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Seismic Vulnerability and Earthquake Losses of RC Frame Buildings of Kathmandu City Core

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Abstract
Kathmandu city core, one of the densest settlement area of Nepal, has its own cultural, historic, religious as well as commercial significance and consists of various structures from masonry to RC frames. The structures in the Kathmandu city core are unique. Construction of large structures within the limited area has resulted in construction of many seismically deficient structures. The dense settlement and thick layer of underlying soft soil make structures within the Kathmandu city core more vulnerable to earthquake. This research thus deals with finding the seismic vulnerability of RC frame buildings within the city core in terms of fragility curves. This research also focuses on comparison of the losses estimated by various researchers adopting various methodology to the actual losses that occurred in RC frame buildings of Kathmandu city core due to the Gorkha earthquake of 2015.

Keywords
Vulnerability – Fragility curves – RC Buildings – Earthquake Loss

1. Introduction

Nepal happens to be the region of high seismicity and large earthquake can be expected in this area as it lies in the Himalayan region formed by subduction of Indo-Australian plate beneath the Eurasian plate which are at the state of continuous motion. Kathmandu valley on particular consists of thick layer of underlying soft soil resulting in amplification of seismic waves as it travels towards surface through these layers. The buildings in the Kathmandu city core are unique. Although a well designed and constructed RC frame buildings are less vulnerable, not all buildings are well designed and constructed. Construction of tall structures within the limited areas without proper design results in seismically deficient structures. So, there is need of assessment of vulnerability of the RC buildings.

The various methods for vulnerability assessment that have been proposed in the past for use in loss estimation can be divided into two main categories: empirical or analytical, both of which can be used in hybrid methods [1]. Lang provided various method for vulnerability analysis such as observed vulnerability, vulnerability based on expert opinions, simple analytical models, score assignment and detailed analysis procedures based on upon the objective of the assessment, expenditure, precision and availability of data and technology [2]. Vulnerability of the buildings has been assessed by developing the fragility curves based on detailed analysis has been done. Fragility function provides the probability of exceeding a prescribed level of damage for a wide range of ground motion intensity.

Attempts of earthquake loss estimation of Kathmandu had been done in past by few researchers. Earthquake loss estimation of Kathmandu city core done by Norwegian Researchers Ketil Asklien, Ole-Bjorn Bakke and Bodil Nohre as part of their thesis work back in 1993 [3]. The loss estimation was done in term of three factors namely Physical loss, Economic loss and Human casualties. The above-mentioned loss estimation was done for three different earthquake scenarios Disaster preparedness earthquake scenario (DPE) having PGA 0.167g and Average return period of 100 years, Moderate scale earthquake Scenario (MSE) having PGA 0.227g and Average return period of 200 years and Large-Scale Earthquake (LSE) Scenario having PGA of 0.32g and Average return period of 500 years. For the physical losses estimation, the degree of damage of the structure was divided into three Damage/Usability-Categories as:

1. D/U-C I: Slight nonstructural damage, very isolated or negligible structural damage.
2. D/U-C II: Extensive nonstructural damage, considerable structural damage but yet repairable structural system
3. D/U-C III: Destroyed, partially or totally collapsed structural system

"The Study on Earthquake Disaster Mitigation in The Kathmandu Valley, Kingdom of Nepal" was done by JICA in 2002 [4]. In the study three new fault models were selected, and the destructive force of each was calculated as follows, based on the natural and social conditions:

1. Mid Nepal Earthquake (Richter magnitude = 8.0); MMI VIII (Modified Mercalli Intensity)
2. North Bagmati Earthquake (magnitude = 6.0); MMI VI or VII.
3. KV Local Earthquake (magnitude = 5.7); Most parts MMI VII or VIII, as high as IX along the fault line.

2. Study area and data collection

The area of study of this research work includes part of ward 16, ward 17, ward 18, ward 20 and ward 29 and whole of the ward 19, ward 22, ward 23, ward 24, ward 25, ward 26, ward 27, ward 28 and ward 30 of Kathmandu metropolitan city.

The damage data and casualties data collected by Central Bureau of Statistics(CBS) after the earthquake under Housing registration for Housing Reconstruction(HRHR) program was obtained from CBS. The data as provided by CBS consisted of the micro data of all buildings damaged by earthquake of all the earthquake affected 31 districts. Thus, the data provided by CBS was filtered so as to obtained the damaged data and casualties data in each ward lying within the Kathmandu core city. The data was further filtered to obtain the damage data regarding RC frame buildings.

Based on the number of buildings and population within each ward as per the census 2001 and 2011, number of buildings and population during 2015 for each ward were estimated and using the ward profiles which consists of data regarding type of buildings and their percentage in each ward, the number of buildings of various type during 2015 i.e. before the earthquake were estimated.

3. Typical buildings

Through the survey of the different wards of the Kathmandu city cores, it was seen that buildings having different stories and different configurations were present within the city core. Based on the assumptions that buildings having different configuration exhibit different level of vulnerability, the surveyed buildings were classified into different categories. From each category, a building best representing the category was selected. Thus, five typical representative buildings present within the Kathmandu city core having different configurations within the Kathmandu city core are considered. The building B1 is building having two or more bays in each direction but having plan irregularity of re-entrant corner, the building B2 is building having single bay in one direction and two bays in other, building B3 is building having single bay in one direction and more than 2 bays in other, building B4 is building having single bay in both the directions and building B5 is building having two or more bays in both direction and having regular geometry.

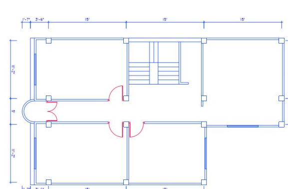


Figure 1: Typical floor plan of buiding B1

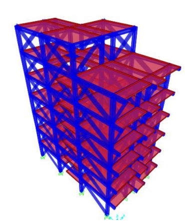


Figure 2: 3D model of building B1 in SAP2000

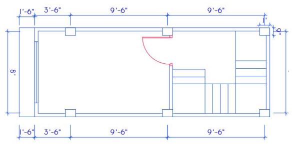


Figure 3: Typical floor plan of buiding B2

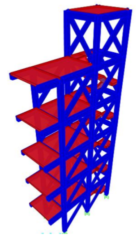


Figure 4: 3D model of building B2 in SAP2000

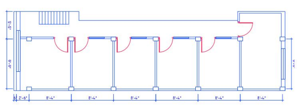


Figure 5: Typical floor plan of buiding B3

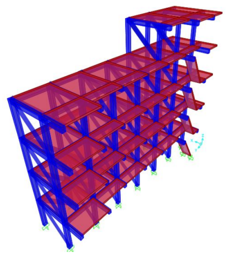


Figure 6: 3D model of building B3 in SAP2000

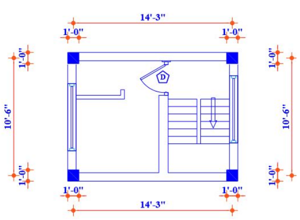


Figure 7: Typical floor plan of buiding B4

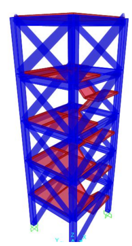


Figure 8: 3D model of building B4 in SAP2000

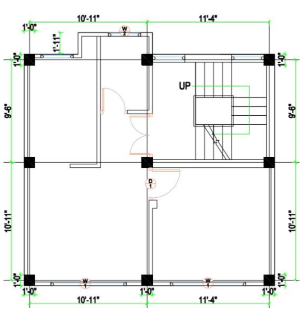


Figure 9: Typical floor plan of buiding B5

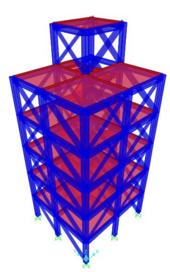


Figure 10: 3D model of building B5 in SAP2000

4. Analysis

The buildings are modeled using SAP 2000. Pushover analyses are performed to determine the capacity of the buildings. The demands are then determined by performing linear time history analysis for five different earthquakes inputs: Chamoli, El Centro, Gorkha, Kobe and Lalitpura. Seismic vulnerability of structure is determined by drawing fragility curves. In this study, fragility curves are constructed to correlate the cumulative probability of failure(Pf), with increasing value of demand displacement (Sd) based on obtaining the best fitted log-normal distribution function of equation which is defined by the median and standard deviation parameters i.e Sc and β respectively.

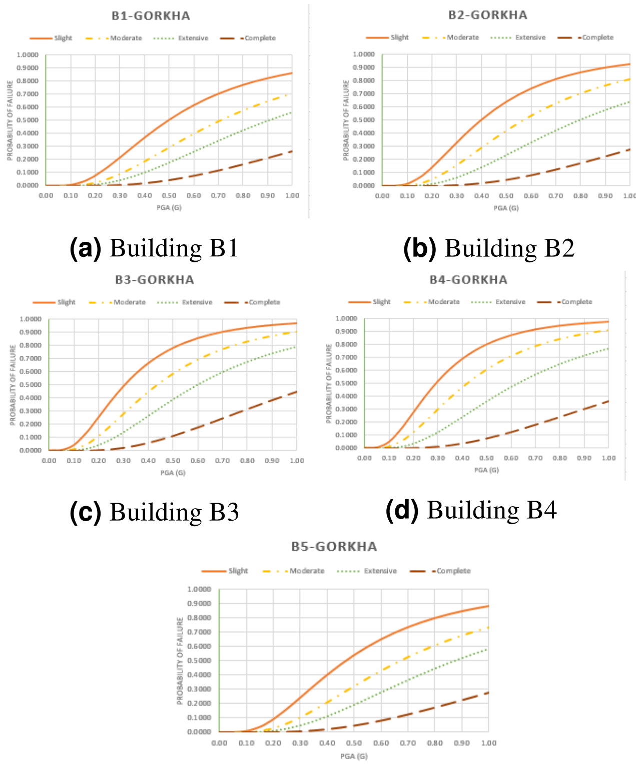
$$P(f) = \phi[\{In(Sd/Sc)\}/\beta]$$

where, $\phi()$ is cumulative log normal distribution function β is log standard deviation that represents total uncertainty. Four damage states namely Slight, Moderate, Extensive and Complete are recommended for analysis. It is further assumed that the total variability of each equivalent - PGA structural damage state, βSPGA, is modeled by the combination of the two contributors to damage variability: uncertainty in the damage-state βM(SPGA) = 0.4 and variability in response βD(V) = 0.5. The two contributors to damage state variability are assumed to be log-normally distributed, independent random variables and the total variability is simply the square root of the sum of the squares combination of individual variability terms βSPGA =0.64 for all damage states (Slight, Moderate, Extensive and Complete damage). The capacity of the reinforced concrete moment resisting frames according to damage state is given as below in terms of yield displacement (dy) and Ulitmate displacement (du) [5]:

1) Slight damage , capacity = 0.7dy
2) Moderate Damage, capacity = dy
3) Extensive Damage, capacity= dy + 0.25 (du - dy)
4) Complete Damage, capacity = du

where, ‘dy’ is yield displacement and ‘du’ is ultimate displacement.

5. Results



(a) Building B1 **(b)** Building B2

(c) Building B3 **(d)** Building B4

(e) Building B5

Figure 11: Fragility curves for building B1, B2, B3, B4 and B5 for Gorkha earthquake input

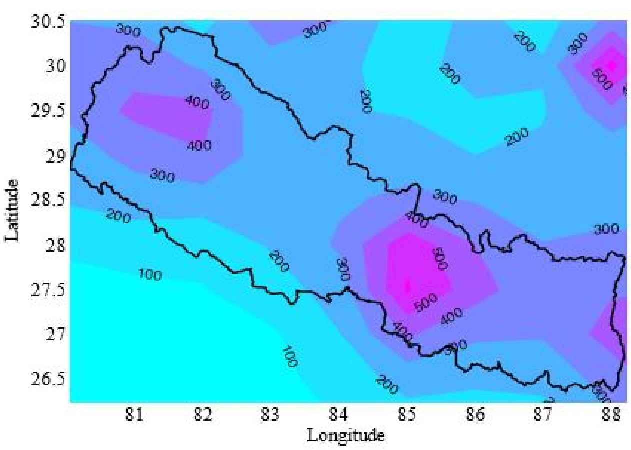


Figure 12: PGA for 10 percent probability of excedence in 50 years

As per the probabilistic seismic hazard assessment for Nepal, the PGA for 10% probability of exceedance in 50 years i.e. of earthquake having return period of 475 years for Kathmandu is approximately 0.55g [6].

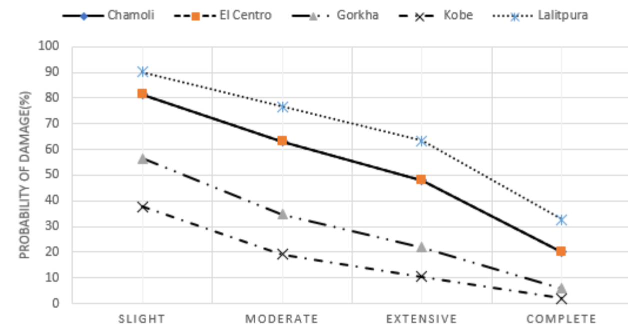


Figure 13: Probability of damage for different damage grades of building B1 for different earthquake inputs at PGA=0.55g

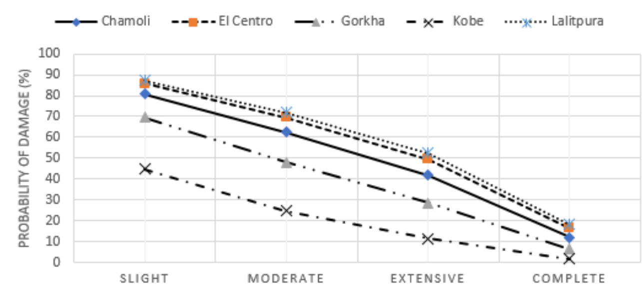


Figure 14: Probability of damage for different damage grades of building B2 for different earthquake inputs at PGA=0.55g

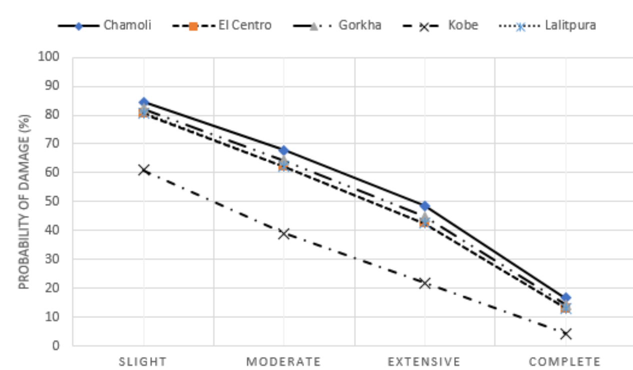


Figure 15: Probability of damage for different damage grades of building B3 for different earthquake inputs at PGA=0.55g

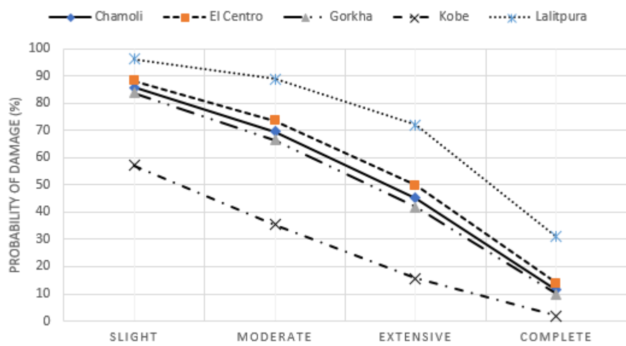


Figure 16: Probability of damage for different damage grades of building B4 for different earthquake inputs at PGA=0.55g

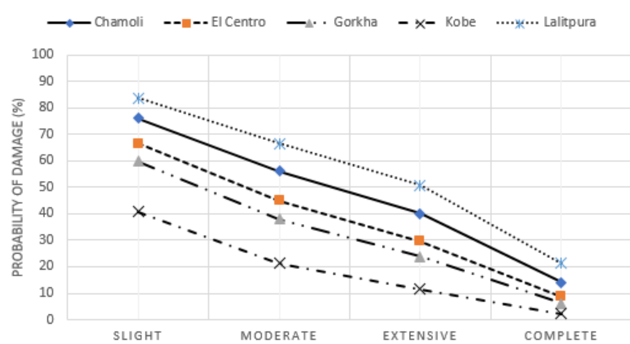


Figure 17: Probability of damage for different damage grades of building B5 for different earthquake inputs at PGA=0.55g

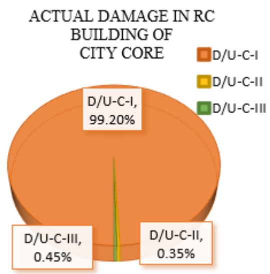
If we look at the vulnerability of the building for 50% probability of damage, different earthquakes results in different level of vulnerability. From the above figures it can be seen that Buildings types B3 and B4 have higher vulnerability than buildings B1 and B5 for Gorkha and Kobe earthquake inputs. For Chamoli earthquake input all the buildings are found to have almost similar level of vulnerability. For El Centro earthquake input buildings B2 and B4 are found to have more vulnerability than buildings B1 and B3 and building B5 has least vulnerability. For Lalitpura earthquake building B4 is found to be the most vulnerable.

Damage states	Probability of damages of Buildings (%)				
	B1	B2	B3	B4	B5
Slight	5.40	10.32	19.81	21.58	6.41
Moderate	1.52	3.43	7.99	8.95	1.88
Extensive	0.54	0.96	2.86	2.40	0.64
Complete	0.04	0.05	0.23	0.11	0.05

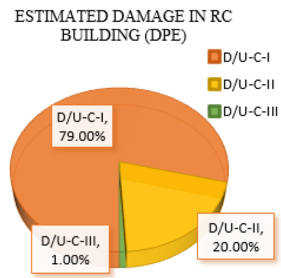
Figure 18: Probability of damage for different damage states for the Gorkha earthquake input for PGA of 0.17g

The damages in buildings as in the Norwegian research work were categorized into three damage usability categories. The damage usability category I (D/U-C-I) consists of buildings having negligible to slight damage. Damage usability category II (D/U-CII) consisted of buildings having moderate to extensive damage. And damage usability category III (D/U-C-III) consisted of buildings having extensive to complete damage. For the Gorkha earthquake input for PGA of 0.17g, it can be noted that the estimated percentages of building having D/U-C-III is 0.54%, 0.96%, 2.86%, 2.40% and 0.64% for buildings B1, B2, B3, B4 and B5 respectively. Similarly, the estimated percentages of building having D/U-C-II is 0.98%, 2.47%, 5.13%, 6.55% and 1.24% for buildings B1, B2, B3, B4 and B5 respectively. From the field survey of the buildings done it is found that approximate percentages of building type B1, B2, B3, B4 and B5 are 20%, 33%, 17%, 10% and 20% respectively.The estimated percentage of RC buildings falling under D/U-C-III and D-U-C-II based on fragility curve for gorkha earthquake for PGA 0.17g are 1.28% and 2.79% respectively.

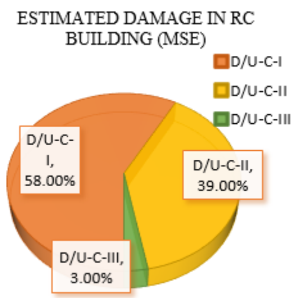
As per the research work of students of NTNU, for the disaster preparedness earthquake scenario, the percentages of RC frame buildings falling under damage usability category I, II and III were estimated to be 79%, 20% and 1% respectively. For the moderate scale earthquake scenario, the percentages of RC frame buildings falling under damage usability category I, II and III were estimated to be 58%, 39% and 3% respectively. For the large-scale earthquake scenario, the percentages of RC frame buildings falling under damage usability category I, II and III were estimated to be 30%, 13% and 30% respectively.



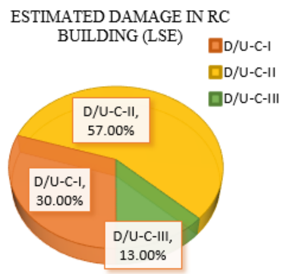
(a) Actaul damage in RC buildings due to Gorkha Earthquake



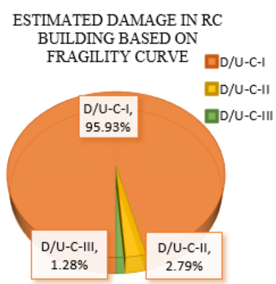
(b) Estimated Damage in RC buildings for DPE scenario



(c) Estimated Damage in RC buildings for MSE scenario

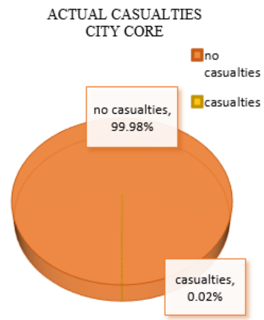


(d) Estimated Damage in RC buildings for LSE scenario

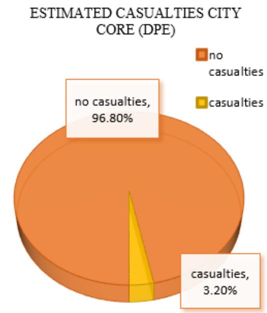


(e) Estimated Damage in RC buildings based on fragility curves for gorkha earthquake at 0.17g PGA

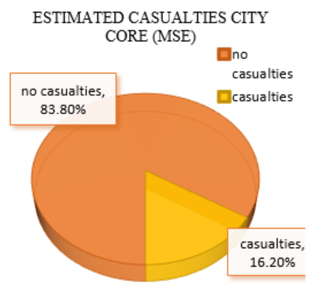
Figure 19: Damages in the buildings



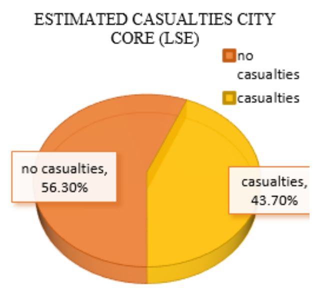
(a) Actual casualties due to Gorkha Earthquake



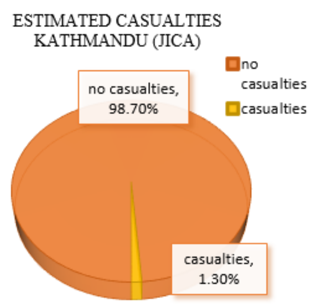
(b) Estimated casualties for DPE scenario



(c) Estimated casualties for MSE scenario



(d) Estimated casualties for LSE scenario



(e) Estimated casualties by JICA for Mid Nepal Earthquake scenario

Figure 20: Casualties observed and estimated

Actual percentages of building falling under damage usability category II and III are 0.35% and 0.45% respectively for Kathmandu city core. Which was very less as compared to that estimated for all the earthquake scenarios even for the DPE earthquake scenario whose PGA was near to that of Gorkha earthquake. Similarly, the percentage of heavily damaged building was estimated to be 21% of the total buildings by JICA. The percentages of heavily damaged buildings is estimated to be 4.08% using the fragility curve for gorkha earthquake at PGA 0.17g.

Casualties were estimated to be around 3.2%, 16.2% and 43.7% of the total population by the Norwegian researchers for DPE, MSE and LSE Scenarios respectively. Similarly, from the JICA study for mid Nepal Earthquake scenario the casualties were estimated to be 1.3% of the population for Kathmandu. The actual casualties were found to be 0.02% of the total population which was very less as compared to that estimated by Norwegian researchers even for DPE scenario. The actual casualties was less than the estimated casualties by 3.18%, 16.18% and 43.68% for

DPE, MSE and LSE scenarios. Casualty was less than that estimated by JICA in 2002 for mid Nepal earthquake by 1.28%.

6. Conclusions

1) Building B4 (building having high height to width ratio) is the most vulnerable building. Moreover, building B4 is also building having single bay on both longitudinal and lateral direction. Buildings having high height to width ratio are more vulnerable.
2) Buildings B2 and B3 also had high vulnerability. Both the buildings had single bay on one direction. So, building having single bay on one or both the directions are more vulnerable.
3) Building B1 had more than 1 bay in both the directions. But it had higher vulnerability than B5. This may be due to plan irregularity (re-entrant corner) in building B1.
4) Buildings B5 is the least vulnerable than other for each earthquake input. So, the buildings having regular geometry, lower height to width ratio and at least two bays in each direction are least vulnerable.
5) Actual losses data as observed after the Gorkha earthquake was found very less than the estimated losses by Norwegian researchers as well as JICA.
6) The analytical damage in RC frame buildings calculated using fragility curves developed using Gorkha earthquake input was also greater than the actual damage but the difference from the actual loss was less than that as compared to that estimated by the Norwegian researchers and JICA.

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