Proceedings of 10th IOE Graduate Conference
Peer Reviewed
ISSN: 2350-8914 (Online), 2350-8906 (Print)
Year: 2021 Month: October Volume: 10

Incremental Dynamic Analysis of RC Framed Structures Under Mainshock-Aftershock Sequencess

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Abstract
Earthquakes are major unpredictable natural phenomenon which often results in major disasters. In any real earthquake, shaking occurs in sequence of foreshocks, main shock and aftershocks.These repeated earthquakes may occur several times with in even few hours or minutes leaving very limited time between occurance of tremors. This may hamper the reoccupancy and restoration activities of structures in post disastral situations.When structrues are subjected to repeated earthquakes,structural damages gets further accumulated which results in degredation in stiffness and strength characteristics of structural members.Therefore, it is important to evaluate the responses of reinforced concrete (RC) buildings under repeated earthquakes to prevent possible damages. This study is mainly focused on fragility assessment of RC framed structure designed according to the Nepal National Building codes of practice under single and repeated ground motions. Incremental dynamic analysis is performed using SAP2000. Results obtained in this study are evaluated in terms of residual displacement, maximum inter-story drift ratio for particular peak ground acceleration. The study concluded that repeated earthquakes have significant effects on seismic responses and seismic vulnerability of structures.

Keywords
Repeated earthquake, Incremental dynamic analysis (IDA), Collapse capacity, Residual Displacement

1. Introduction

Earthquakes are major unavoidable and unpredictable natural phenomenon which often results in major disasters. In any real earthquake, shaking occurs in sequence and these are randomly oriented [1]. These repeated earthquakes may occur several times with in even few hours or minutes leaving very limited time between occurance of tremors.This may hamper the reoccupancy and restoration activities of structures in post disastral situations.When structrues are subjected to repeated earthquakes,structural damages get further accumulated which results in degredation in stiffness and strength characteristics of structural members [2]. Nepal being situated in diffuse collisional boundary of two tectonic plates- (Indo-Australian plate and Eurasian plate) where Indian plate under thrusts Eurasian plate has experienced many powerful destructive historic earthquakes with moment magnitude greater than or equal to 7.6 since 1255 which lead to serious loss of lives and sizeable economic loss.

Kathmandu Valley and adjoining areas are designated as a severe zone with seismic zoning factor of 0.35 and categorized to soil type 'D' which is very soft soil sites (According to NBC 105:2020 [3]). Looking back, this region has been widely damaged during different historic earthquakes like 1408 earthquake Bagamati Zone (Mw=8), 1767 earthquake- Northern Bagamati zone (Mw=7.9), 1833 Kathmandu- Bihar earthquake (Mw=8), 1988 Kathmandu -Bihar earthquake (Mw=6.9). Recently in 2015, an earthquake named Gorkha earthquake with moment magnitude 7.8 struck near by Kathmandu city in central Nepal which devastated rural villages around the region and some of mostly densely populated parts of Kathmandu city. Two large main shocks with magnitude 6.6 and 6.7 shook the region within one day and next day of main shock with several dozen of smaller aftershocks during succeeding days which further added no of death count and damaged large no of structures.Constructing the new structure and rehabilitating existing building with better code provisions can considerably reduce the possible

damages. However, the existing codal provision of seismic desing is using single design earthquake in form of response spectrum or using single sever ground motion for time history analysis of structure.But considering only single seismic force is not adequate to evaluate the dynamic responses of structures under repeated seismic forces.Also, after getting hit by major earthquake, when structure is subjected to aftershocks, aftershocks can threaten the life safety of structure even if only minor damge is present from major shock. So, it is very crucial to study the effects of sequential ground motions on the non-linear behavior of structure.

2. Structural models

The building configuration present in chosen locality i.e Kathmandu zone, Nepal is mostly low rise and midrise configuration. Construction of high rise structures for apartments and hotels is also rapidly increasing. But for this study, regular ordinary moment resisting RC framed buildings representing building categories (Low rise-4 stories, midrise-7 stories) have been considered. This area falls under severe seismic zone with seismic zone factor of 0.35 and very soft soil profile as per NBC: 105(2020). Any types of irregularities like vertical setbacks, variation in number of bays and bay length are not considered for simplicity. The type of building considered in this study is of regular type having three bays of 5m length each in both horizontal directions and particular storey height is 3.2m. Diaphragms are supposed to be rigid and the details of beam and columns are clearly shown in Table:1. The 3D modeling and analysis of structure is done by using Finite element analysis software SAP2000 v21.2.Non-linearity of beams and columns were modeled by generating plastic hinges at their ends using default hinges.

Table 1: Structural Member Details

Member	Building Type	Storey	Width (mm)	Depth (mm)
Beam	Low Rise and Midrise	1st	250	450
		Between 1st and last	250	400
		Last	250	350
Column	Low Rise	All	450	450
	Mid Rise	All	508	508

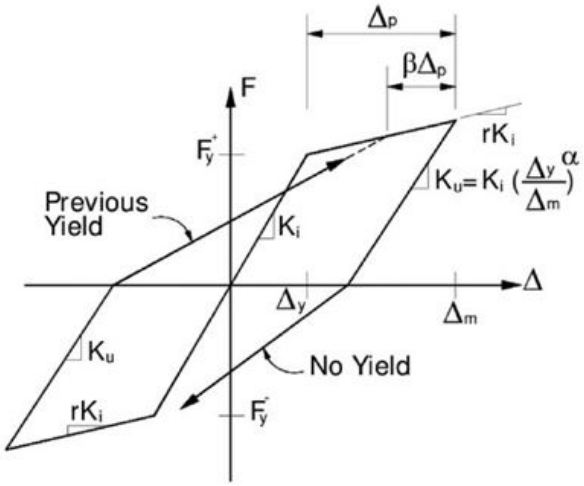


Figure 1: Takeda hysteresis model

The Takeda hysteresis model is used to define the degradation caused by cyclic loading , as shown in Fig.1. The concrete grade used is M25 with an elastic modulus equal to 25000 MPa. The concrete weight per unit volume is assumed to be 25,000 N/mm2 with poisson's ratio of 0.2. Reinforcement grade HYSD415 TMT with elastic modulus of 200000 MPa is used in the design process. Its unit weight is taken to be 76900 N/m2 and poisson's ratio is fixed to be 0.3. Infill walls are not modeled for simplicity and only their weights are considered for analysis. The weight of infill wall of size 230 mm is applied as uniformly distributed load on beams. The dead load (inclusive of floor finish) of 3.75 kN/m2 and the live load of 3 kN/m2 is applied on slab. The effective moment of inertia (Ieff) of the sections was adopted as per the recommendations of NBC 105:2020 for beams Ieff = 0.35Igross and for columns Ieff =0.70Igross, where Igross is the gross moment of inertia.The base conditions of structure are supposed to be fixed.

3. Input Ground Motion

Considering adequate number of ground motion data is very crucial to perfrom non-linear dynamic analysis. According to NBC 105:2020 , If less than 7 numbers of ground motion records are used, maximum values the response quantities from these ground motions shall be used. If the number of ground motions used is more than 7, then average values of the considered number of ground motions shall be used for evaluation of response quantities. So, the seven ground motion data are selected form the Pacific Earthquake Engineering Research (PEER) Center

strong ground motion data base and Consortium of Organization for Strong-Motion Observation System (COSMOS) database and are presented in Table:2. The selected ground motion records were scaled with appropriate scale factors to the target response spectrum, i.e., Kathmandu Zone(Zone factor Z=0.35 and very soft soil) elastic design spectrum of NBC 105:2020 using the SeismoMatch software.

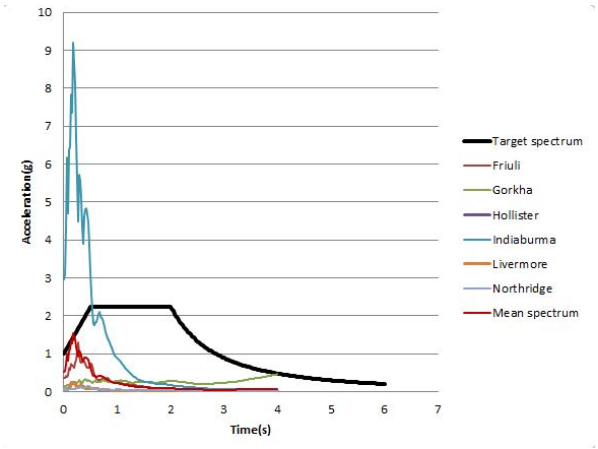


Figure 2: Unmatched response spectrum of ground motion data

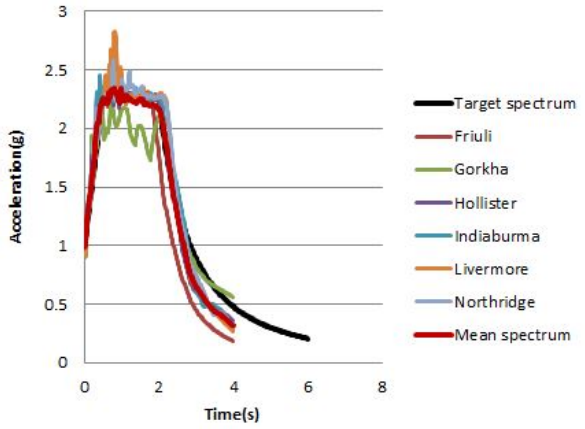
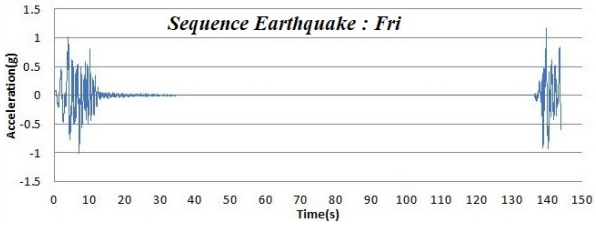
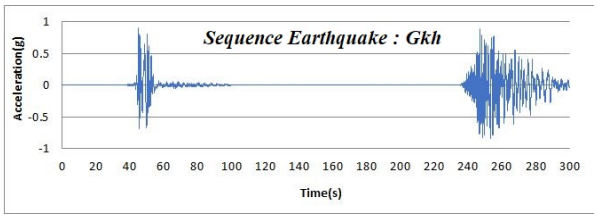
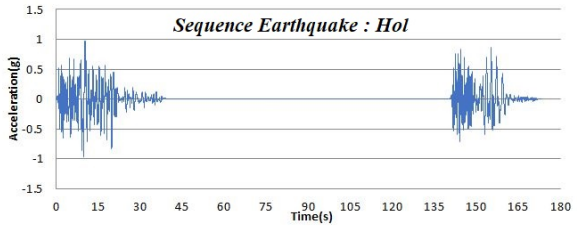
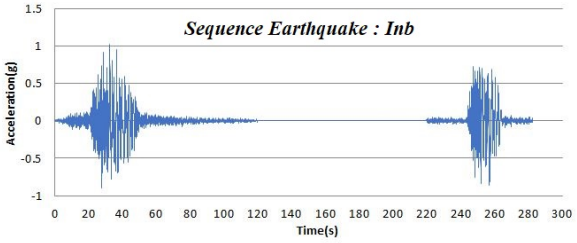


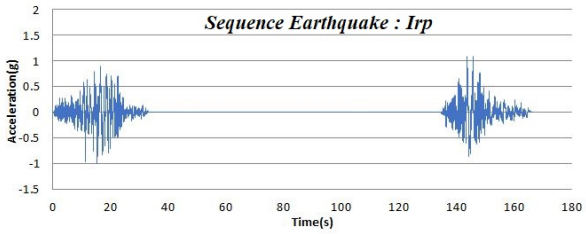
Figure 3: Matched response spectrum of ground motion data

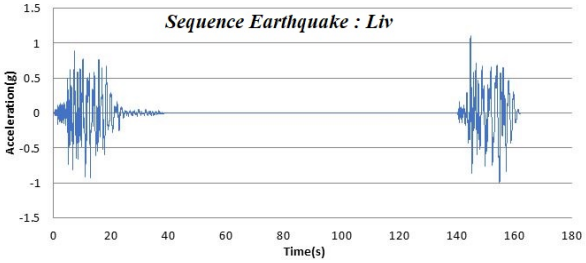












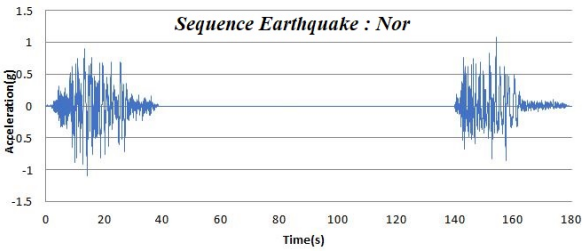


Figure 4: Combined Sequence earthquakes of different earthquake ground motions

Table 2: List of Earthquake Ground Motion Data

SN	Earthquake	Station	Date	Magnitude	Source	Denotation
1	Irpinia Italy	Auletta	11/23/1980	6.90	PEER	Irp-1
	Irpinia Italy	Auletta	11/23/1980	6.20	PEER	Irp-2
2	Northridge	Anaverde valley	01/17/1994	6.69	PEER	Nor-1
	Northridge	Anaverde valley	01/17/1994	6.05	PEER	Nor-2
3	Gorkha	KATNP	25/04/2015	7.80	COSMOS	Gkh-1
	Gorkha	KATNP	12/05/2015	7.30	COSMOS	Gkh-2
4	India-Burma border	Berlongfer	08-06-1988	7.20	COSMOS	Inb-1
	India-Burma border	Berlongfer	01-09-1990	6.10	COSMOS	Inb-2
5	Friuli	Tolmezzo	05-06-1976	6.50	PEER	Fri-1
	Friuli	Tolmezzo	05-07-1976	5.20	PEER	Fri-2
6	Hollister	Hollister city hall	04-09-1961	5.60	PEER	Hol-1
	Hollister	Hollister city hall	04-09-1961	5.50	PEER	Hol-2
7	Livermore	APEEL 3E Hayward CSUH	01-24-1980	5.80	PEER	Liv-1
	Livermore	APEEL 3E Hayward CSUH	01-27-1980	5.42	PEER	Liv-2

Fig.2 and Fig.3 shows the unmatched and matched response spectrum of selected ground motion data. Accelerograms in only one orthogonal direction is applied to the RC frame building. Further, matched main-shock and aftershock ground motions are combined by keeping a time interval of 100 seconds to create the combined earthquake. This gap of 100s has zero acceleration ordinates and it is assumed that this gap is enough to cease the moving of any structure due to damping as stated in Liolios, 2010 and Hatzigeorgiou et al [4]. The accelerograms of seven sequential earthquakes generated (i.e. Irp, Nor, Gkh, Hol, Inb , Fri, Liv) from their corresponding single accelerograms (Irp1 and Irp2, Nor1 and Nor2, Gkh1 and Gkh2, Hol1 and Hol2, Inb1 and Inb2, Fri1 and Fri2, Liv1 and Liv2) are shown from fig.4.

4. Non-linear dynamic analysis

IDA is one of the emerging tools of Performance-based earthquake engineering framework to evaluate the seismic demand and seismic performances of structures [5].In order to carry out IDA, multiple non-linear dynamic analyses of structural model are performed under multiple ground motion records scaled to various levels of seismic intensity. Results of IDA analysis is presented in form of IDA curves which are the plot of Intensity Measures (IM) verses Engineering Demand Parameters (EDP) of structure.For this study,Peak Ground Acceleration (PGA) is taken as Intensity Measure (IM) and the inter-story drift ratio (IDR) is chosen as the Engineering Demand Parameter(EDP).A nonlinear gravity case is defined as the initial case which includes the total dead load plus 30 percent load. For time integration method, Newmark-beta method is used and for considering geometric non-linearity effects in the models, P-delata effects are also taken into account.Then,IDA is contineously performed until IDR is monitored as a 3% threshold which is designated as the collapse state of the structure, as recommended by Xue et.al [6].

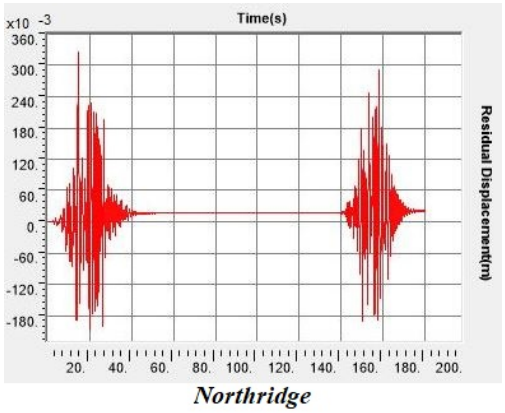
5. Seismic behavior of structures

IDA has been performed on the both type of building models under single and combined earthquakes (Table:2). Total 203 simulations of non-linear dynamic analysis are performed for this study and the seismic behavior of the building is monitored and expressed in terms of following parameters:

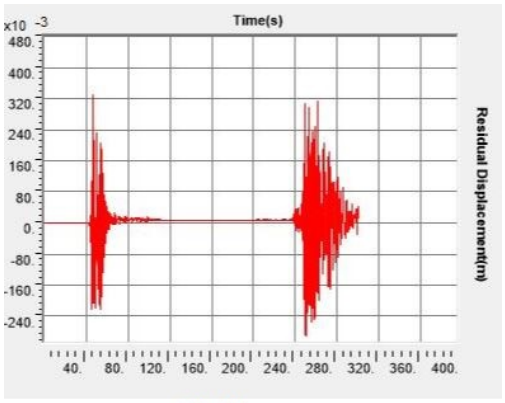
5.1 Residual Displacement

Residual displacement is permanent drifts recorded at the end of the seismic event. These are the permanent

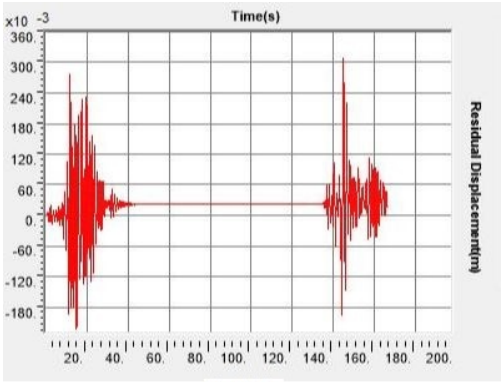
damage manifested in the structure after geting hit by main shock as the structure remains in the plastic state [7]. And when the strucure is exposed to subsequent repeated quakes, these damages increases significantly .Plot of residual displacement for seismic sequence events (Nor, Gkh,



Northridge



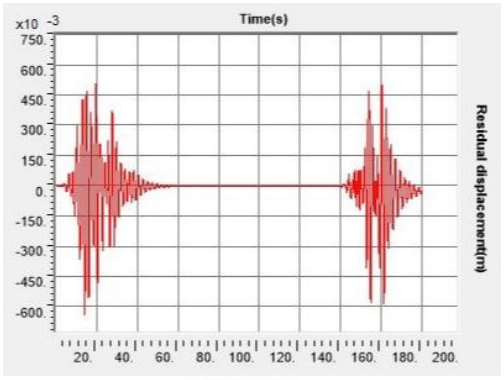
Gorkha



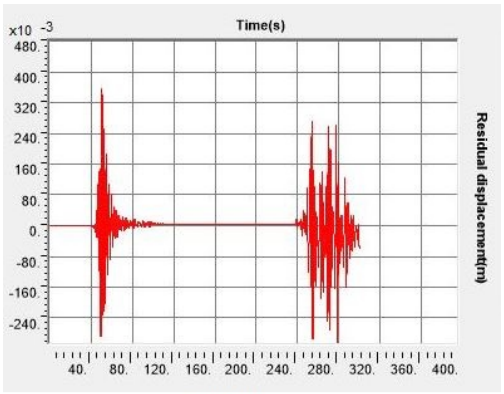
Irpinia

Figure 5: Residual displacement under repeated earthquake for low rise structure

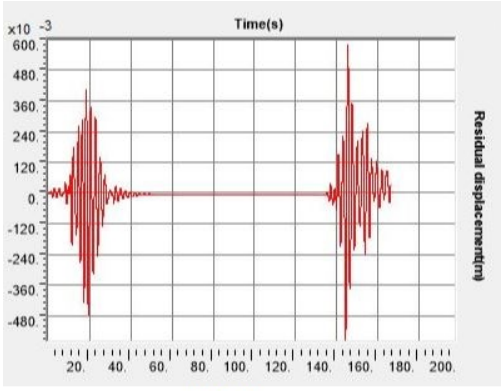
Irp) are presented in Fig.5 and Fig.6. As seen in figures, residual displacement after first earthquake is further accumulated and increased when structure is continuously hit by aftershocks. This means that vulnerability of structure increases significantly due to seismic sequences. So there is need to consider main shock – after shock sequences to assess seismicity vulnerability of structures during seismic events.



Northridge



Gorkha



Irpinia

Figure 6: Residual displacement under repeated earthquake for mid rise structure

5.2 Inter-storey Drift Ratio (IDR)

As Inter-storey Drift Ratio (IDR) is used as Engineering Demand Parameter (EDP), it is used to

develop dynamic capacity curves and fragility curves. The IDA curves developed in this study are the outcome of 203 simulations of non-linear time history analysis performed on two different types of buildings. These curves are plotted between PGA and IDR as shown in Fig: 7 and Fig: 10. After getting mean IDA curve which are shown in Fig. 11 and 12, Performance levels are defined based on performance based seismic design. Performance levels of buildings such as operational phase (OP), immediate occupancy(IO), damage control (DC), life safety (LS), and collapse prevention (CP) were studied from FEMA 356 [8] . From the research done by Xue et.al [6] the IDR values corresponding to the performance levels are obtained and shown in table: 3.These graphs clearly signifies that building meets collapse prevention limit state (3% IDR in our study) at lower PGA value under repeated earthquake force compared to that of individual earthquake. Thus the performance of the buildings seem to be better when analysis is done considering only main shock earthquakes, but due to the occurrence of sequential shocks, the performance of the same building is poor.

Table 3: Performance Limits

RCC structure	CP	LS	DC	IO	OP
IDR limit	0.025	0.02	0.015	0.01	0.005

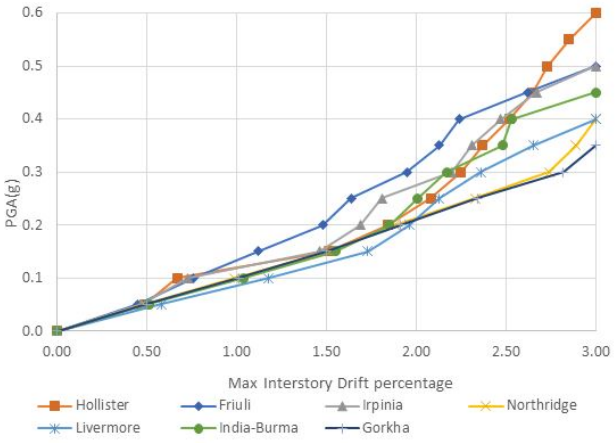


Figure 7: IDA curve under single earthquake for low rise structure

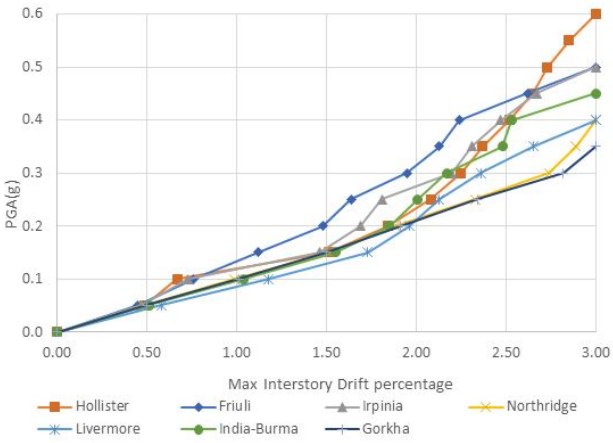


Figure 8: IDA curve under single earthquake for mid rise structure

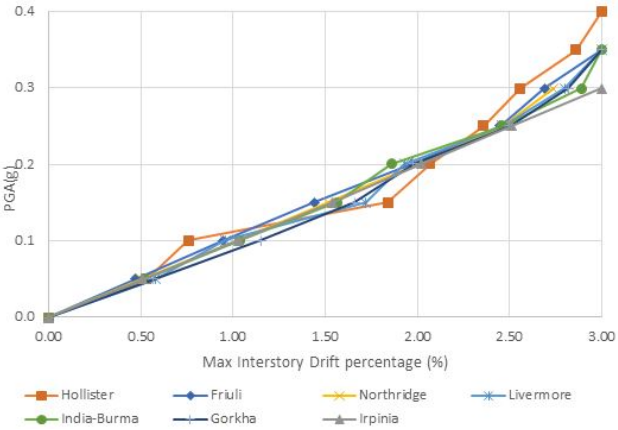


Figure 9: IDA curve under repeated earthquake for low rise structure

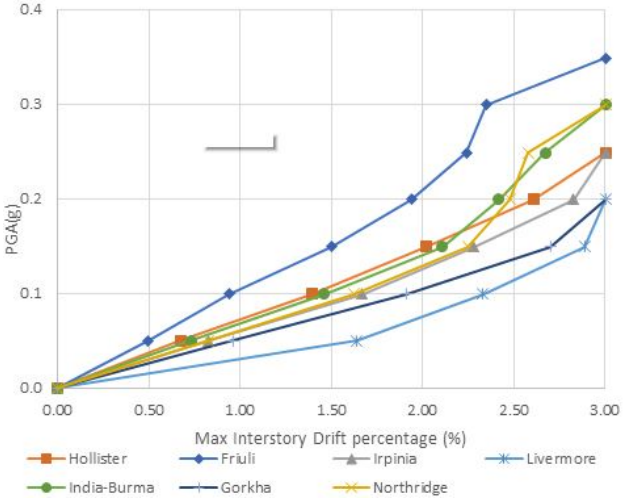


Figure 10: IDA curve under repeated earthquake for mid rise structure

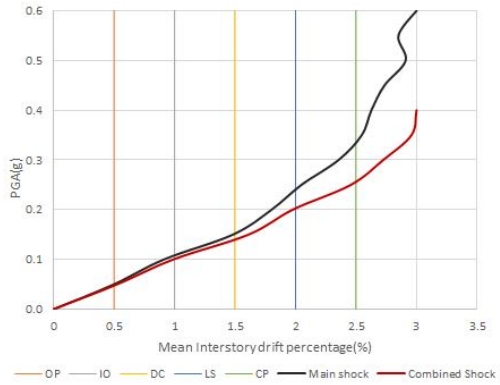


Figure 11: Comparison of Mean IDA curves for low rise structure

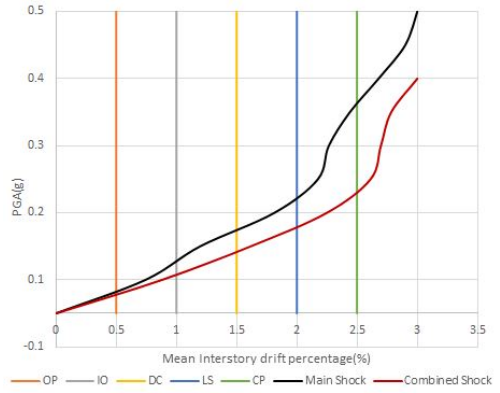


Figure 12: Comparison of Mean IDA curves for mid rise structure

5.3 Development of fragility curves

For generation of fragility curves, the fragility parameters (viz., the mean $'\mu'$ and standard deviation $'\sigma'$ values) are calculated as per ATC 40 guidelines for collapse limit state. These parameters are evaluated form Mean IDA curves and are listed in Table: 4 and Table: 5.

Table 4: For Low Rise Building

Type of earthquake	OP		IO		DC		LS		CP	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Main shock	-3.168	0.009	-2.136	0.016	-1.639	0.028	-1.309	0.04	-1.061	0.053
Combined Shock	-3.103	0.003	-2.295	0.003	-1.854	0.005	-1.549	0.008	-1.316	0.011

Table 5: For Mid Rise Building

Type of earthquake	OP		IO		DC		LS		CP	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Main shock	-3.507	0.007	-2.379	0.019	-1.862	0.033	-1.553	0.043	-1.27	0.061
Combined Shock	-3.583	0.011	-2.656	0.019	-2.183	0.029	-1.864	0.038	-1.622	0.048

After obtaining fragility parameters the probability of exceedance is calculated as per Eq. (1) stated by Nazri [9].

$$P(D/PGA) = \phi\left(\frac{\ln(PGA) - \mu}{\sigma}\right) \quad (1)$$

Where, D is damage, PGA is peak ground acceleration, $'\phi'$ is standard normal cumulative distribution,$'\mu'$ is mean,$'\sigma'$ is standard deviation of of PGA. The plot of the probability of collapse for a given intensity measure (PGA) is shown in Fig. 13 to 16.

After analysis of the results from Fig.13 to Fig.16 , it can be clearly understand that the probability that the structure reaches its collapse point becomes high at much lower PGA under repeated earthquake forces compared to single or individual earthquake. This signifies that when buildings are subjected to second or subsequent earthquake after getting damaged by the first one, the collapse capacity of structure gets significantly reduced. It also shows that considering only single earthquake for designing and analyzing the structure is not sufficient.

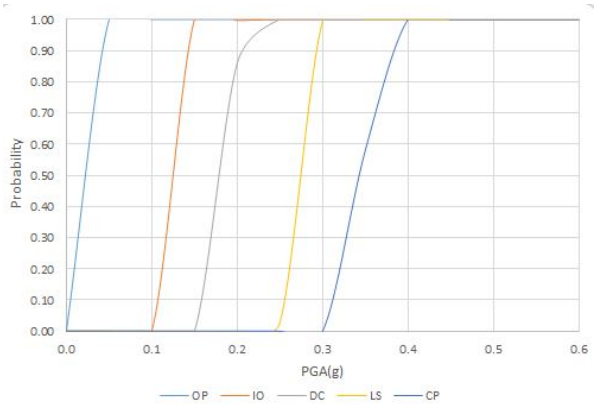


Figure 13: Fragility curve under single earthquake for low rise structure

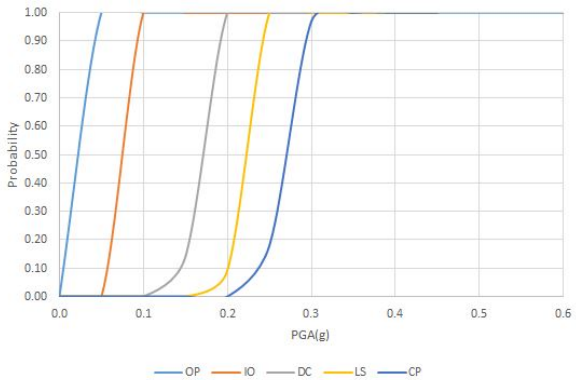


Figure 14: Fragility curve under single earthquake for mid rise structure

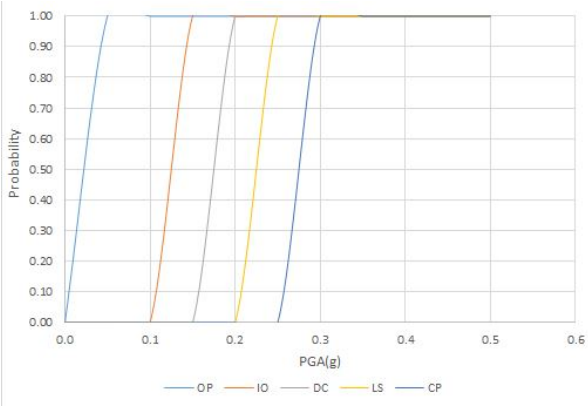


Figure 15: Fragility curve under repeated earthquake for low rise structure

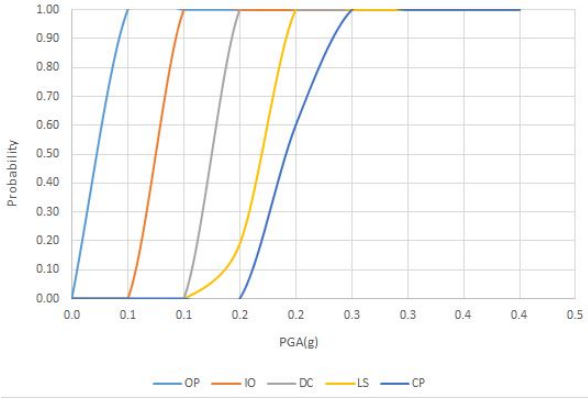


Figure 16: Fragility curve under repeated earthquake for mid rise structure

6. Conclusions

This study is mainly focused on seismic fragility assessment of structures with different number of storey in Kathmandu area of Nepal conformed to NBC 105:2020 under single earthquake and sequence earthquakes. In this investigation, IDA is performed for both single and repeated ground motions to investigate structural performance in terms of residual displacement with respect to repeated ground motions, inter-storey drift ratio (IDR) with respect to PGA and the probability of collapse in terms of PGA. The following are the conclusions:

- Residual displacement accumulated in structure after the major shock found increased when the structure got hit by repeated earthquakes. This accumulation of residual displacement is very vulnerable for structures. So analyzing structures considering repeated earthquake is found to be necessary.
- Also the influence of repeated earthquakes is found to be significant in collapse capacity of structure. Probability of collapse of structure became high in lower PGA in case of repeated earthquake.

Hence, this study accentuates the neccesity of considering repeated earthquake forces to analyse and design the structure to make it seismic resilient.

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