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INCREMENTAL DYNAMIC ANALYSIS AND SEISMIC FRAGILITY ANALYSIS OF REINFORCED CONCRETE FRAME

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Abstract

Due to technological developments in last decade, new methods of seismic evaluation are in use like simulation based, algorithm based, probabilistic, software based etc. These developments have enabled researchers to move from linear to non-linear methods of analysis. Incremental dynamic analysis (IDA) is performance evaluation method where a suite of ground motions applied to structure are further scaled to particular levels of seismic intensity. Seismic fragility curves become significant in estimation of structures risk possibility from the point of view of potential earthquakes and helps in predicting the economic consequences for forthcoming earthquakes. The paper reflects IDA and seismic fragility analysis of ground storey + 7 floor (G + 7) reinforced concrete frame subjected to suite of eleven ground motions. Primary objective was to perform equivalent static and linear-dynamic analysis to meet the National and International codal requirements. Then, pushover analysis is carried out by introducing parametric auto hinges as per ASCE 41-13 tables. To carry out pushover analysis, both geometric and material non-linearity was introduced. Strong ground motions were selected as per suitable criteria of seismic intensity. IDA is then carried out as per SeismoStruct 2022 software and using IDA curves, the fragility analysis was carried out. The results of study found useful for researchers to predict the probability of damage of the structure under earthquakes.

Keywords:

Incremental dynamic analysis;
Seismic fragility curves;
Linear-dynamic analysis;
Pushover analysis;
SeismoStruct 2022 software.

1 Introduction

Demand and capacity of structure plays vital role in seismic analysis of any structure. High rise or mid-rise structure when subjected to ground motions might suffer considerable damage depending upon magnitude of an earthquake. Further precise response of structure cannot be predicted through time history analysis, in such case IDA is observed to be more efficient as it consists of meticulous calculations and also scaling and matching of ground motion data carried out to provide an efficient results. Many methods are evolved in evaluating seismic response of structure when subjected to seismic excitation. Vamvatsikos, D. et al. [1], found that IDA is computer-based procedure that conducts thorough prediction of demand and capacity by using non-linear dynamic time-history analysis under the suite of various ground motion records. Katsanos, E.I. et al. [2], presented the latest techniques developed for selecting an "appropriate" set of ground motion records beneficial for dynamic analysis of structural systems with reference to performance-based design. Patil, A.S. and Kumbhar, P. D. [3], recommended that Time-History analysis must be used for multi-storied reinforced cement concrete (RCC) building to ensure safety against earthquake force.

Shimpi, V. and Bhat, G. [4], studied performance evaluation of RC frame structure through IDA. The structure in Zone-V showed much higher performance in comparison to other. It concluded that

IDA gives more realistic and reliable results, also it gives exact behaviour of the structure. Vamvatsikos, D and Cornell, A. [5], carried out IDA and its application to performance-based engineering for 9-storey building. The static pushover curve and median 50 % IDA was compared. When it was plotted, the elastic region of IDA matches pushover curve. When pushover curve gets negative slope, the IDA curve gets softened and acquires local shape lesser than initial elastic position. Javanpour, M. and Zarfam, P. [6], preferred IDA over Pushover non-linear static method for analysis and design due to its accuracy and effect of higher modes at the same time intervals.

Darius, S. et.al. [7], observed that fragility curves gives probability of exceeding the standard damage level for the considered ground motion range. Patel, S. A. et al. [8], developed fragility curves in terms of peak ground acceleration (PGA) for limit state as slight, moderate, major and collapse in lognormal distribution. Fragility analysis is an important in predicting the risk of structure under the potential earthquakes and also it is useful to predict the behaviour of it for the future earthquakes. Folic, R. and Cokic, M. [9], studied the difference between probabilities of the damage states obtained from fragility analysis results. Further, Folic, R. and Cokic, M. [10], carried out seismic fragility analysis of reinforced concrete frame with damage state thresholds calculated using FEMA 356, EN 1998 (Part 1), Eurocode 8 and EN 1998 (Part 3). The maximum drift ratio is used to define the damage state of the analyzed structure. Prasad, C. A. et al. [11], concluded that structure will collapse for a flat-slab structure as drift increases drastically for a slight increase in intensity measure. Siva, S. et al. [12], conducted seismic fragility analysis of regular and setback G+10 RCC frame by capacity spectrum method (CSM) as per IS:1893 and Part 1:2016 [13]. Overall conclusion was that setback frames were showing more damage probability. However with the help of infill walls, structure was found to behave similar to conventional RC frame. FEMA 356 [14], recommended that every fragility curve specifies some probability value to show some uncertainty in the estimation of fragility. This probability value corresponds to performance level.

2 Description of selected model

Ground storey + 7 floor (G+7) Reinforced Concrete-Moment Resisting Frame is selected and designed according to IS-456:2000, [15] and seismic load combinations are provided as per IS-1893, Part 1: 2016, [13] and analyzed in ETABS 19.0.0. Dimensions of columns and beams are varied for stilt level and rest of the floors. The suite of 11 ground motion is selected with six of them being in near-fault zone and rest five in far-field zone to study and compare the behaviour of structure. The ground motion scaling is done by matching the response spectra for zone V with the ground motion accelerogram. The guidelines provided by Najafi L. H. and Tehranizadeh, M. [16], used for ground motion scaling for any type of soil and engineering demand parameters. The Incremental Dynamic Analysis is performed in SeismoStruct 2022 software. Table 1 describes geometrical configuration of G+7 building frame.

Table 1: Geometrical configuration of the selected frame.

Dimensions of building	25 m x 35 m	
Height of structure	25.7 m	
Location	Guwahati, Assam State, India	
Bay spacing	5 m	
Number of bays	*X* direction	05
	Y direction	07
Storey height	Stilt Level	4 m
	Storey to storey	3.1 m
Column dimension	Stilt Column	650 mm x 950 mm
	Column	600 mm x 900 mm
Beam dimension	Stilt Beam	500 mm x 650 mm
	Beam	450 mm x 600 mm
Thickness of slab	150 mm	
Grade of concrete	M30	
Grade of steel	Fe500 (Longitudinal bars)	Fe415 (Lateral ties)

3 Methodology

The different intensities of ground motion are applied on the structure till it collapses. Then the IDA curve is plotted having damage measure parameter (such as maximum inter-story drift) on *X*-axis and Intensity Measure (such as Spectral acceleration S_a) on *Y*-axis. When the slope of IDA changes from linear to non-linear, it indicates that yield is reached. The study starts with the basic design of structural members and the performing linear static analysis with load cases like modal, dead, imposed and earthquake load. From the results, it is useful to check whether the difference between the time periods are as per codal requirements. Also, the modal mass participation factor is checked. Further the concrete frame is designed and verified whether the all the members pass the stress/capacity check, which ensures that structure is able to carry elastic loads. Response spectrum analysis is then carried out to match the base shears in the two principal directions. In order to carry out pushover analysis, nonlinear gravity load case is introduced comparising of dead and imposed load. In present study, capacity spectrum method (CSM) was used to find out pushover curve. Then auto hinges was assigned as per tables of ASCE41-13 [17]. These hinges has been assigned for beams at all floors. For columns, auto hinges was applied as per tables of ASCE41-13 [12]. Pushover curve is obtained with base shear versus monitored displacement. The structure is redesigned if performance point of the structure is not obtained and vice-versa.

Before proceeding for incremental dynamic analysis, the main task is to select the ground motion. While selecting the ground motion, various factors are to be encountered. Many of the researchers have suggested the magnitude of earthquake need to be more than 6.5 if else, it is less than 6.5 in most of the cases causes non-structural damage. Lie, S. and Xie, L. L. [18], considered another factor of fault distance, near fault ground motion are those which are at the distance less than 20 kms from the fault line and far field are those beyond 20 km. The minimum/maximum number of ground motions as per the codal provisions are; ASCE 7-10 [19], is 7 ground motions, for ATC 40, it is 11. UBC 1997, IBC 2000, FEMA 356 [14], European Code 8 considered minimum 3 and maximum 7 ground motions. So overall, it was decided to experiment with 11 ground motions confirming to the requirement of ASCE 7-10 [19]. The details of selected ground motion data for this study is presented in Table 2.

Table 2: Selected ground motion.

Sr. No	Earthquake Name	Year	Recording Station	Magnitude	Ground motion ID	R_{rup}(km)	Scale Factor	Sa [g]
1	San Fernando	1971	Tehachapi Pump	6.61	RSN89	63.79	5.66	0.164
2	Friuli Italy-01	1976	Barcis	7.6	RSN121	49.38	2.366	0.1
3	Trinidad	1980	Rio Dell Overpass-FF	7.2	RSN280	76.26	0.506	0.224
4	Irpinia Italy-01	1980	Arienzo	6.9	RSN283	52.94	0.958	0.101
5	Northridge-01	1994	LA-S Vermont Ave	6.69	RSN1002	32.27	0.314	0.417
6	Kocaeli Turkey	1999	Goynuk	7.51	RSN1162	31.74	0.323	0.661
7	Gazli USSR	1976	Karakyr	6.8	RSN126	5.46	0.061	2.743
8	Tabas Iran	1978	Dayhook	7.35	RSN139	13.94	0.129	1.452
9	Imperial Valley-06	1979	Cerro Prieto	6.53	RSN164	15.19	0.121	0.661
10	Corinth Greece	1981	Corinth	6.6	RSN313	10.27	0.146	0.647
11	Nahanni Canada	1985	Site 3	6.76	RSN497	5.32	0.71	0.678

The above ground motion data is obtained from Pacific Earthquake Engineering Research (PEER) website [24]. The scale factor of ground motion is found by providing the input ground motion response spectra and then the fundamental time period is provided. The input ground motion is then matched with the target response spectra with the help of SeismoMatch software. The matching is necessary because the ground motion record taken is of different regions and it need to correlate it with structure’s location response spectrum. The Fig. 1 shows the matched ground motion with response spectrum of zone V as per IS 1893:2016, Part 1 [13].

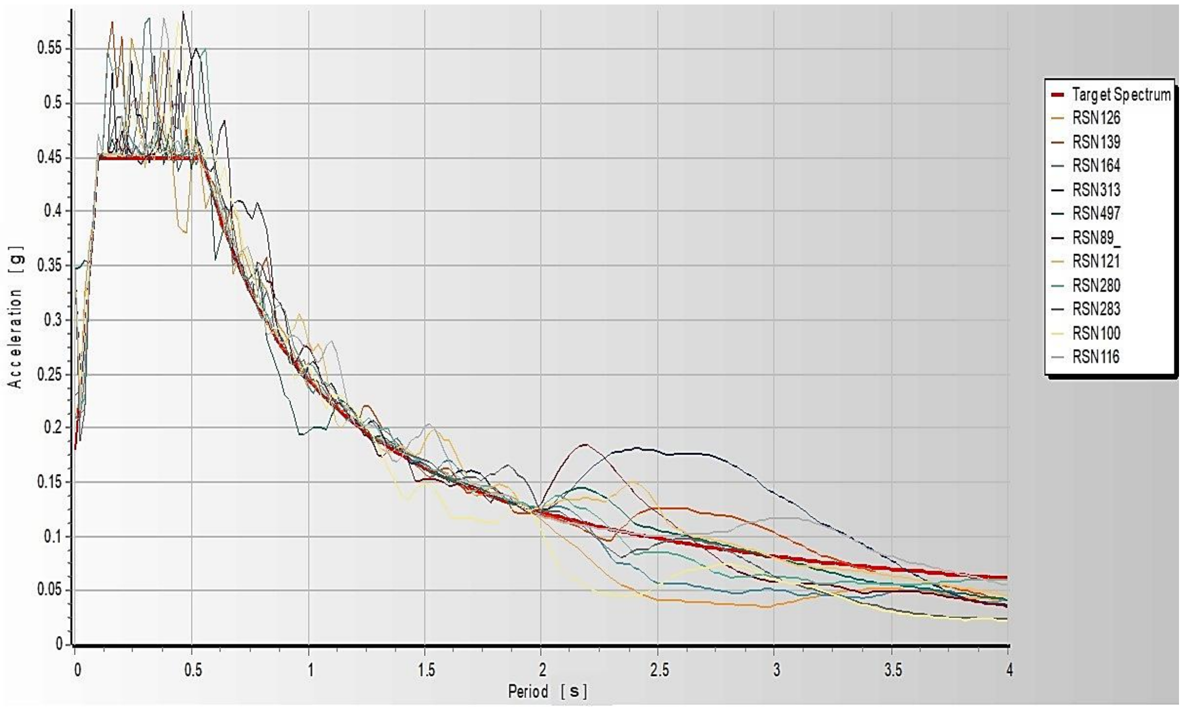

Fig. 1: Matched ground motion accelerograms.

According to ASCE 7-10 [19], considered scaled time history is greater than target response spectrum from 0.2Tn to 1.5Tn. Where 'Tn' is the fundamental time period of a structure. In this study, all the ground motions satisfy the above criterion.

Figure 1 shows the ground motion accelerograms are scaled with target response spectrum. The ground motion scaling is important because whatever the ground motion is used for study has to match as mentioned in the above ASCE 7-10 [19] provisions. It was observed that with time between 1 to 2 seconds, all the ground motion accelerograms are well matched with target spectrum.

The IDA procedure is confirming to FEMA 355, Chapter 5. The analysis was performed using SeismoStruct software. The initial step to perform IDA considering 0.1g and the step size an increment of 0.3g is followed and step is repeated until the structure collapses. Simultaneously, the plot of spectral acceleration S_a versus maximum inter-story drift θ_{max} is plotted and known as IDA curve.

To carry out the fragility analysis as per first table of C1-3 of FEMA 356 [14], referred to study the structural performance levels which is within permissible limits for drifts. Immediate Occupancy (IO), Life Safety (LS) and the Collapse Prevention (CP) are the three performance levels defined. The drift limits for IO is 1 %, 2 % for LS and 4 % for CP. These limits are used to find the fragility curve for corresponding three performance levels. The values of Intensity Measure (IM) i.e. Sá corresponding to IO and LS are obtained from single IDA by interpolating the curve. These spectral acceleration values are then arranged in chronological order. The natural logarithm of it is taken and then mean and standard deviation of the data is worked out. The standard function suggested by Baker, J. W. [20], for fragility function is expressed as:

$$F_x[x] = P[X \leq x] = \phi\left[\frac{ln(x)-\mu}{\sigma}\right], \quad (1)$$

where:
$\phi = F_x[x]$ = Cumulative distribution function of the standard normal distribution,
P is the probability function,
X is the random variable (in this case it is spectral acceleration S_a)
μ is mean of ln(x),
σ stands for standard deviation of ln(x)

3.1 Fragility analysis procedure

The following procedure is adopted to establish relationship of intensity measure (IM) with probability of occurrence of an earthquake.

i. From IDA curves, determine the IM values for which the damage measure (DM) falls in three defined damage states.

ii. After taking IM values for defined limit state e.g. Immediate Occupancy arrange the IM values in the order of smallest to largest.

iii. As assumed in the equation 1, variables are log normally distributed, take the ln(*x*) for all IM of ground motions.

iv. Calculate the mean and standard deviation of the ln*(x)* using following equations;

$$M = \frac{\sum_{i=1}^{n} \ln(x_i)}{n}, \tag{2}$$

$$\boldsymbol{\sigma} = \sqrt{\frac{\sum_{i=1}^{n} (\ln(x_i) - \mu)^2}{n-1}}, \tag{3}$$

where:
μ = mean of ln(x),
σ = standard deviation of ln(x),
x = intensity measure (IM).

v. Calculate S for converted log normal values using equation 4

$$S = \frac{\ln[x] - \mu}{\sigma}. \tag{4}$$

vi. Apply standard normal distribution function using equation 1 for probability function.

vii. Plot the curve taking IM on X-axis and probability on Y-axis which is known as fragility curve derived by Baker, J. W. [20].

4 Results and discussions

4.1 Incremental dynamic analysis

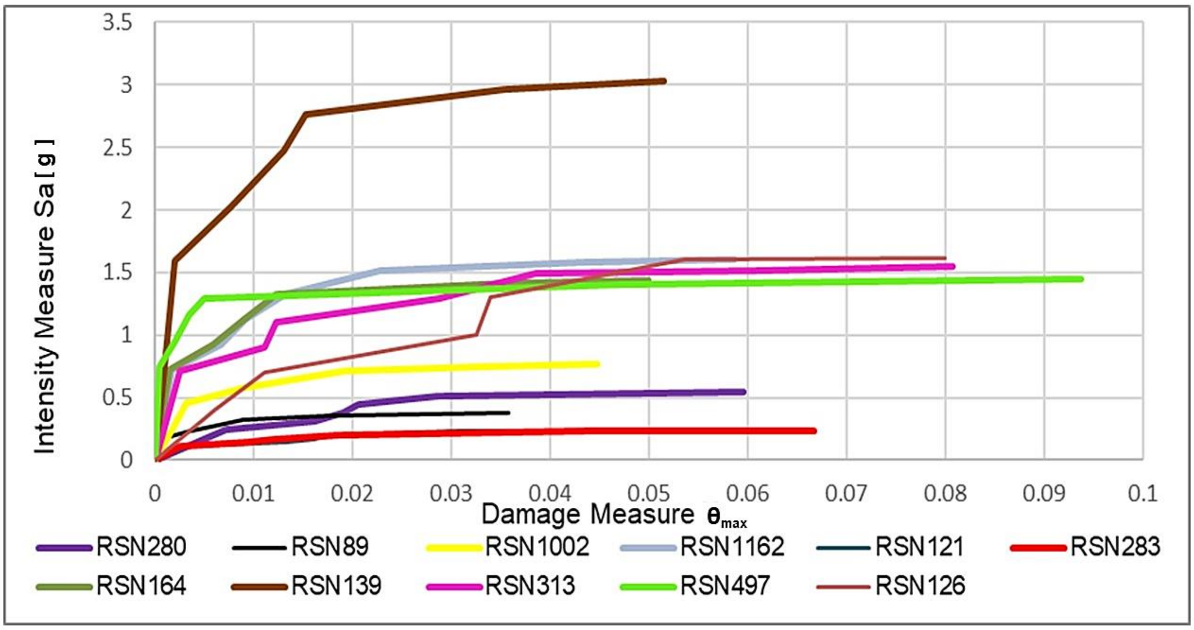

Fig. 2: Multi-record IDA curve for ground motions.

From multi-record IDA curves presented in Fig. 2, it was observed that the near fault ground motions (RSN126, RSN139, RSN164, RSN313 and RSN497) {RSN stands for Record Sequence Number, it is an identity given to ground motion by PEER} have recorded more drift than compared to far field ground motions (RSN89, RSN121, RSN280, RSN283, RSN1002 and RSN1162). The reason behind this may be due to spectral acceleration. Since the near-fault ground motions has more spectral acceleration compared too far- field. Due to this, the structure has suffered more drift with less increment of IM in case of near fault ground motions.

Therefore, it has taken combinations of far field and near fault ground motions to study the combine response of the structure. Kruep, S. J. [21], got to know the response of structure subjected to different intensities of one earthquake with the help of single-record IDA curves. Intensity measure (IM) and damage measure (DM) values can be determined with single IDA.

Since single record IDA curve does not predict seismic response of structures of future earthquakes, so multi-record IDA is used to resolve this problem. Vamvatsikos, D. and Cornell, A. [22], studied multi-record is the combination of single-record IDA curves of the similar structure subjected to various ground motions, which are scaled on same IM and DM. Generally, it is difficult for construction of structure which can resist all the ground motions, but with the help of multi-record IDA curves with the same parameters will at least reduce the probability of damages of structure under the future earthquakes.

4.2 Fragility analysis

With the help of equation 1 the fragility curve generation was done with the help of table 3. The intensity measure values for three limit states were taken by interpolating every incremental dynamic analysis curve as per Fig. 3 for structural performance levels.

Table 3: Fragility curve calculation

Immediate Occupancy (IO)				Life Safety (LS)				Collapse Prevention (CP)			
x=Sa(t1,5%)g	ln(x)	s	Probability	x=Sa(t1,5%)g	ln(x)	s	Probability	x=Sa(t1,5%)g	ln(x)	s	Probability
0.092	-2.386	-2.497	0.006	0.600	-0.511	-2.850	0.002	0.770	-0.261	-2.779	0.003
0.120	-2.120	-2.095	0.018	0.706	-0.348	-1.861	0.031	0.840	-0.174	-2.299	0.011
0.194	-1.640	-1.370	0.085	0.824	-0.193	-0.920	0.179	1.090	0.086	-0.863	0.194
0.361	-1.020	-0.434	0.332	0.841	-0.173	-0.799	0.212	1.140	0.131	-0.616	0.269
0.428	-0.848	-0.175	0.431	0.878	-0.130	-0.538	0.295	1.180	0.166	-0.425	0.335
0.462	-0.772	-0.059	0.476	0.933	-0.069	-0.169	0.433	1.290	0.255	0.066	0.526
0.528	-0.639	0.141	0.556	0.961	-0.040	0.009	0.504	1.360	0.307	0.357	0.640
0.636	-0.453	0.423	0.664	1.017	0.017	0.358	0.640	1.400	0.336	0.517	0.698
0.762	-0.272	0.696	0.757	1.047	0.046	0.529	0.702	1.420	0.351	0.595	0.724
0.791	-0.234	0.752	0.774	1.051	0.050	0.556	0.711	1.430	0.358	0.634	0.737
0.920	-0.083	0.980	0.837	1.209	0.190	1.408	0.920	1.450	0.372	0.711	0.761
1.024	0.023	1.141	0.873	1.213	0.193	1.426	0.923	1.620	0.482	1.322	0.907
μ	-0.732			μ	-0.042			μ	0.243		
σ	0.662			σ	0.165			σ	0.181		

It was observed from the Fig. 3 that the fragility curve of life safety limit state lies approximately in between immediate occupancy and collapse prevention. The maximum probability of structure to exceed IO state in this case is 87.31 %. Similarly, for LS it is 92.31 % and 90.69 % for CP. However, it was observed that collapse prevention fragility is bit close to life safety fragility curve indicating that the structure is expected to collapse soon after crossing life safety state.

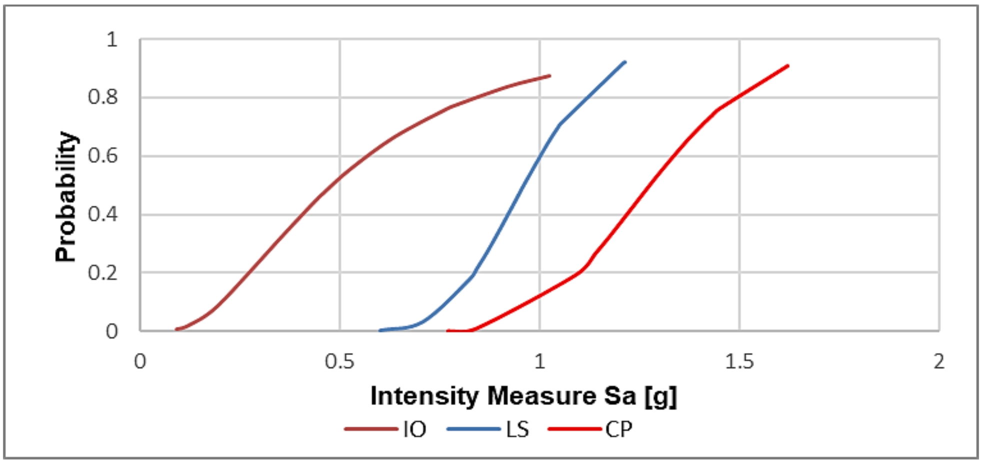

Fig. 3: Fragility curve for limit state as per FEMA 356.

5 Conclusion

The main objective of present study was to understand the response of the structure designed according to IS code, under the application various ground motions. By applying the ground motions the ultimate aim was fulfilled to perform incremental dynamic analysis. The IDA curves acted a tool for fragility analysis. Then based on probabilistic calculations the seismic fragility curves are developed. The main salient conclusions drawn based on present study is summarized below:

1) While selecting the ground motion data, it is necessary to study the parameters affecting it. Like magnitude of earthquake, fault distance and site condition are some of the major factors which may decide the nature of the ground motion record.

2) Since IDA gives step-by-step procedure, the results of the IDA show that this method can become important asset of seismic engineering.

3) IDA curves showed large record-to-record variability in the drifts for various ground motions like for RSN89 San Fernando earthquake the IDA curve started resurrecting, i. e. curve was restoring from flat line to rapid decrease in drift with further increase in intensity measure. In present case, we have truncated the IDA curve as per the literature referred.

4) On the other hand, the IDA curve for RSN 121, RSN 280, RSN 126, RSN 313 ground motions have complicated shape. IDA in RSN 121 curve starts softening about 0.11g but it hardens again and it flattens at IM of 0.2g. It indicates that building has not yet reached to global collapse yet at 0.11g intensity measure.

More detailed study can be carried for present research to obtain more reliable results either by increasing the number of ground motions or by changing the direction of ground motion application on structure. It can be further used in the study of the structure subjected to seismic excitations. The changed direction of ground motion results and the current results can be compared and the comparative study is possible.

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