be seen in table 2. Mass participation in the first and second mode is only present in translational direction after the addition of shear walls. So these buildings are torsionally regular after the addition of shear walls.

Table 2: Modal Participating mass ratios

Case	Building 'A'			Building 'A1'			Building 'B'			Building 'B1'		
Mode	Ux	Uy	Rz	Ux	Uy	Rz	Ux	Uy	Rz	Ux	Uy	Rz
1	0.276	0.029	0.418	0.720	0.002	0.000	0.675	0.053	0.050	0.754	0.020	0.000
2	0.272	0.385	0.068	0.002	0.708	0.001	0.104	0.194	0.524	0.022	0.708	0.020
3	0.179	0.307	0.235	0.000	0.000	0.695	0.005	0.510	0.056	0.000	0.022	0.747

3.2 Incremental dynamic Analysis (IDA)

For making the IDA curve, the intensity measure is in the form of peak ground acceleration (PGA) and the damage measure is in form of inter-story drift ratio (IDR). IDR is plotted along the x- axis and PGA along the y-axis. The analysis was stopped when the drift ratio was more than 2-2.5% because the largest limit state value defined is 2%. The result of the IDA analysis can be seen in figures 5 and 6. The dispersion in the engineering demand parameter can be seen for the same intensity measure, this signifies that the response of the structure is dependent on the selected ground motion. The value of IDR is low for the same value of PGA after the addition of shear walls. This shows the performance of building increases after the addition of shear wall. From the generated IDA curve, the fragility parameters i.e. mean (μ) and standard deviation (σ) is evaluated for all the building cases and shown in table 3. These parameters are used to determine the probability of exceedance using equation (i).

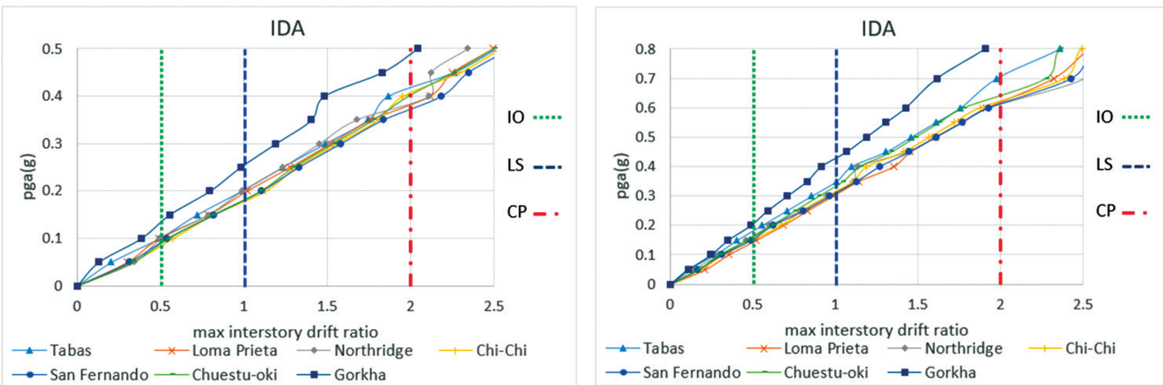

Figure 5: IDA curve for building 'A' (left) and building 'A1' (right)

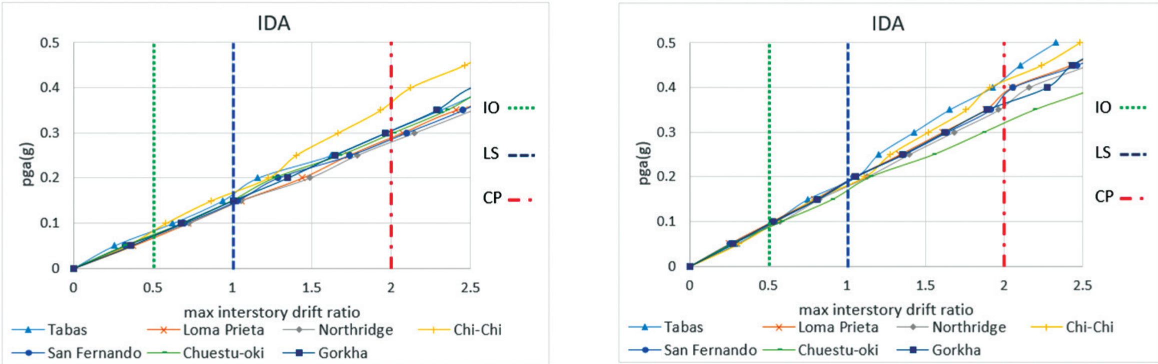

Figure 6: IDA curve for building 'B' (left) and building 'B1' (right)

Table 3: Parameters of log-normal distribution from IDA curve

Building type	IO		LS		CP	
	μ	σ	μ	σ	μ	σ
A	-2.3306	0.1622	-1.6012	0.1022	-0.8922	0.0774
A1	-1.7891	0.1184	-1.0966	0.1035	-0.4042	0.0993

Building type	IO		LS		CP	
	μ	σ	μ	σ	μ	σ
B	-2.5677	0.0677	1.8836	0.0670	1.1959	0.0789
B1	-2.3761	0.0330	1.6837	0.0618	-0.9919	0.0829

3.3 Fragility Curve

Figure 7 and 8 show the fragility curve for different building cases and the different performance level. The discussion is carried out for PGA of 0.35g which represents the earthquake with a return period of 475 years as per the Nepal Building Code [9] for the given location. From figure 7, it can be seen that the probability of exceeding IO is 100% for both buildings A and A1 at 0.35g PGA. The probability of exceeding LS is 100% and 65% for building A and A1 respectively at 0.35g PGA. The performance is improved by 35% after the addition of shear walls to minimize torsion in the building. The probability of exceeding CP is about 2% and 0% for building A and A1 at 0.35g PGA. Here, the performance is improved by 2% after the addition of shear walls.

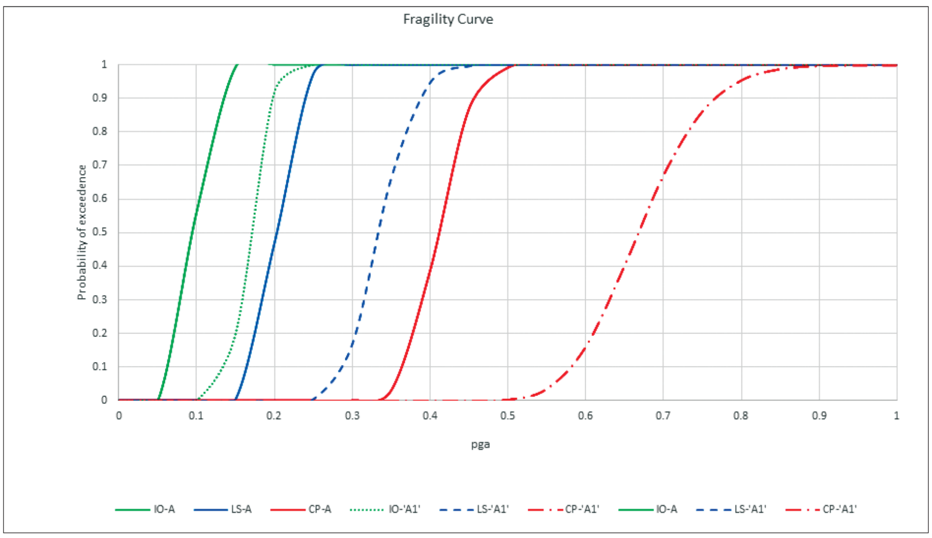

Figure 7: Fragility curve for building types 'A' and 'A1'

From figure 8, it can be seen that the probability of exceeding IO and LS is 100% for both building B and B1 at 0.35g PGA. The probability of exceeding CP is about 95% and 25% for buildings B and B1 at 0.35g PGA. The performance improvement is 70% after the addition of shear walls to minimize torsion. The entire plot shows that the performance of buildings improves significantly after minimizing torsion in the building after the addition of shear walls. Comparing both the plots, performance of building A is better than that of building B.

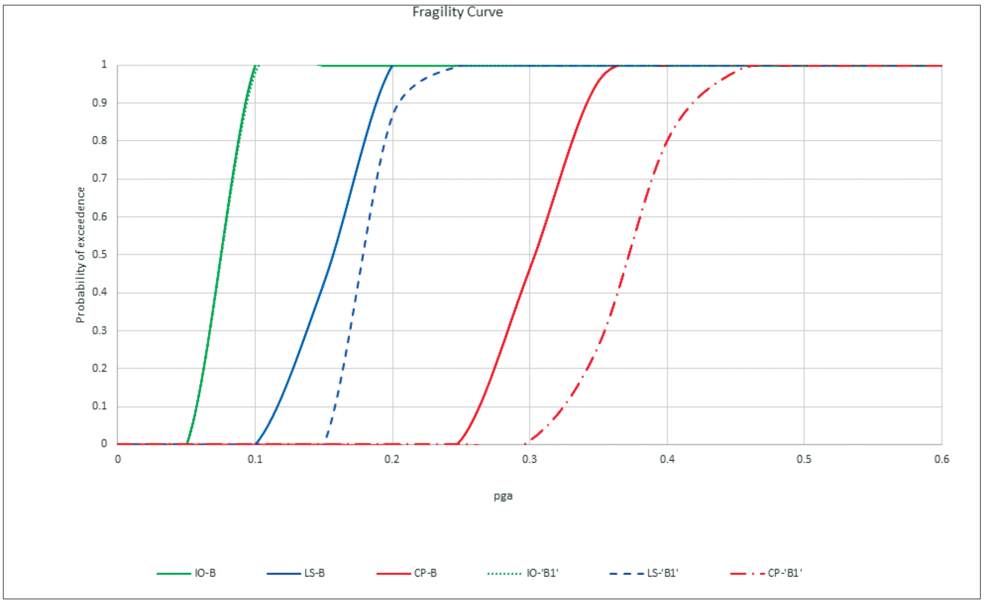

Figure 8: Fragility curve for building types 'B' and 'B1'

4. Conclusions

Two irregular high rise buildings were taken as study buildings that had pre-existing torsion. One is ten story building and the other is twelve story building. Shear walls are added to both buildings to minimize torsion in the building. Incremental Dynamic Analysis is carried out for all the buildings using seven pairs of ground motions scaled to the required intensity. The fragility curve is plotted using the result from IDA. Performance of buildings increases after minimizing torsion in the building by adding shear walls. The performance in building A is improved by 35% during life safety considering 0.35g PGA. The performance of building B is improved by 70% during collapse prevention considering 0.35g PGA. It can be concluded that IDA is a useful method to determine the performance of structures.

The main limitation of the study is that weight of the infill wall is considered and no actual modeling of the wall is done during analysis. Infill wall plays a significant role in the seismic performance of structures [12]. Soil structure interaction is not considered during the study and the base of the structure is considered fixed. The seismic response of structure may get amplified in some regions when soil structure interaction is considered [13]. Further study can be carried out considering infill wall and soil structure interaction to justify the performance of buildings.

Conflict of interest

Not declared by the author(s).

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