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Seismic Fragility Assessment for Steel Buildings with Different Performance Levels

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Abstract The probability of failure associated with drift criterion exceeding certain performance levels for the intensity of earthquake record ground motions has been necessitated for the development of fragility curves in the recent past as a better performance check tool. In the recent past, the reappraisal of fragility curves formation due to incremental dynamic analysis has been possible because of modeling and simulation of structures under varying earthquake ground motions. The content of this paper is the formation of fragility curves using drift as the output of steel building frames under varying earthquake ground motions. The fragility curves were developed through nonlinear time-history analysis assessments of selected ground vibrations with varying magnitudes, distances from the source, and site circumstances. The entire process given in this paper can be utilized to develop probabilistic fragility curves for structural buildings of various layouts. As an illustration, fragility curves for two steel building structures for various performance levels: Collapse prevention (CP), Life Safety (LS), Immediate occupancy IO), & operational performance (OP), were developed using Ram Perform 3D, using a set of 20 earthquake ground motions. The fragility curves formed using drift for different performance levels reveal a robust damage index for evaluating building structures under the high level of seismic hazards.

Keywords Fragility Curves, Drift, Damage Index, Incremental Dynamic Analysis, Performance Levels, Time History Analysis

1. Introduction

Fragility curves show how likely it is that structures or buildings will be damaged by earthquakes based on ground motion indices like the PGA and PGV. They are used to predict how much damage earthquakes will cause. Through nonlinear time-history assessments of selected ground motions with a wide variety of magnitudes, distances to the source, and site circumstances, the parameters of lognormal cumulative distribution function for the four defined damage states were determined, and the fragility curves were derived. Hysteretic energy assesses seismic safety based on the energy that a structure can dissipate as an alternative to its cyclic behavior. Though, specific experiments have verified that structures going under reversal of stress having less plastic deformation have no real relevance to the level of damage [1]. Accelerograms can be scaled up to increase their ordinates in incremental dynamic analysis (IDA), which is a type of nonlinear dynamic analysis [2].

A considerable amount of studies were carried out on buildings to develop seismic fragility curves, such as the formation of vulnerability curves and damage probability matrices for structures with the assistance of damage index developed by Park and Ang [3]. The seismic vulnerability curves of some existing residential buildings were formed using ATC-40 and HAZUS methodology [4], with base shear capacity and ultimate drift [5]. For different materials' structural properties, such as for variability of steel & others [6], [7], fragility curves have been formed, which were used for assessment of designed structures for earthquake loadings [8]. Fragility curves of the buildings constructed using seismic codes and without seismic codes are formed with varying plan dimensions [9]. Polese et al. studied buildings constructed using seismic codes and without seismic codes to form vulnerability curves with varying plan dimensions. The drift criterion is mostly used for the evaluation of the damage potential of the structures.

2. Damage Index

Damage indices are robust tools that could be integrated with future design code procedures because they likely lead to better effective and reasonable solutions of optimum design. The indexes based on plastic ductility are among the major indexes in this category. Powell et al. [10] defined the damage index based on plastic ductility in the structure as an equation Eq. 1. The capacities of the response variables are well-defined for their corresponding maximum values during monotonically growing deformations. The structure's deformation capacity under the powerful earthquake motion was based on a component of the ultimate capacity during structure deformation with monotonically expanding horizontal deformations (u_{mon}). This simple concept and the comfort of using the damage index are popular between engineers and researchers.

$$DI_{\mu} = \frac{u_{max}-u_y}{u_{mon}-u_y} = \frac{\mu-1}{\mu_{mon}-1} \quad (1)$$

μ_{mon}, is the maximum amount of deformation the system can handle during a monotonically rising horizontal deformation. u_{max} and u_y are the maximum and yield deformation, respectively. The ground motion's displacement ductility is $\mu = u_{max}/u_y$, while the system's monotonic ductility capacity is $\mu_{mon} = u_{mon}/u_y$. Anyhow, displacement ductility does not disclose info of the inelastic deformations during repeated cycles of ground motion and the demand for energy dissipation. Roufaiel and Meyer [11] expressed global level damage of the system to deflections at roof level as shown in Eq. 2 as

$$G_{lobal} = \frac{\delta_m-\delta_y}{\delta_f-\delta_y} \quad (2)$$

where: The displacement just at yield limit is represented by δ_y; the displacement just at the ultimate limit is represented by δ_f; the maximal displacement is represented by δ_m.

The damage index developed by Park and Ang considers both maximum plastic energy dissipated and the plastic deformation, which is supported with a comprehensive correlation with the damage observed in the structure. However, the determination of the variable β is hard as it is experimental and shown in Eq. 3 as

$$D = \frac{\delta_{max}}{\delta_u} + \frac{\beta}{(Q_y\delta_u)}\int dE \quad (3)$$

where: δ_{max} is the maximum displacement corresponding to the maximum capacity of the system, δ_u is the ultimate displacement during monotonic increasing loading, β is the variable which represents the cyclic effect of the loads, dE is incremental energy dissipated hysterically, Q_y is yielding force.

3. Methodology

Incremental Dynamic Analysis

The IDA, or incremental dynamic analysis, is indeed a nonlinear dynamic pushover technique that is used to assess seismic demand and collapse of structures. Analyses are performed for various scaled intensity levels of earthquake ground motion till dynamic instability structural failure or collapse is encountered (non-convergence). RAM PERFORM 3D software program, which is known for its leadership of performance-based analysis & design, has been used for nonlinear dynamic analysis (IDA). At the end of each study, the inter-story drift was recorded & tabulated till the referred structure reached its collapse capacity.

Fragility Curves

Existing fragility curves are divided into four categories by Rossetto and Elnashai [12] analytical fragility curves, expert fragility curves, empirical fragility curves, and hybrid fragility curves.

Evaluating the structural integrity of earthquake-damaged structures, empirical fragility curves were constructed using statistical methods. Expert fragility curves are indeed the simplest way for obtaining fragility curves since they are based mostly or exclusively on expert opinion, which makes them the most straightforward technique. The curves incorporated in the HAZUS database are an example of expert fragility curves.

Analytical fragility curves could be created by simulating system behavior with numerical models. Analytical tools are the only way to look into the vulnerability of a building when there is no experimental data, observations, or expert opinion to look into it. Due to a limitation of field data and experimental data from the earthquake, for RC high-rise buildings, the fragility curves could only be computed using analytical methods [13]. In our study, we also used the analytical fragility curves, as shown in figure 1. These two said curves are combined to create hybrid fragility curves.

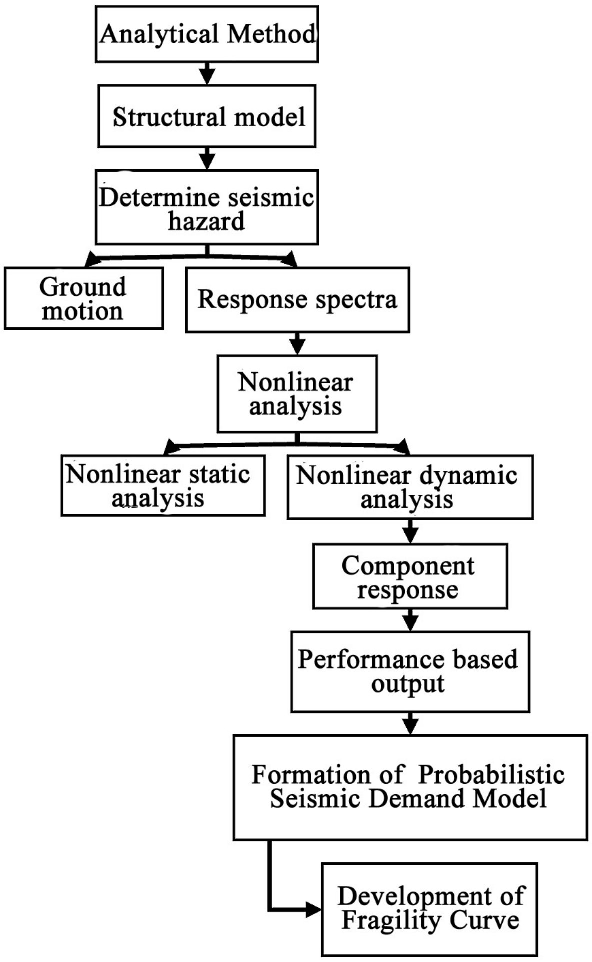


Figure 1. Steps for development of fragility curve

The fragility curves indicate the probability of exceedance of damage to the engineering demand parameter. In this study, peak ground acceleration is an engineering demand parameter. The equation Eq. 4, for the probability of damage greater than or equal to the assumed level, is

$$P(C \leq X) = \phi\left(\frac{\ln X - \theta}{\beta}\right) \quad (4)$$

Where $P(C \leq X)$ represents the probability when a ground motion of IM = X will lead the structural model to collapse, X represents the lognormal distributed ground motion index, θ and β represent the mean and the standard deviation of ln X respectively, and $\phi(\frac{\ln X - \theta}{\beta})$ represents the standard normal cumulative distribution.

The fragility curve's fundamental parameters are the mean and standard deviation. The median of intensity measure wherein the probability of surpassing the damage state limit is 50% the mean value for the lognormal cumulative distribution. The natural logarithm of the intensity measure for a given damage condition is its standard deviation (β). The ideal values for these two parameters are determined during the fitting of fragility curves.

Building Model and Earthquake Records

The nonlinear time-history analysis is performed using the PERFORM-3D software [14]. Two models which are referred to from the literature review, used for performance-based analysis & design, are considered in this study to develop a fragility curve for the structure under various earthquakes loadings. The first model is a five-story steel building model with a plan of three bays, each in the X and Y orientation. The second model is of a three-story steel building model with five bays in the X orientation and four bays in the Y orientation. The mathematical models being used for elastic analysis contain the strength of structural parts as well as their post-elastic behavior. The elemental properties are based on the average values of the material's qualities. Critical response modeling, for example, incorporates plastic curvature and plastic strain within a defined hinge length, resulting in inelastic behavior (FEMA-356). In this context, a sequence of hinges can be represented to capture plasticity dispersed over the length of a member.

To prevent the risk of progressive collapse and ensure numerical convergence, the modeling of strength loss is disregarded. The negative slope is automatically limited to 10% of elastic stiffness in CSI Software, PERFORM3D, and overriding options are available. According to the desired limit, additional limit states (IO, LS, CP) can be defined for the analysis, as shown in Fig 2. The slope of initial stiffness is followed while unloading from the point of plastic deformation. Both P-M2-M3 and fiber hinges are used in the frame members to show how the axial and biaxial-bending behavior is linked together. The fiber hinge is better for hysteretic dynamics, whereas the P-M2-M3 hinge is best for a nonlinear static pushover.

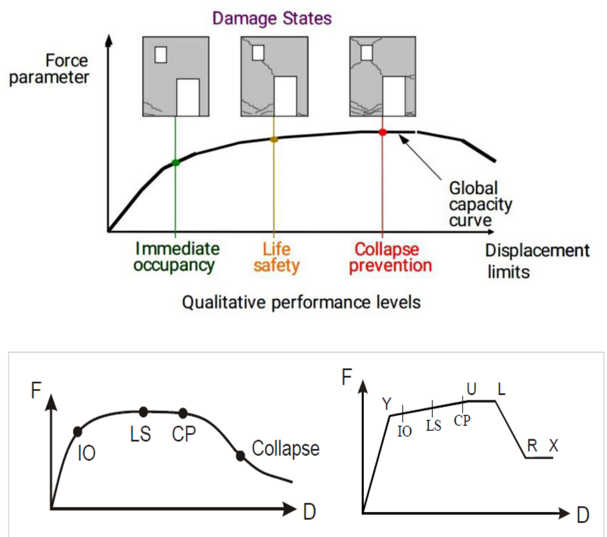
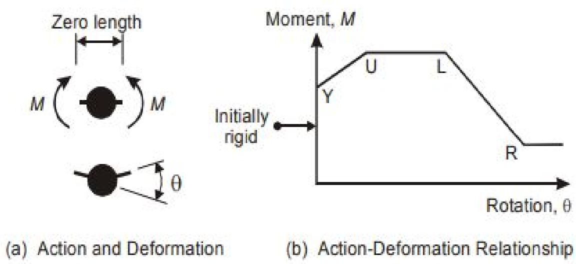


Figure 1. Deformation controlled mechanism

Figure 3 depicts beams and columns made using frame compound components. The attributes of a frame compound component's beam and column elements are defined using additional essential components. In theory, PERFORM- 3D allows us to combine many sorts of basic components into a single compound component model. A fiber segment is made by connecting it to a fiber cross-section and defining the length of the fiber segment that it is part of. It is essential to understand how a fiber segment acts when the fiber section becomes nonlinear as a result of the yielding of steel fibers or the crushing and cracking of concrete fibers, among other factors.

A moment plastic hinge just precisely that: a hinge, very similar to a rusted hinge in that it spins only after a sufficient amount of moment has been given to overcome the frictional resistance between the casing and the hinge pin. Figure 3 depicts a hinge and a potential moment-rotation relationship. At the yield point, the hinge becomes rigid and commences to rotate. The mechanical properties of the structure, such as stiffness, bending stress, shear stress, young's modulus, poisson's ratio, and shear modulus of beam and column components, are incorporated in the PERFORM 3D model.



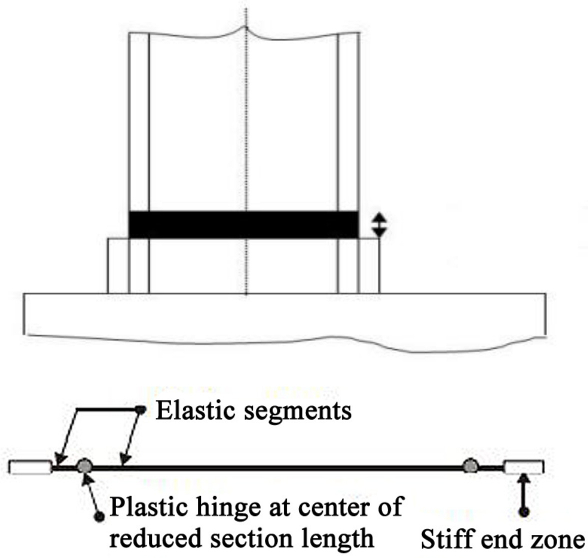


Figure 2. Frame elements and hinges

The sectional properties of beams and columns used for a five-story steel building with a three-story steel building are shown in Tab. 1 & Tab. 2, Fig. 4 & Fig. 5.

Table 1. Beam and column details for two-story steel building

Floors	Beams	Columns	
		Exterior	Interior
Ground	W_{33x114}	W_{14x257}	W_{14x311}
First	W_{30x116}	W_{14x257}	W_{14x311}
Second	W_{24x68}	W_{14x257}	W_{14x311}

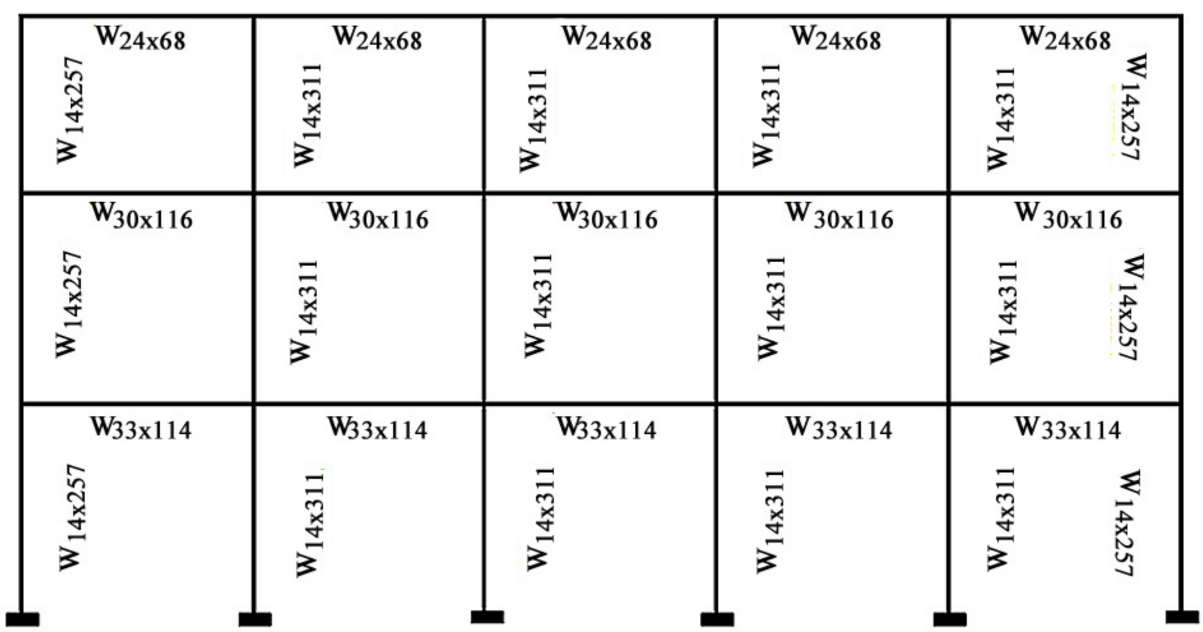


Figure 3. Three-story steel building with five bays in the X direction

Table 2. Beam and column details for five-story steel building

Floors	Beams	Columns	
		Exterior	Interior
Ground	W_{36x182}	W_{14x398}	W_{14x398}
One	W_{36x182}	W_{14x398}	W_{14x398}
Two	W_{36x160}	W_{14x342}	W_{14x342}
Three	W_{36x160}	W_{14x342}	W_{14x342}
Four	W_{36x135}	W_{14x257}	W_{14x257}
Five	W_{36x135}	W_{14x257}	W_{14x257}

The ground motion records set were considered for the Dynamic Analyses with 6 < Mw < 7, 4 < R < 45 km characteristics. The earthquake records are obtained from the PEER strong motion database and shown in Tab. 3 and Fig. 6. There can be a lot of variety in the results if we do analysis for numerous different ground motions. This is partly due to the fact that nonlinear behavior is naturally sensitive to modest changes in varying ground motions. It's partly due to the procedures utilized to choose the ground motions. A computer program only looks at the model used for analysis, not the real structure itself. For the same structure, various engineers may use different modeling assumptions and produce different results with minor changes. Furthermore, a structure's response may be influenced by its components' strengths and stiffnesses, which may not be correctly determined. Prototype structure may help to eliminate a lot of uncertainty. The characteristics of the records that were chosen are shown in the table 4. These earthquakes are calibrated appropriately to ensure that the frames do not collapse or aggravate distress but instead yield. A greater number of mild earthquakes are now being identified thanks to an increased number of seismic monitoring stations, not because of an increase in earthquakes themselves. As far as we can tell, the global rates of severe are rare. Every three days or so, an earthquake of magnitude six or greater is recorded, and every month, at least one of magnitude seven or greater is recorded. The relatively consistent frequency of earthquakes can be explained by basic principles of geology.

The convergence criterion chosen is the maximum permissible limit for each performance level, as shown in the table 3. Analyses are carried out at rapidly raising the levels of IM till the numerical convergence of prescribed limit or till the non-convergence is observed (indicating global dynamic instability), after which additional analyses are carried out at intermediate IM-levels to adequately bracket the global catastrophe and enhance the accuracy at lesser IMs. The term "global dynamic instability" refers to the condition in which a slight rise in the intensity measure causes a more significant increase in the DM. Due to the fact that the algorithm is implemented in software that can be wrapped around the majority of current analytic programs (e.g., PERFORM 3D, DRAIN-2DX), it makes IDA virtually effortless, necessitating little or no human involvement. It takes 1000-time steps of 0.02 secs per step (20 seconds earthquake duration) to complete a single set of nonlinear dynamic analyses with different components of horizontal seismic ground motions. It is also necessary to conduct a gravity load analysis before the nonlinear dynamic analysis. As a first step, the above-described models were subjected to equivalent static analysis for validation, and then Incremental dynamic analysis (IDA) was done using PERFORM 3D with scaled ground motion records to perform nonlinear time history analyses on the models. The fragility curves made from the results of the analysis are compiled and used for additional analysis as the goal of this paper.

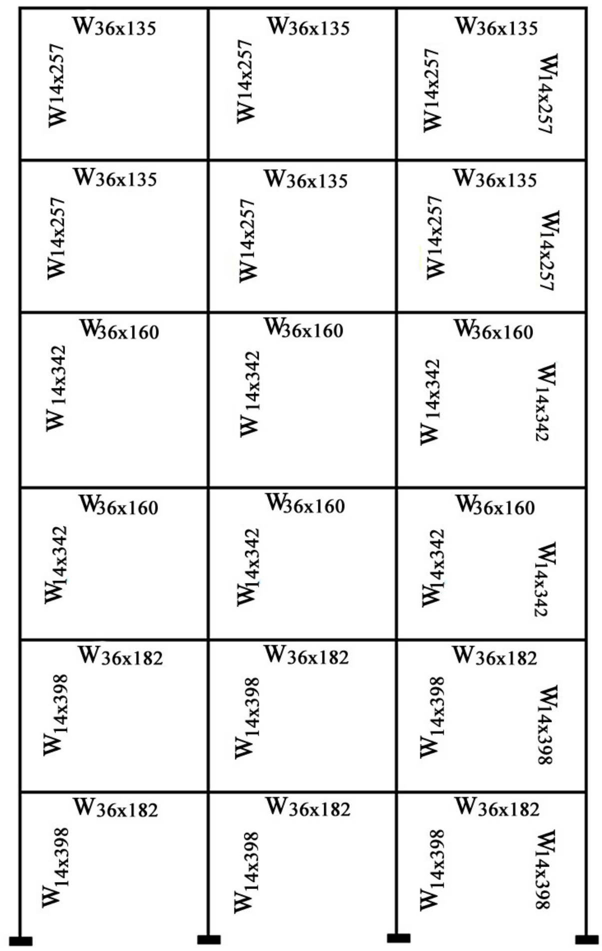


Figure 4. Five-story steel building with the plan of three bays in each direction

Table 3. Criteria selected for different performance level

Structural performance level	Permissible maximum top story drift
Immediate Occupancy (IO)	1%
Life Safety (LS)	2%
Collapse Prevention (CP)	4%

Table 4. Ground motion records

Record	Event	Magnitude	Radius (Km)	Station
EQ 1	El Centro	6.6	23.7	Imperial Co Srvcs Bld
EQ 2	El Centro	6.6	27.6	Imperial Co. Center Grounds
EQ 3	El Centro	6.6	18.5	Hwy8/Meloland Overpass
EQ 4	Northridge	6.7	5.5	Tarzana - Cedar Hill Nursery
EQ 5	Northridge	6.7	29.5	Sylmar - Pacoima Dam Upper Left Abutment
EQ 6	Northridge	6.7	19.2	Los Angeles, CA - 10660 Wilshire Blvd
EQ 7	Northridge	6.7	16.0	Sylmar - County Hospital Grounds
EQ 8	Northridge	6.7	13.0	6334 Katherine Rd., Simi Valley
EQ 9	Northridge	6.7	22.5	Santa Monica - City Hall Grounds
EQ 10	Northridge	6.7	18.0	Los Angeles - UCLA Grounds
EQ 11	Northridge	6.7	15.5	12520 Mulholland Dr., Beverly Hills
EQ 12	Northridge	6.7	19.8	Newhall - County Fire Sta.
EQ 13	Northridge	6.7	40.5	Castaic - Old Ridge Route
EQ 14	Northridge	6.7	11.1	13248 Roscoe Blvd., Sun Valley
EQ 15	Northridge	6.7	25.2	3960 Centinela St., Los Angeles
EQ 16	Northridge	6.7	19.2	Sylmar - Pacoima Dam Downstream
EQ 17	Northridge	6.7	18.0	Pacoima - Kagel Canyon Fire Sta
EQ 18	Northridge	6.7	26.5	607 N. Westmoreland Ave., Los Angeles
EQ 19	Northridge	6.7	38.5	Los Angeles - Obregon Park Geotech Array
EQ 20	Northridge	6.7	21.5	26835 W. Pico Canyon Rd., Newhall

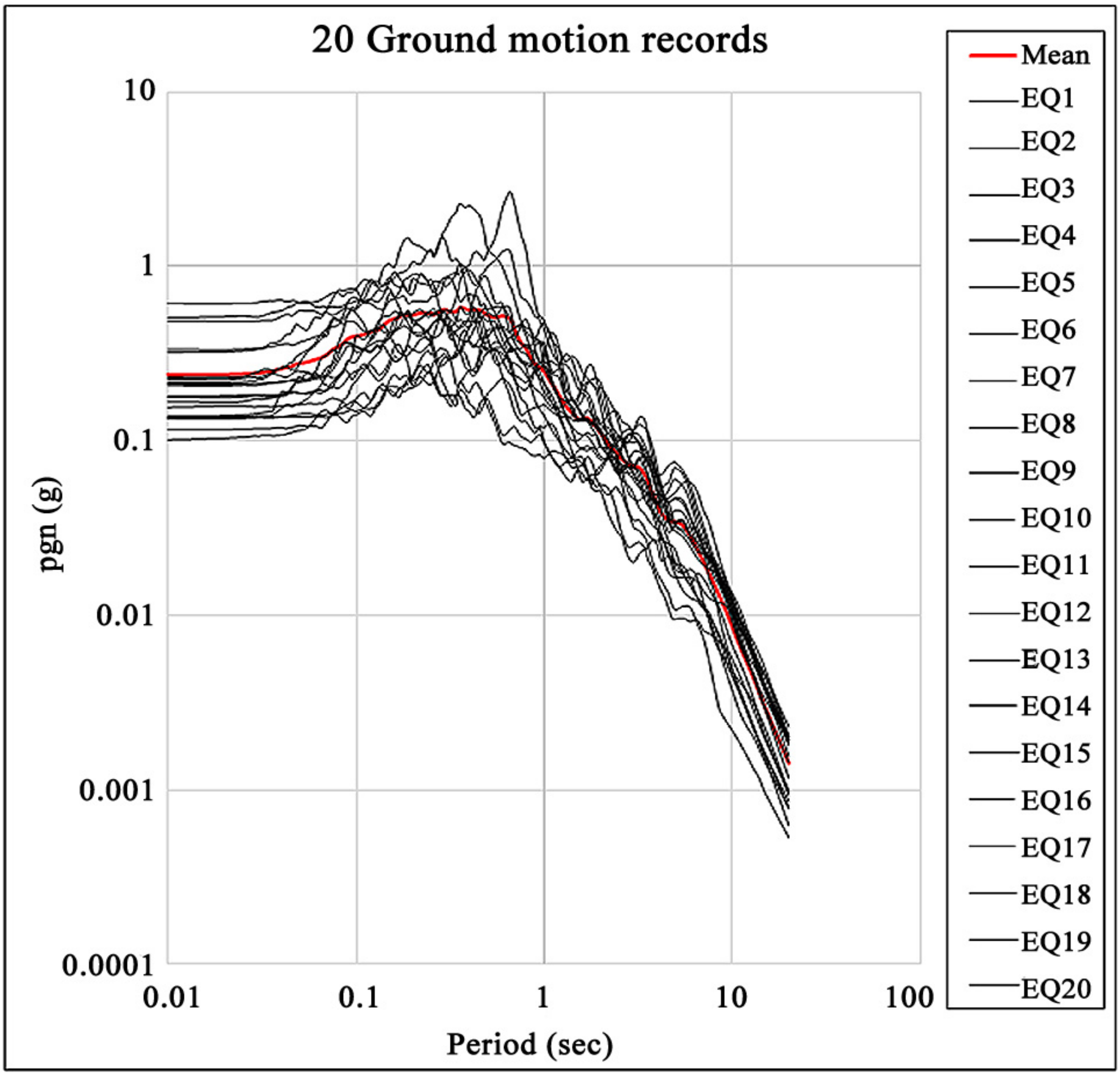


Figure 5. Ground motion records

4. Results and Discussion

For the prototype structures, nonlinear time-history studies were performed to calculate inter-story drifts at the threshold of a given damage state, and thus the IDA curve was created. With the help of the IDA curve and the above equation, the fragility curves are produced for drift criteria. These curves are known to estimate the damage potential index during the ground motion of an earthquake. They indicate the fragility assessment for seismic records and are used as a gauge to detect the bodily damage during the mainshock ground motion. For seismic demand calculations, nonlinear time-history analyses are perhaps the most accurate method due to the fact that structures often respond well beyond their elastic capacity under severe seismic loading. These kinds of analyses are used on a regular basis. When we observe that structures, particularly tall structures, "collapse" in some circumstances due to strength deterioration and/or considerable other consequences, there appears to be no approach currently available to define seismic demand calculations. The structures are modeled in a way that is stable, but once it reaches collapse prevention, even for a small increment in IM, the model will have large deformations. In such a case, we consider it dynamically unstable and considered as collapse.

Fragility curves using IDA required the critical properties of the structural model for performance-based design and are included in the present work. It would be realistic if the structural model was built with (numerically) robust and well-tested elements. However, such issues are inclusive in RAM Perform 3D. The dynamic analysis algorithm should be able to accurately track the structure's response through things like yielding events, sharp strength drops, load redistribution, and geometric nonlinearities; it would only fail to converge when the structure has used up its resources to become dynamically unstable. Using the results of nonlinear time-history studies for selected ground motions, the following graphic depicts the points of pairs formed (Damage index and intensity measure). Out of 20, single record analysis results are tabulated in the table 5. The maximum inter-story drift and Park and Ang damage index based on PGA were calculated for each ground motion and shown in Fig. 7.

Table 5. Intensity measure and damage measure of a particular record

IM	DM
0.2	0.00649
0.4	0.012955
0.6	0.016192
0.8	0.025587
1	0.030514
1.2	0.036189
1.4	0.04009
1.6	0.04189
1.8	0.04189
2	0.04189

Table 6. Mean (θ) and Standard deviation (β) values of five-story steel building model

Performance levels	OP	IO	LS	CP
Mean (θ)	0.35	0.48	0.8	1.4
Standard deviation (β)	0.21	0.25	0.28	0.38

Table 7. Mean (θ) and Standard deviation (β) values of two-story steel building model

Performance levels	OP	IO	LS	CP
Mean (θ)	0.28	0.39	0.65	1.1
Standard deviation (β)	0.15	0.25	0.28	0.3

The results of the probability of damage for the drift criterion, which is used to form fragility curves, are found by IDA and shown in Tab. 6 & Tab. 7. The Fragility curves for the drift criterion for different performance levels are plotted for different ground motions and tabulated as Tab.8 and Tab. 9. The curves are shown in the following from Fig. 8 to Fig. 10.

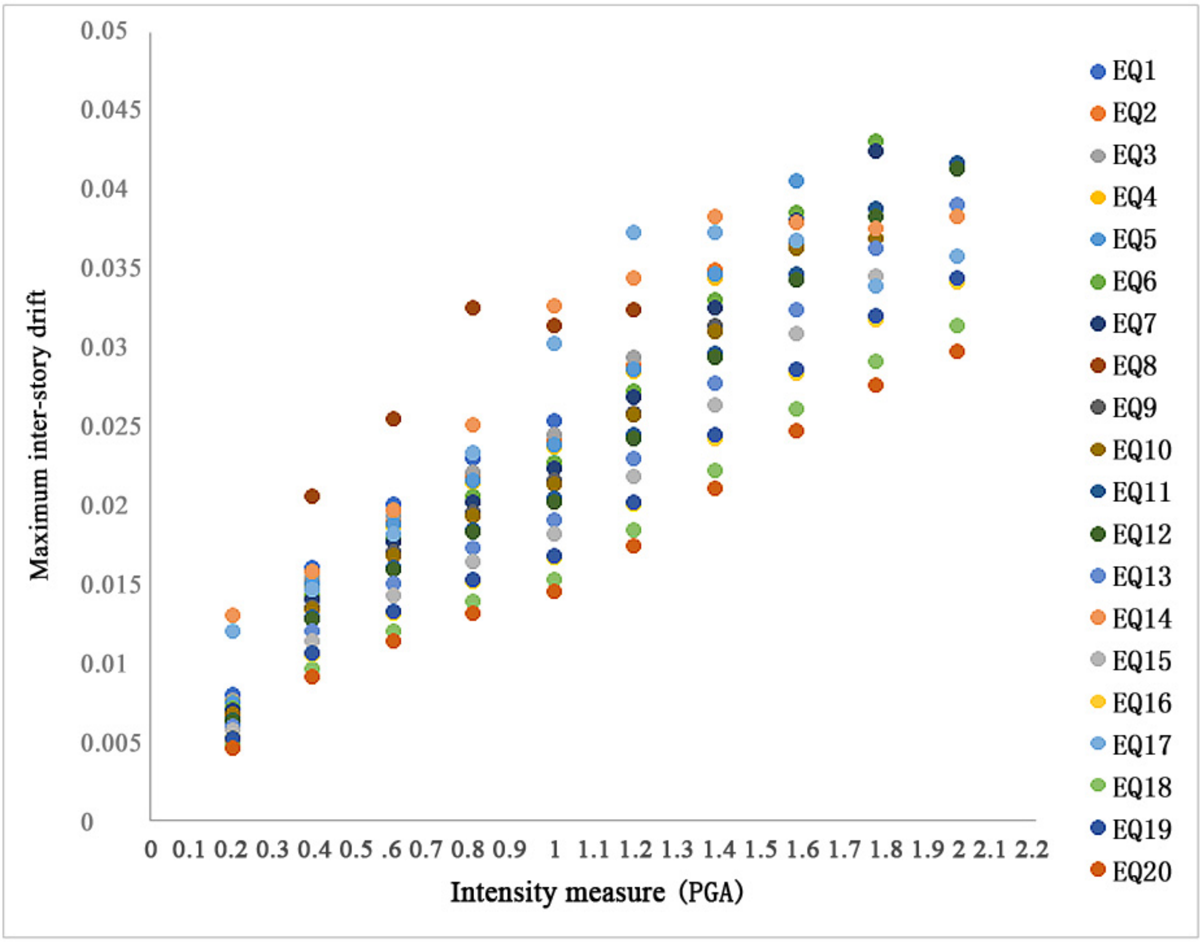


Figure 6. Maximum inter-story drift vs. Intensity measure points

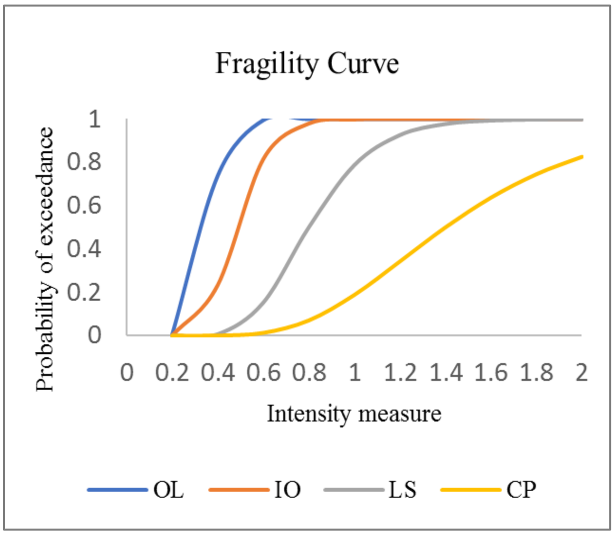


Figure 7. Fragility curve of a five-story steel building model for different performance levels

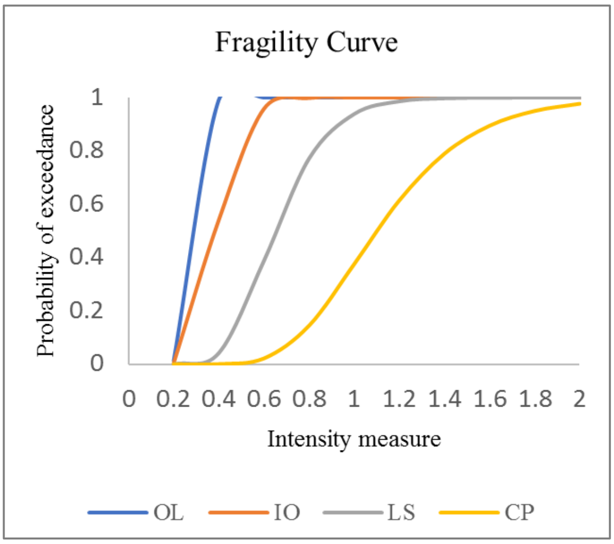


Figure 8. Fragility curve of a two-story steel building model for different performance levels

Table 8. Probability of exceedance values of five-story steel building model

Intensity measure (PGA)	Probability			
	OP	IO	LS	CP
0.2	0.003851	0.000231	3.64E-07	1.52E-07
0.4	0.737567	0.232913	0.006629	0.000489
0.6	0.994866	0.813957	0.151987	0.012883
0.8	0.999959	0.979489	0.5	0.07042
1	1	0.998337	0.787373	0.187956
1.2	1	0.999876	0.926305	0.342496
1.4	1	0.999991	0.97723	0.5
1.6	1	0.999999	0.993371	0.637355
1.8	1	1	0.99812	0.745807
2	1	1	0.99947	0.826037

Table 9. Probability of exceedance values of three-story steel building model

Intensity measure (PGA)	Probability			
	OP	IO	LS	CP
0.2	0.012444	0.003778	1.27E-05	6.64E-09
0.4	0.991293	0.540332	0.041386	0.000373
0.6	1	0.957568	0.387435	0.021668
0.8	1	0.997973	0.770938	0.144229
1	1	0.999917	0.938132	0.375356
1.2	1	0.999997	0.985765	0.614106
1.4	1	1	0.996943	0.789265
1.6	1	1	0.999356	0.894163
1.8	1	1	0.999863	0.949662
2	1	1	0.99997	0.976858

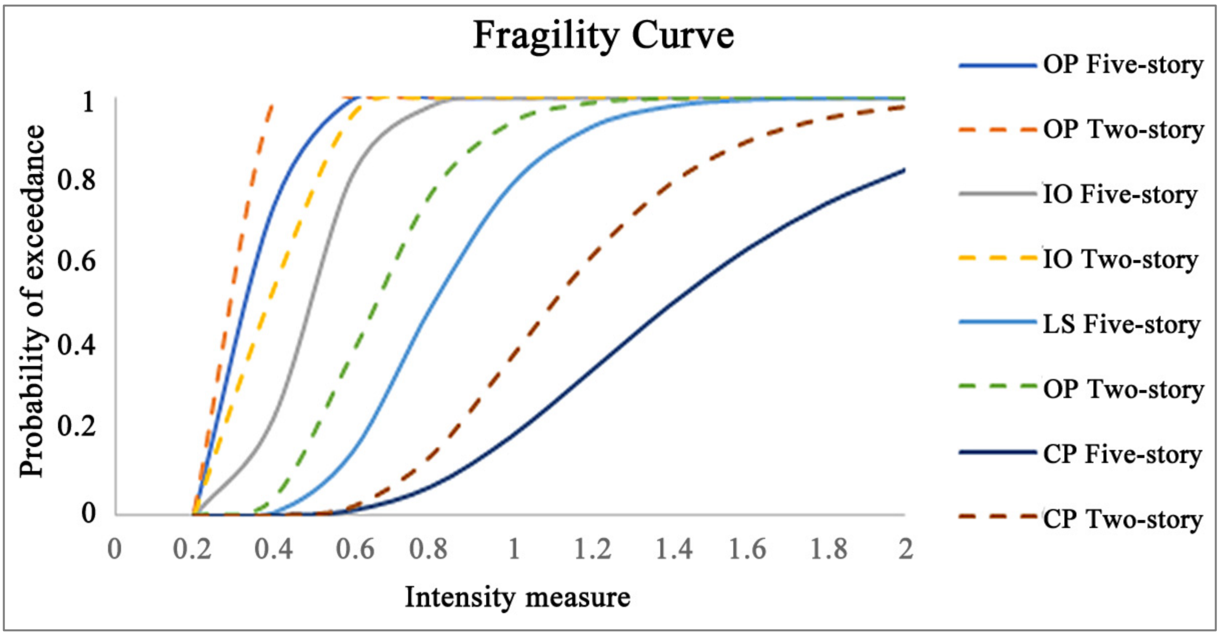


Figure 9. Comparison of fragility curves of both models

For each level, the two-story model gives the greater probability of exceedance at each intensity measure (PGA). The fragility curves for four different performance levels of three-story and five-story steel buildings are compared and shown in Fig.10.

The fragility function is widely used to lessen the cost of damage and loss of life during an earthquake. The probability of ground motion damage for aftershocks also needs to be inspected for deciding when to authorize re-occupancy of a building if not collapse. So, fragility curves are helpful as a tool for decision-making in both situations before and after the ground motion earthquake.

5. Conclusions

In order to account for the indeterminate character of following ground vibrations, methodologies to evaluate structural damage based on probabilistic nature must be developed and implemented. A fragility curve is a suitable approach for structural damage estimation for specific structures subject to possible earthquakes in the future. The method of producing fragility curves included an extensive probabilistic seismic damage study of the designed buildings model, which resulted in the inclusion of limit states and corresponding damage states for structures as variables in the fragility curves' development. At the damage state thresholds, inter-story drifts were established as variables, including a range of distinct values. The fragility curves for the building model's four damage states were calculated. This paper investigated the impact of the drift criterion on the model structure using sufficient time history analysis. The entire process to generate probabilistic fragility curves for buildings of various layouts is given in this paper and can be utilized to generate more curves for another model by the same process.

The fragility curve developed using this incremental dynamic analysis curve may be of considerable importance for assessing the general danger for the essential civil infrastructure from the impact of potential future earthquakes and for foreseeing the economic effect of future potential earthquakes. They may also be used to ease the danger by fine-tuning the current seismic codes for the design of the new building. They can be much valuable for emergency measure response and the planning for disaster through a national authority. A fragility curve established with the help of experimental value may help decrease the epistemological uncertainties on the damage response. It may help estimate the probability of failure or damage degree level which a building could be sustained at a particular level of earthquake ground motion. The information could be further applied for recognizing the buildings which are deficient and thus to provide the suitable retrofitting technique, thereby decreasing its catastrophic failure when the building is subjected to the possible impact of future earthquakes.

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