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Seismic Performance of Unreinforced Brick Masonry Buildings Considering Plan Irregularities

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Abstract
The present study deals with the seismic evaluation of unreinforced masonry buildings with plan irregularities (re-entrant corners). This study mainly focuses on comparison of seismic performance of unreinforced masonry buildings with plan irregularities based on fragility curves. The development of fragility curves for estimating the probability of damage of a building for a given damage state usually requires ground motion records. Here, three real earthquake ground motion records are selected for the development of fragility curves. These ground motion data are imposed on a set of unreinforced masonry buildings consisting of nine building models (with 2, 3 and 4 stories each for L-shaped, T-shaped and Regular Square shaped). Linear time history analyses are performed on SAP 2000 v20 to evaluate the dynamic response of the structures. Following that, top roof displacement, maximum drift ratio and base shear are determined from the analysis for each model and fragility curves are developed for four damage states (slight, moderate, extensive and complete) using the three earthquake time histories. This study also compares the fragility of L-shaped and T-shaped buildings with the regular ones.

Keywords
Fragility Curve, Unreinforced Brick Masonry, Seismic Performance

1. Introduction

Nepal lies in active seismic zone. It has a long history of devastating earthquake. In Nepal, there were several significant earthquakes recorded in 1255 AD, 1408 AD, 1810 AD, 1866 AD, 1934 AD, 1980 AD and 1988 AD (Chitrakar and Pandey 1986). More than 8,500 people died as a result of the 1993 earthquake, which largely affected the Kathmandu valley. Thirty-eight percent of the buildings suffered severe damage and 19% of the buildings were entirely demolished.

Recent Gorkha earthquake, 2015 of Nepal resulted into nearly 9,000 deaths, 22,000 injuries and 773378 building damages as per Ministry of Home Affairs,Nepal.Thus, the past earthquakes clearly depict the vulnerability of buildings in Nepal. The major building typology that exists in Nepal are: RC frame structures, Brick Masonry structures and Stone Masonry Structures. Masonry buildings are commonly practiced in the rural area, while RC frame structures are constructed as modern infrastructure in cities. Still, masonry construction is abundant in urban areas as well.

Most of the existing buildings in Nepal has low compliance of building code which makes them more vulnerable to earthquake. In particular, unreinforced masonry structures, which constitute a significant percentage of the building inventory in Nepal, are more susceptible to damage during earthquake due to its low tensile strength and brittle behavior. It has also been witnessed that most of the buildings damaged by the earthquake were masonry building.

Masonry buildings have been built since early ages. Masonry, especially unreinforced, is a common material for building construction but is also known for its seismic vulnerability. There are various factors that influence the damage of masonry structure during earthquake. One of them is irregularities present in masonry buildings. Irregular buildings are subjected to larger displacement compared to regular ones which results in localized damage near the region of irregularities.

2. Objectives

The general objective of carrying out this study is to find out the performance of L-shaped, T-shaped and Regular square-shaped unreinforced masonry buildings in terms of story displacement, drift ratio and base shear by performing a linear time history analysis. Specific objectives of the study is:

- To compare the seismic performance of L-shaped and T-shaped unreinforced masonry buildings with regular square-shaped buildings when excited by different ground motion time histories.

3. Methodology

The idealization of a structure is largely responsible for the accuracy of the computed response. Although masonry wall is composed of brick units and mortar which exhibit heterogeneous and anisotropic behavior, masonry is idealized as a homogeneous and isotropic material when it comes to the overall behavior of the structure. Hence, finite element macro modeling is used for this study considered masonry as homogeneous and isotropic material.

3.1 Selected Builidng Irregularity for Unreinforced Masonry

Building with geometric shapes like squares or rectangles perform better than those with irregularities as there are no torsional effects in symmetrical buildings. Under gravity loads, compression is the primary mode of load transfer with its magnitude increasing downwards. Whereas, under lateral loads, shear forces are also developed in masonry walls causing formation of diagonal cracks in the walls. The present study is limited to plan irregularities. The three building geometry type selected for the study are regular square shaped, L shaped and T shaped building. Each building type has same floor plan story wise. The floor plan of each building type selected for the study are shown below:

Table 1: Selected Building Models

Building Geometry	2 stories	3 stories	4 stories
L-shaped	L2	L3	L4
T-shaped	T2	T3	T4
R-shaped	R2	R3	R4

3.2 Material Properties

In this research work, brick masonry in cement mortar is used as material for finite element macro modeling of the structure which is assumed to be homogeneous, isotropic and linearly elastic. The material properties used in the present study are taken from the relevant earlier research works which are tabulated below:

Table 2: Concrete Properties for Slab

Concrete Grade for Slab	M20
Modulus of Elasticity	22GPa
Poisson’s Ratio	0.2

Table 3: Material Properties for Brick Masonry in Cement Mortar

Description	Value	Unit
Modulus of Elasticity	2300	MPa
Compressive Strength of masonry	4.1	MPa
Poisson’s Ratio	0.25	
Modulus of Rigidity	920	MPa

(Source: Kausik et al.(2007)

3.3 Structural Modeling

Buildings considered for the study are modeled in finite element software, SAP 2000 version 20. Masonry walls and slabs are modeled as shell element. The foundations are treated as rigid since soil structure interactions are not taken into account. Rigid floor diaphragms are assigned to all concrete floor slabs. The slab thickness is taken as 125mm for each level. The story height of each floor of each building is considered as 2.7m. The presence of similar opening size on each story level is considered in the modeling. The models have same wall thickness at each levels. The thickness of both outer and inner unreinforced brick masonry walls is considered to be 350mm.Based on the material’s unit weight, the gravity load calculation was done. Live load and floor finish load were taken as 2KN/m2 and 1.135KN/m2 respectively. The 3D model of the building used for the analysis in SAP 2000 are shown in figure below:

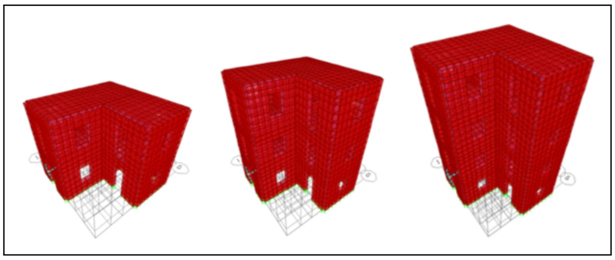

Figure 1: a) Two stories, b) Three stories, c) Four stories L-shaped building models

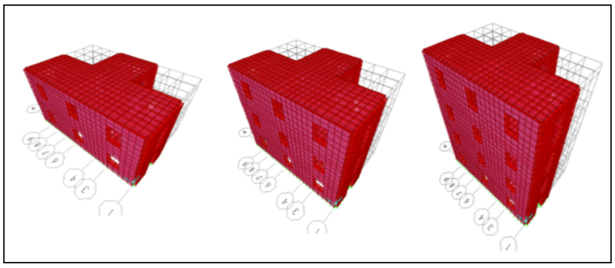

Figure 2: a) Two stories, b) Three stories, c) Four stories T-shaped building models

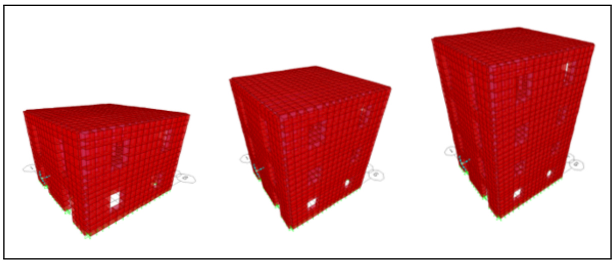

Figure 3: a) Two stories, b) Three stories, c) Four stories Regular building models

3.4 Analysis

After the completion of modeling of two to four story L shape, T shape and regular unreinforced masonry buildings in SAP 2000 version 20, modal analysis was carried out to understand the dynamic behavior of the structures. As per IS 1893:2016, in buildings with re-entrant corners, three dimensional dynamic analysis shall be adopted. Hence, linear time history analysis was carried out for following earthquake with scaled PGA.

Table 4: Material Properties for Brick Masonry in Cement Mortar

SN	Earthquake
1	Gorkha Earthquake
2	Imperial Valley Earthquake
3	Northridge Earthquake

Scaling of each time history records was done to get PGA value of 0.1g, 0.2g, 0.3g, 0.4g, 0.4g, 0.5g, 0.6g, 0.7g, 0.8g, 0.9g and 1g so that comparison can be done for same PGA value even they have different characteristics of time period, amplitudes, frequency, etc.

As deformations are more meaningful than forces, the maximum top story displacement is used as a parameter in terms of which damage state is defined. Finally, fragility curves were obtained.

Fragility curve is the curve showing probability of reaching in or exceeding a specific damage state under earthquake excitation.The fragility simply defines the likelihood that the seismic demand placed on the structure(D) exceeds the structure's capacity (C). For structural damage, given the spectral displacement, Sd, the probability of in or exceeding a given damage state, ds is modeled as:

$$P[ds/S_d] = \varphi\left[\frac{1}{\beta ds}\left[\ln\left(\frac{Sd}{\overline{Sd}_{ds}}\right)\right]\right]$$

Where Sd,ds is the threshold spectral displacement at which the probability of the damage state ds is 50%,
β ds is the standard deviation of the natural logarithm of this spectral displacement,
ϕ is the standard normal cumulative distribution function and
Sd is the spectral displacement.The damage state thresholds for unreinforced masonry buildings are given in Barbat et al. (2006).

Table 5: Damage state thresholds

Damage State	Slight		Moderate		Extensive		Complete	
Building class	$\overline{Sd}_1$	β_1	$\overline{Sd}_2$	β_2	$\overline{Sd}_3$	β_3	$\overline{Sd}_4$	β_4
Low rise masonry (2 stories)	0.19	0.28	0.27	0.37	0.54	0.54	1.36	0.72
Mid-rise masonry (3-4 stories)	0.44	0.40	0.63	0.50	1.20	0.75	2.91	0.70

4. Results and Discussion

Nine unreinforced masonry building models as described in table 1 were used for the analysis. Macro modeling of the buildings was done in SAP 2000 version 20. Linear time history analysis was carried out to determine how the selected nine building models respond to various earthquakes at various PGAs in terms of story displacement, drift ratio and base shear. Three real ground motion records as tabulated in table 4 were selected for the present study.

Those ground motion records were scaled to PGA value of 0.1g, 0.2g, 0.3g, 0.4g, 0.4g, 0.5g, 0.6g, 0.7g, 0.8g, 0.9g and 1g.

For two storied L-shaped, T-shaped and Regular buildings, the modal time period was 0.087secs, 0.089secs and 0.086secs respectively. Similarly, the modal time period for three-story L-shaped, T-shaped and regular buildings was 0.143secs, 0.144secs and 0.14secs respectively. And for four-story L-shaped, T-shaped and Regular buildings, the modal time period was 0.2115secs, 0.2116secs and 0.2013secs respectively. For each floor plan, the number of wall panel with similar opening size is 10 for L-shaped buildings, 13 for T-shaped buildings and 12 for regular square-shaped buildings The lowest time period is obtained for regular shape buildings and the highest for T-shaped buildings although the mass of L-shaped building is the lowest and of T-shaped building is the highest for the corresponding number of stories. This is due to higher overall stiffness of the regular buildings compared to T-shaped and L-shaped. Also, with the increase in building height, the mass of the building increases whereas the overall stiffness decreases. Therefore, it is observed that the modal time period of vibration increases with the increase in number of stories.

It is observed that the base shear, maximum story drift and maximum top displacement increase gradually with the increase in the number of stories for a given PGA value.The base shear and other parameters are seen varying linearly with the increase in PGA values. This is because of the linear time history analysis. Also for two to four stories of the same building type, the base shear and roof displacement were increased on increasing the PGA values as anticipated. For buildings with the same number of stories, the maximum story displacement for the ground motion is maximum for T-shaped and minimum for regular buildings. The maximum top displacement of a building for each building type was different in three different earthquake records. This variation is caused by differences in the duration and peak amplitude of various earthquakes. For 3 different building model types (L-shaped, T-shaped and Regular) of the same number of stories, the base shear of an L-shaped building is the lowest due to its lower inertial mass whereas the base shear of a T-shaped building is the highest due to its higher inertial mass compared to the others. Although the base shear of the L-shaped buildings is lower than the regular ones, the maximum top displacements are higher for L-shaped buildings compared to regular ones. This could be done to the uniform stress distribution in regular plans whereas stress concentration in irregular plans.Also, the lowest story drift ratio is obtained for regular shape building for the corresponding number of stories. Whereas, story drift ratio is the highest for T-shaped buildings with few cases being within the same range as that of L-shaped buildings for the corresponding stories.

Fragility curves defining the probability of failure of buildings sustaining minor, moderate, extensive and total damage states were obtained using the results of the linear time history. The fragility curves showing the probability of damage at various damage states for different earthquake intensities(PGA) of each building model are shown in Figures 4.4, 4.5 and 4.6. The peak ground acceleration of Kathmandu Valley ranges from 0.475g to 0.52g for a 10% probability of exceedance in 50 years (Guoxin et al. (2013)). Therefore, the probability of failure for the 0.5g PGA value is selected for the comparison of results. The damage expected under different time histories for 0.5g PGA is described as below.

For 2 Stories Building Configuration:
Gorkha Earthquake: The probability of failure of the regular model for PGA 0.5g is about 23%, 6.7%, 1% and 0.12% for slight, moderate, extensive and complete damage states respectively. The probability of failure of the L-shaped model for PGA 0.5g is about 33%, 10%, 2% and 0.2% for slight, moderate, extensive and complete damage states respectively. The probability of failure of the T-shaped model for PGA 0.5g is about 43%, 14%, 2% and 0.3% for slight, moderate, extensive and complete damage states respectively. It is observed for a given damage state, the probability of damage for T-shaped building is 1.8 to 2 times more than that for regular ones whereas the probability of damage for L-shaped building is 1.4 to 1.5 times more than that for regular ones.

Imperial Valley Earthquake: The probability of failure of the regular model for PGA 0.5g is about 54%, 19%, 3% and 0.35% for slight, moderate, extensive and complete damage states respectively. The probability of failure of the L-shaped model for PGA 0.5g is about 69%, 29%, 5% and 0.6% for slight, moderate, extensive and complete damage states respectively. The probability of failure of the T-shaped model for PGA 0.5g is about 84%, 43%, 8% and 1% for slight, moderate, extensive and complete damage states respectively. It is observed for a given damage state, the probability of damage for T-shaped building is about 1.5 to 2.7 times more than that for regular ones whereas the probability of damage for L-shaped building is about 1.3 to 1.6 times more than that for regular ones.

Northridge Earthquake: The probability of failure of the regular model for PGA 0.5g is about 54%, 19%, 3% and 0.35% for slight, moderate, extensive and complete damage states respectively. The probability of failure of the L-shaped model for PGA 0.5g is about 63%, 24%, 3.9% and 0.5% for slight, moderate, extensive and complete damage states respectively. The probability of failure of the T-shaped model for PGA 0.5g is about 67%, 27%, 4.4% and 0.2% for slight, moderate, extensive and complete damage states respectively. It is observed for a given damage state, the probability of damage for T-shaped building is about 1.2 to 1.5 times more than that for regular ones whereas the probability of damage for L-shaped building is about 1.1 to 1.3 times more than that for regular ones.

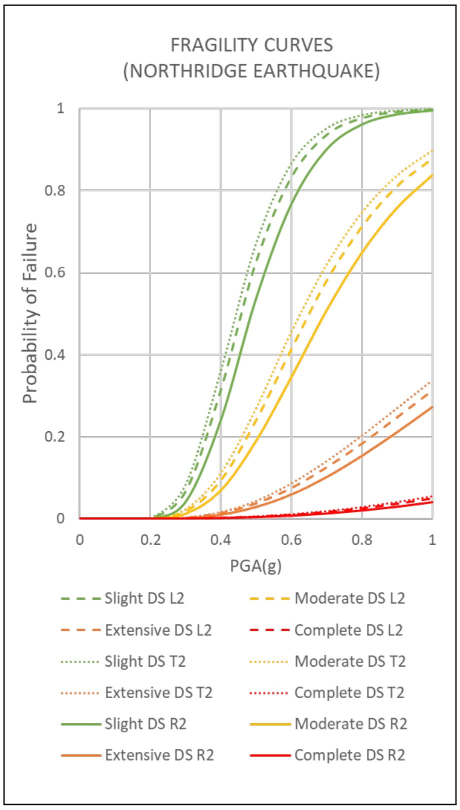

Figure 5: Fragility Fragility Curves for 2 storied models(Northridge Earthquake)

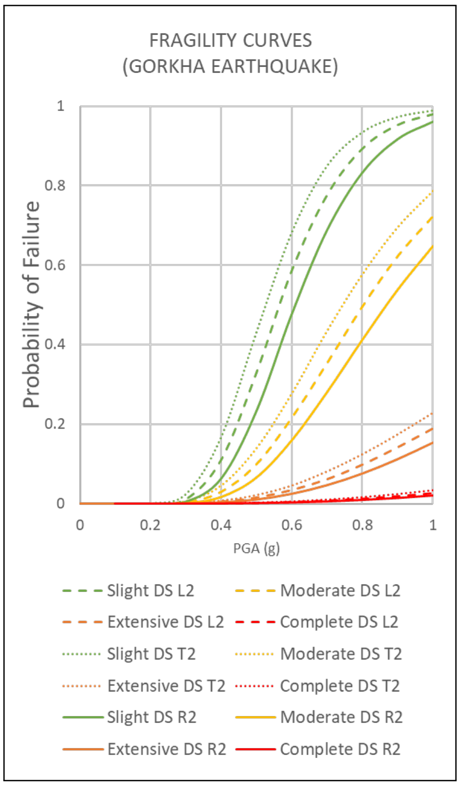

Figure 4: Fragility Curves for 2 storied models(Gorkha Earthquake)

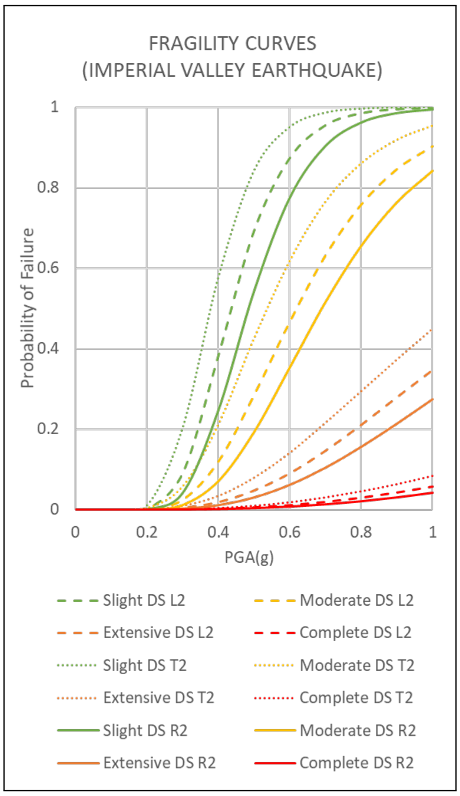

Figure 6: Fragility Curves for 2 storied models(Imperial Valley Earthquake)

For 3 Stories Building Configuration:

Gorkha Earthquake: The probability of failure of the regular model for PGA 0.5g is about 53%, 26%, 10% and 0.4% for slight, moderate, extensive and complete damage states respectively. The probability of failure of the L-shaped model for PGA 0.5g is about 62%, 32%, 12% and 0.6% for slight, moderate, extensive and complete damage states respectively. The probability of failure of the T-shaped model for PGA 0.5g is about 66%, 35%, 13% and 0.7% for slight, moderate, extensive and complete damage states respectively. It is observed for a given damage state, the probability of damage for both T-shaped building is about 1.2 to 1.7 times more than that for regular ones. whereas the probability of damage for L-shaped building is 1.1 to 1.4 times more than that for regular ones.

Imperial Valley Earthquake: The probability of failure of the regular model for PGA 0.5g is about 85.6%, 55%, 22% and 1.8% for slight, moderate, extensive and complete damage states respectively. The probability of failure of the L-shaped model for PGA 0.5g is about 90.6%, 63%, 26.3% and 2.6% for slight, moderate, extensive and complete damage states respectively. The probability of failure of the T-shaped model for PGA 0.5g is about 90.3%, 62.6%, 26% and 2.5% for slight, moderate, extensive and complete damage states respectively. It is observed for a given damage state, the probability of damage for both T-shaped and L-shaped building is about 1.1 to 1.4 times more than that for regular ones.

Northridge Earthquake: The probability of failure of the regular model for PGA 0.5g is about 78.6%, 46.6%, 18% and 1.2% for slight, moderate, extensive and complete damage states respectively. The probability of failure of the L-shaped model for PGA 0.5g is about 87.4%, 57.9%, 23.4% and 2% for slight, moderate, extensive and complete damage states respectively.The probability of failure of the T-shaped model for PGA 0.5g is about 88.4%, 59.4%, 24.2% and 2.2% for slight, moderate, extensive and complete damage states respectively. It is observed for a given damage state, the probability of damage for both T-shaped and L-shaped building is about 1.1 to 1.7 times more than that for regular ones.

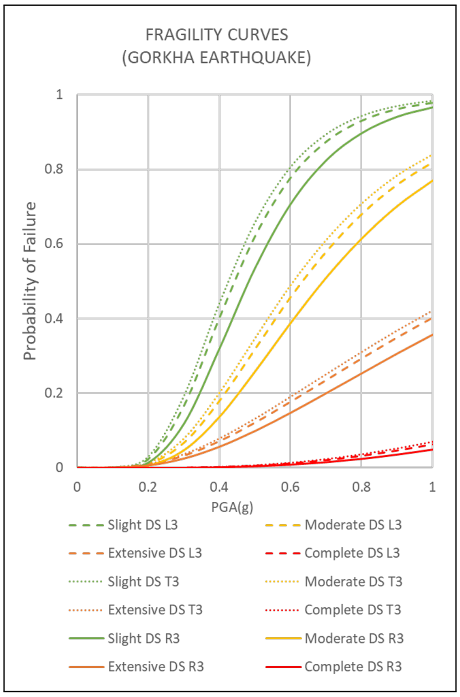

Figure 7: Fragility Curves for 3 storied models(Gorkha Earthquake)

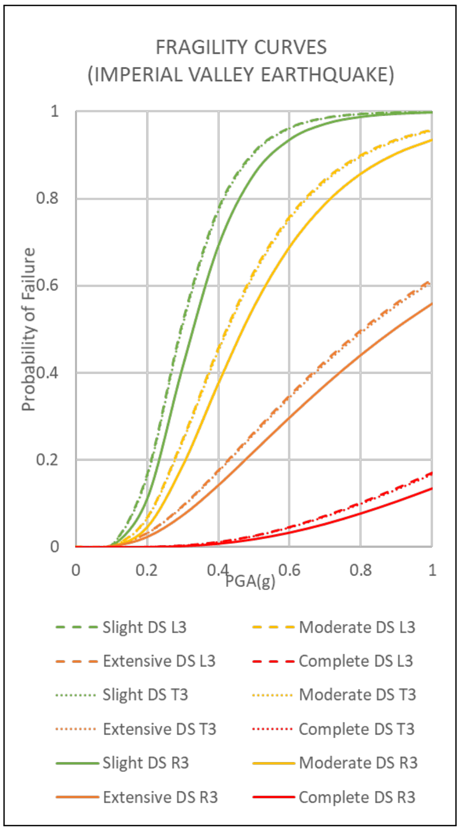

Figure 8: Fragility Curves for 3 storied models(Imperial Valley Earthquake)

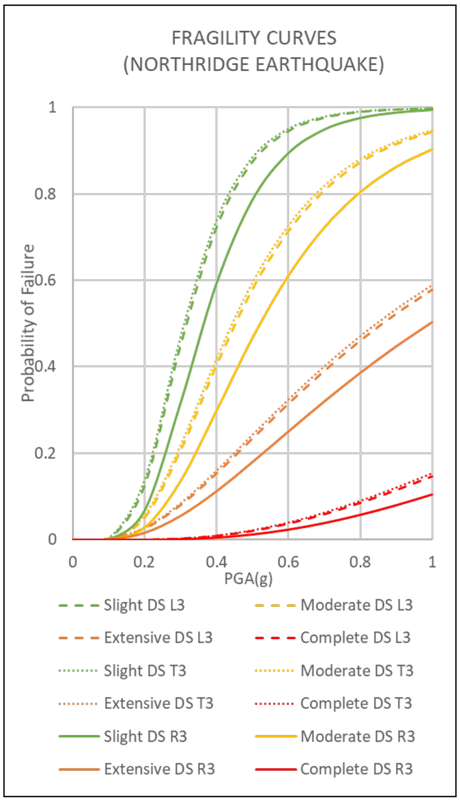

Figure 9: Fragility Curves for 3 storied models(Northridge Earthquake)

For 4 Stories Building Configuration:

Gorkha Earthquake: The probability of failure of the regular model for PGA 0.5g is about 98.6%, 85%, 43% and 7% for slight, moderate, extensive and complete damage states respectively. The probability of failure of the L-shaped model for PGA 0.5g is about 99.64%, 92.4%, 53.8% and 12.25% for slight, moderate, extensive and complete damage states respectively. The probability of failure of the T-shaped model for PGA 0.5g is about 99.64%, 92.5%, 54% and 12.3% for slight, moderate, extensive and complete damage states respectively. It is observed that the probability of damage for L-shaped and T-shaped building is almost within the same range as that of regular ones for slight and moderate damage state whereas 1.2 to 1.6 times more for extensive and complete damage state compared to that for regular ones.

Imperial Valley Earthquake: The probability of failure of the regular model for PGA 0.5g is about 99.96%, 99.22%, 77.4% and 32.3% for slight, moderate, extensive and complete damage states respectively.The probability of failure of the L-shaped model for PGA 0.5g is about 99.99%,99.64%, 99.64%, 82.58% and 39.7% for slight, moderate, extensive and complete damage states respectively.The probability of failure of the T-shaped model for PGA 0.5g is about 99.99%, 99.66%, 82.75% and 39.98% for slight, moderate, extensive and complete damage states respectively. It is observed that the probability of damage for L-shaped and T-shaped building is almost within the same range as that of regular ones for slight and moderate damage state whereas about 1.1 to 1.2 times more for extensive and complete damage state compared to that for regular ones.

From the fragility curves, high probability of slight to moderate damage of for 2 to 3 stories buildings were found whereas significant probability of damage even in extensive damage state was observed for 4 storied buildings.From this obsetvation, it is seen that the masonry buildings are comparatively safer up to 3 stories. Among all the models considered, four storied T-shaped building model was found to have lowest seismic performance.

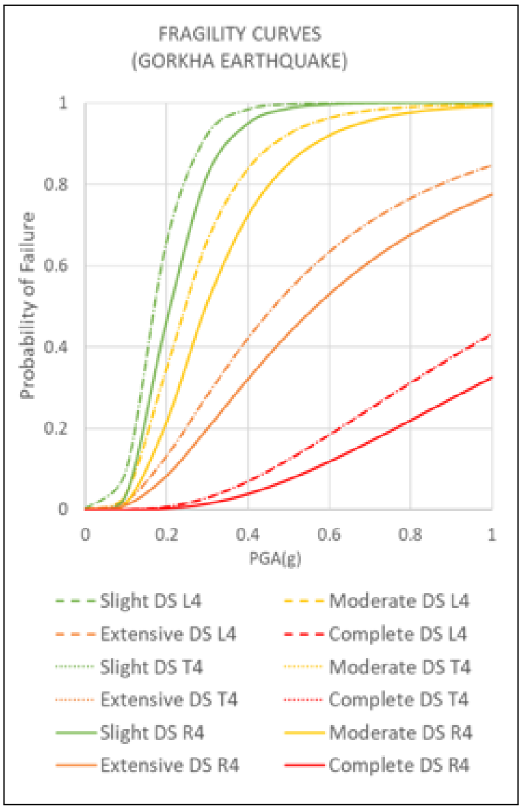

Figure 10: Fragility Curves for 4 storied models(Gorkha Earthquake)

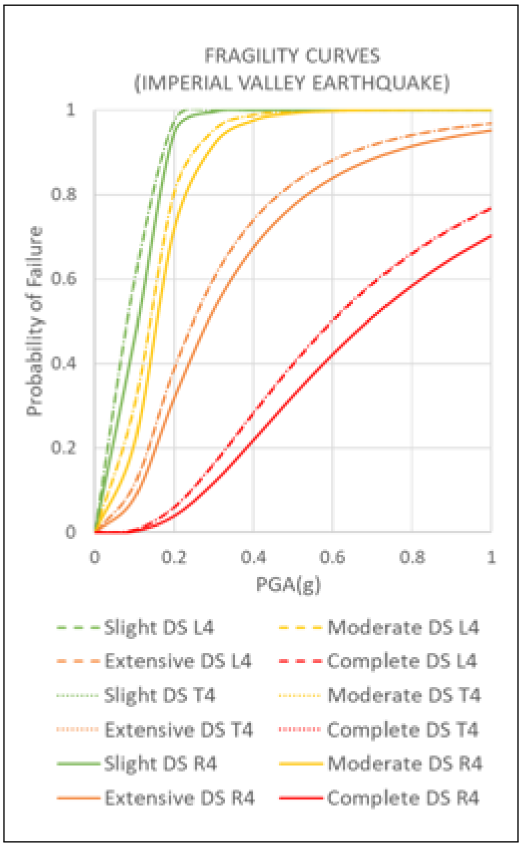

Figure 11: Fragility Curves for 4 storied models(Imperial Valley Earthquake)

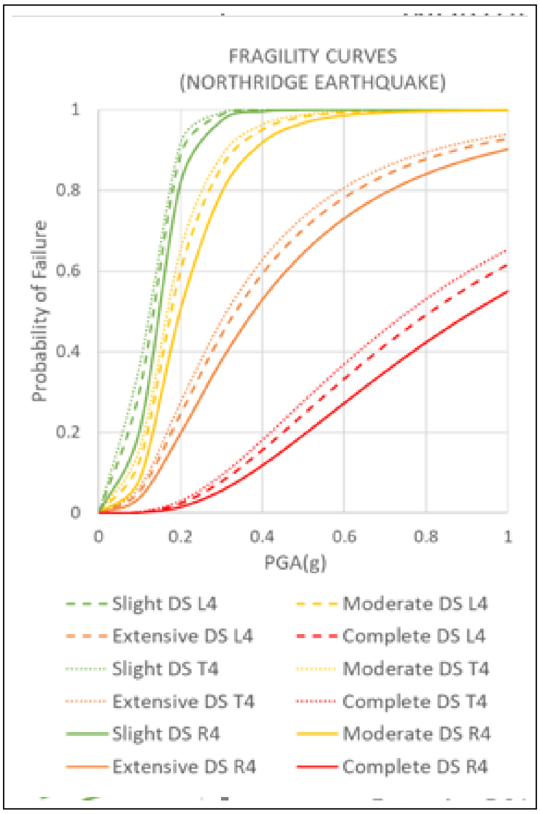

Figure 12: Fragility Curves for 4 storied models(Northridge Earthquake)

5. Conclusion

The following major conclusions are drawn from the study :

- Top displacement and story drifts are significantly lower in regular buildings whereas higher in T-shaped buildings.
- The base shear of T shaped building is more than that of L-shaped and regular square-shaped. The lowest base shear is obtained for L-shaped buildings. It is due to the higher inertial mass of T-shaped and lower inertial mass of L-shaped building. Although the base shear of L-shaped building is less than that of regular, the probability of failure is more for L-shaped buildings compared to Regular shaped.
- For same value of PGA and identical building models, the probability of damage for a given damage state is higher for Imperial Valley Earthquake whereas lower for Gorkha Earthquake. This is due to the difference in the characteristics (time period, frequency content, amplitude at various time interval, etc) of Gorkha earthquake, Imperial Valley earthquake and Northridge earthquake.
- The probability of failure of T-shaped building is higher than that of an L-shaped and regular building for equal PGA values of the same earthquake of and equal number of stories. This is a result of uneven building edges having higher stress concentrations.
- Also, the probability of failure of regular building is lower among the selected building model types. This shows that the seismic performance of regular buildings are better than irregular ones and T-shaped building is more vulnerable than the L-shaped and regular ones.

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