SEISMIC FRAGILITY CURVE DEVELOPMENT FOR RC STRUCTURES

A DISSERTATION

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FOR THE AWARD OF A DEGREE
OF**

**MASTER OF TECHNOLOGY
IN
STRUCTURAL ENGINEERING**

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I, Sudarshan Saikia, Roll No. 2K/20/STE/23 student of M.Tech. (Structural Engineering). Hereby declare that the project dissertation titled "**SEISMIC FRAGILITY CURVE DEVELOPMENT FOR RC STRUCTURES**" which is submitted by me to the Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, or other similar title or recognition.

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CERTIFICATE

I, hereby certify that the Project titled "**SEISMIC FRAGILITY CURVE DEVELOPMENT FOR RC STRUCTURES**" which is submitted by Sudarshan Saikia, Roll No. 2K/20/STE/23, Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of degree the of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any degree or diploma to this university or elsewhere.

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Date:	**SUPERVISOR**

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SUDARSHAN SAIKIA

ABSTRACT

Strong earthquake in recent history has caused major physical damage and casualties. Parts of India facing destructive earthquakes are at high risk. As many reinforced concrete buildings are not built according to the current building code, seismic activity is not taken into account during the selection of the structural framework, and in most cases inspection during the construction process is not adequate which in turn causes deficiencies. Researchers introduced fragility curves to measure the seismic efficiency of reinforced concrete frame structures. The fragility curve offers estimates of the probabilities of approaching or exceeding different limit states at defined ground shaking intensity levels for an individual structure or structural population. The seismic susceptibility of these structures to different earthquakes can be interpreted. The pushover analysis (PA) was performed by using the ETABS software. Limit state functions were defined as per HAZUS methodologies.

Keywords: Pushover analysis, Damage parameters, Spectral displacement, Probability distribution.

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CHAPTER 1

INTRODUCTION

1.1 SEISMIC FRAGILITY CURVE

It's a tool for determining the level of risk or safety. For a given potential earthquake hazard (PEH), a fragility curve (FC) is a calculation of the probability of being in or above each damage state over time.

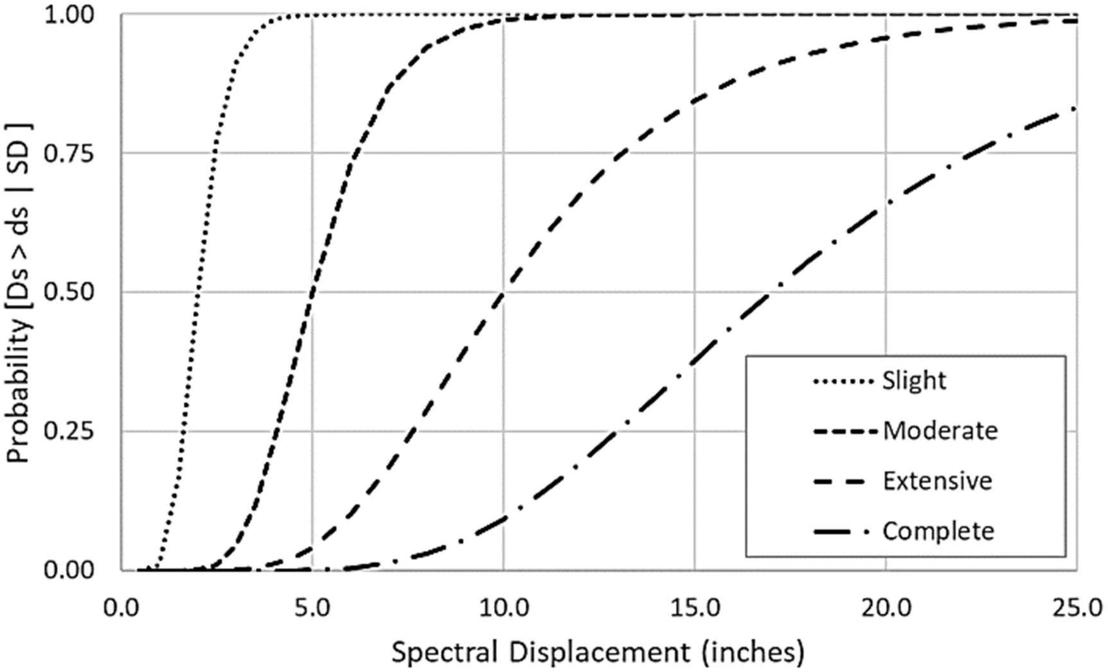


Figure 1: Typical Fragility Curve.

Fig.1 is a typical FC plotted to assess the risk of a particular building subjected to a PEH. The FC is plotted when a PEH parameter is exceeded. Peak spectral acceleration (S_a) or peak spectral displacement (S_d) is the PEH parameter used to define the fragility curve for ground shaking. Peak ground acceleration (PGA) is used in assessing the damage to a structure that is part of a utility or transportation system.

Earthquake engineering has progressed over time, moving away from force-based approaches and toward performance-based solutions. The concept of designing for the force is evolving into designing for a specific performance goal set by stakeholders. Engineers are familiar with performance metrics like strain, drift, and acceleration, but stakeholders may be more comfortable with the cost of design. Many aspects must be considered when converting the performance of a structure to a format that includes repair costs in a systematic manner.

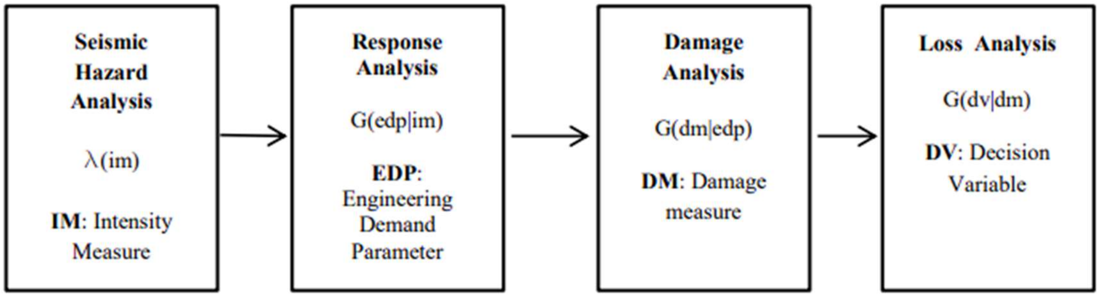


Figure 2:Framework of Performance-based design.

The components of a performance-based seismic engineering framework are shown in Figure: 2. The construction of FC is the second component of this framework.

1.2 DAMAGE STATES

The expected damage pattern of earthquakes in different areas is studied using the building damage states (DS) or limit state function (LSF). The HAZUS technique defines distinct DS that correlates to different types of buildings and seismic levels, as well as how these states evolve. This section's discussions are based on the manual. For an RC moment resistant frame, the DS is defined as:

1. Slight Structural Damage: Hairline fractures due to flexural or shear damage have been seen in a number of beams and columns close to or within joints.
2. Moderate Structural Damage: The yield capacity of the ductile frame members is reached. Large shear cracks and spalls can occur in non-ductile frames.
3. Extensive Structural Damage: Large flexural fractures, spalled concrete, and bowed primary reinforcement show that ductile frame parts have reached their maximum capacity. In non-ductile frames, shear failures or bond failures such as reinforcement splices, broken connections, or bowed main reinforcement may have occurred.
4. Collapse Structural Damage: Due to the brittle disintegration of nonductile frame elements or a lack of frame stability, the structure has collapsed or is about to collapse.

A median value of the PEH demand parameter that corresponds to the DS threshold defines the probability of exceedance for each DS. S_d is the spectral displacement that identifies a specific damage condition.

$$S_d = \overline{S}_{d,\,ds} * \varepsilon_{ds} \text{ --- } (1)$$

Where, $\overline{S}_{d,\,ds}$ = Damage spectral displacement median value.

ε_{ds} = lognormal random variable with unit median value and logarithmic standard deviation, β_{ds}

$\overline{S}_{d,\,ds}$ are based on building drift ratios, which specify the damage state's threshold.

The damage state drift ratios are related to S_d using the following formula:

$$\overline{S}_{d,\,ds} = \delta_{R,\,Sds} * \alpha_2 * h \text{ --- } (2)$$

Where, $\delta_{R,\,Sds}$ = the drift ratio at the structural damage state's threshold.

α = at the position of the pushover mode displacement, a percentage of the building roof height

h = typical roof height.

β_{ds}, the total variability of each damage state is modeled as,

$$\beta_{sds} = \sqrt{CONV\left[\beta c, \beta D, \overline{S}d, ds\right]^2 + \beta M(ds)^2} \text{ --- } (3)$$

Where, β_{sds}= lognormal standard deviation that describes the total variability for structural damage, ds.,βc = lognormal standard deviation parameter that describes the variability of the capacity curve, βD = lognormal standard deviation parameter that describes the variability of the demand spectrum, and $\beta M(sds)$= lognormal standard deviation parameter that describes the uncertainty in the estimate of the median value of the threshold of the structural damage state, ds.

The values of β_{ds} and $\overline{S}_{d,\,ds}$ required in equation no: 1 are given in the HAZUS manual as structural fragility parameters for each DS, type of building, and seismic design level.

Given the S_d, the conditional chance of being in or exceeding a specific DS is,

$$P[ds/S_d] = \phi\ [1/\beta_{ds} * \ln (S_d/S_{s,\,ds})] \text{ --- } (4)$$

Reliability analysis has been widely used to quantify uncertainty in a variety of engineering domains. In general, using the simulation approach, the "precise" chance of structural failure for sophisticated structures can be computed. When the genuine limit state cannot be described explicitly, a random sampling technique combined with a computer-based analytical or numerical model is used to simulate the structural system's behavior. Although the Monte-Carlo simulation can produce correct results, it always necessitates a significant amount of computational work and is frequently impractical in circumstances where there is no closed-form limit state function (LSF). Other approaches to reducing total CPU time have been proposed. Two of these are the first-order reliability method (FORM) and the response surface method (RSM). When the LSF is implicit, the FORM is a gradient-based approach, and the gradients of LSF with basic variables can be computed using the finite difference method. Typically, the RSM is employed to approximate the implicit LSF.

The RSM's basic principle is using a similar explicit mathematical function of the random variables involved in the LSF to approximate the implicit LSF. The FORM can be used to assess the chance of failure because the approximated LSF is explicit. The response surface's quality is mostly determined by the response surface function chosen and the sample points chosen.

1.3 PUSHOVER ANALYSIS

Pushover analysis (PA) is a non-linear static analysis method. Although the building is nonlinear, the seismic stress is idealized as a static load. A monotonically growing lateral stress applied in increments up to a preset state or value softly 'pushes over' the structure (computer Model). The methods of pushover analysis, namely the Displacement Coefficient method or the Capacity Spectrum method, define the predetermined value or state to which the structure (computer model) is to be pushed. H_k, which is specified in IS1893:2016, is proportionate to lateral load. H stands for the height of the structure.

In traditional seismic analysis, lateral loads of a predetermined intensity are applied all at once. The lateral load is distributed in a parabolic pattern (in the Seismic coefficient method). The modal combination determines the lateral load (in the Response spectrum method).

A pushover curve, also known as a capacity curve, is a graph that depicts a structure's lateral load resistance as a function of lateral displacement. The force base shear (V_b) axis is transformed to S_a, while the displacement axis is turned to S_d to facilitate direct comparison with earthquake demand. Because of the relationships between V_b, roof displacement ($\Delta_{\text{roof top}}$), and time period (T).

$$S_a = \frac{\text{Vb/W}}{Mk/M} * g \text{ --- (5)}$$

$$S_d = \frac{\Delta\text{roof top}}{\text{Pk } \varphi\text{k,rooftop}} \text{ --- (6)}$$

Where, M_k, P_k, and $\varphi_{\text{k, rooftop}}$ are Modal mass, Mode participation factor, and Mode amplitude at rooftop respectively for the ‘k’ mode. The total mass and weight of the structure are M and W.

Building capacity curves describe the reaction of a structure. The intersection of the building capacity curve and the response spectrum of PEH shaking demand at the building's location is used to estimate peak building response. The demand spectrum is a condensed version of the PEH input spectrum with a damping factor of 5% for higher effective damping levels.

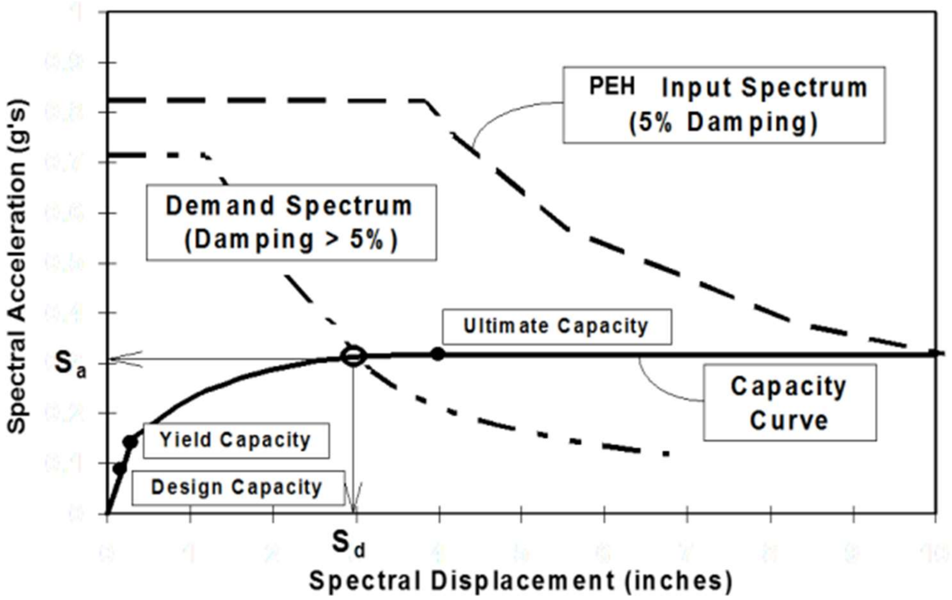


Figure 3: Capacity and Demand curve

Figure 3 depicts the intersection of a typical building capacity curve with a typical demand spectrum. Design, yield, and ultimate capacity points significantly influence the shape of building capacity curves. The parameter utilized with FC to predict DS probability is peak building response at the point of intersection of the capacity curve and demand spectrum.

Non-linear hinges are used to incorporate non-linearity in PA. Hinges on a structure are expected to experience more cracking and yielding than other parts of the structure. They can be found on both ends of the beam and in the columns. Flexural and shear hinges are installed at the ends of beams and columns. The axial hinges are installed at both ends of the diagonal struts, which serve as masonry infills.

A hinge, as shown in fig. 4, displays an element's localized force-displacement connection under seismic stress through its elastic and inelastic phases. Within their ductile range, these hinges have non-linear states such as immediate occupancy (IO), life safety (LS), and collapse prevention (CP). These states are defined in fig:2 by dividing BC into halves. Several standard standards suggest different criteria for splitting the BC division.

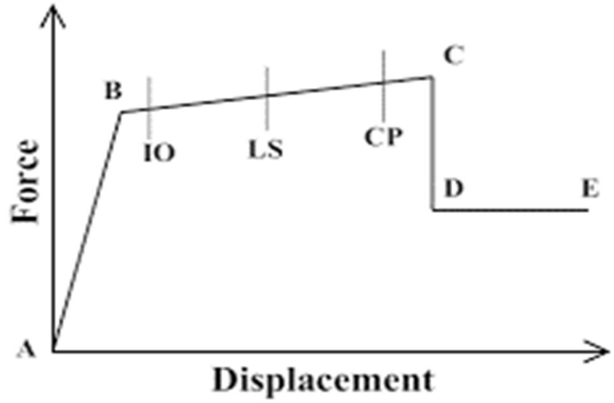


Figure 4: Elastic- Plastic Behavior.

AB: Linear elastic range.

BC: Inelastic but linear response is reduced.

CD: Load resistance drops suddenly.

DE: Resistance has been reduced.

EF: Depletion of total resistance.

1.4 OBJECTIVE OF THE STUDY

The main purpose of this research is to provide a tool for analyzing the seismic susceptibility of structures. Defining a damaged condition is judged to be the most significant parameter when assessing any vulnerability. The structural behavior of a structure subjected to seismic loads is represented by the capacity demand characteristics study. The following are the study's objectives:

1. Determine the reaction of the structure under seismic loads.
2. Establishing an upper limit for damaged conditions.
3. Calculating the seismic risks of a structure using a fragility curve.

1.5 THESIS ORGANIZATION

The second chapter, which follows the introduction chapter, undertakes a literature study on building fragility evaluation. In Chapter 3, the methodologies used to achieve the goal are outlined. Finally, the conclusions, limitations of the work, and future scope of this study are discussed in Chapter 4.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL:

The knowledge needed to achieve the study's goal was gleaned from a variety of sources. The purpose of reviews is to have a better understanding of the methodologies used by researchers to plot the fragility curve. To do pushover analysis, various standards were explored to characterize the damage states.

2.2 FRAGILITY CURVE DEVELOPMENT

Patel and Vasanwala (2020) discuss the analytical approach using the HAZUS technical manual's requirements. The plastic yielding phenomenon is studied using nonlinear static analysis. FC for 3, 6, and 12-story buildings was plotted.

Bakhshi and Soltanieh (2019) used OpenSees to simulate a three-dimensional building with buckling braces. As discussed in FEMA 356, limit states were defined. The FEMA P 695 approach was used to identify ground motion records and analyze uncertainty.

Unnikrishnan et al (2012) found that the Monte Carlo technique takes a significant number of simulations to generate a sufficiently valid estimate of the fragilities, and simulating the thousands of time history analysis is computationally expensive and time-consuming. In this paper, a response surface method based on high dimensional model representation (HDMR) is proposed. When compared to Monte Carlo simulation, the computational effort required to compute the fragility curve using HDMR is quite minimal. The HDMR method reduced the computational effort for a 3-bay 6-story RC plane frame examined using nonlinear time history analysis by 97.4 percent.

Fujimura and Kiureghian (2006) discussed the tail equivalent linearization method (TELM) from a broad perspective. TELM is a linearization method for nonlinear systems with stochastic inputs that employs first-order reliability (FORM) to construct a tail-equivalent linear system and estimate the tail probability of the response distribution. The response surface approach is used to plot fragility curves.

Akkar et al (2005) studied building capacities are gathered from field data, and their dynamic reaction is computed using response history analysis. The PGA is used as the earthquake intensity. The global drift ratio is used to evaluate damage states. At each damage limit state, the difference between predicted and measured fragilities was less than 10%.

2.3 DAMAGE STATES CONSIDERATIONS

DS are classified as per the HAZUS methodology. DS is distinguished by the fragility curve parameter of each level's median and standard deviation values. The values taken into account are discussed in Section 1.3 and 4.2.

Damage states are defined by FEMA 273 criteria as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). The drift ratio is used to calculate these damages.

2.4 PUSHOVER ANALYSIS PROCEDURE

The Displacement coefficient approach, detailed in FEMA 356, involves calculating a target displacement to which the structure is pushed. The similar method is used in Eurocode 8 (EN 1998-1, 2003). The capacity spectrum approach, described by ATC-40, involves increasing the load and checking it at each stage until the 'Performance Point' condition is attained.

CHAPTER 3

METHODOLOGY

3.1 MODELLING OF THE STRUCTURE:

In the ETABS software, a 3-bay 4-story RC plane frame building is modelled with specified parameters. The structure is built in accordance with the provisions of the IS code.

Table 1: Building specifications

Height of building	12 m	Seismic Parameters	
Beam Size	8” X 12”	Seismic Zone	V
Column Size	12” X 12”	Zone Factor Z	0.36
Slab Thickness	150 mm	Importance Factor I	1
Concrete Grade	M30	Reduction Factor R	5
Steel Grade	Fe415	Soil Type	Type II
Dead Load	2 kN/m²		
Live load	3 kN/m²		

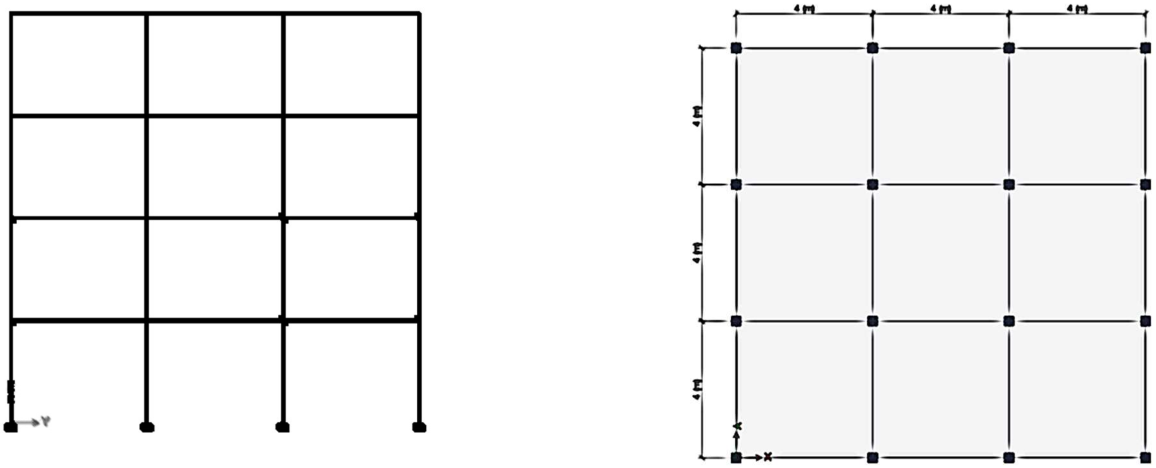


Figure 5: Elevation and Plan view.

3.2. PERFORMING PUSHOVER ANALYSIS

The first chapter covers the fundamentals of PA. PA is accomplished in the ETABS software by following the processes outlined below:

1. In 'Load Cases,' dead load is considered nonlinear.
2. Hinge attributes are ascribed to beams, columns, walls, and other structural elements.
3. Only Dead loads and PA 'Load cases' are used in the analysis.

Plastic hinges are assigned at a 10% relative distance from the joints to perform Pushover analysis on the model shown above.

3.3. DEFINING DAMAGE STATE FUNCTION

DS are established according to the HAZUS methodology outlined in Chapter 1. Fragility curves are depicted for various DS, which corresponds to seismic design levels.

3.4. PLOTTING FRAGILITY CURVE

Finally, the fragility curve is presented as a function of spectral distance and the chance of exceeding the stated damage states. A cumulative lognormal distribution is used to calculate (Equation No.:4) the likelihood of exceeding the threshold.

CHAPTER 4

RESULTS

4.1 SOLUTIONS OF PUSHOVER ANALYSIS

Procedures described in section 1.3 can be used to derive the capacity curves for Δ_{Roof} vs V_b and S_d vs S_a. The capacity curves shown here were generated using Etabs software (Table:3).

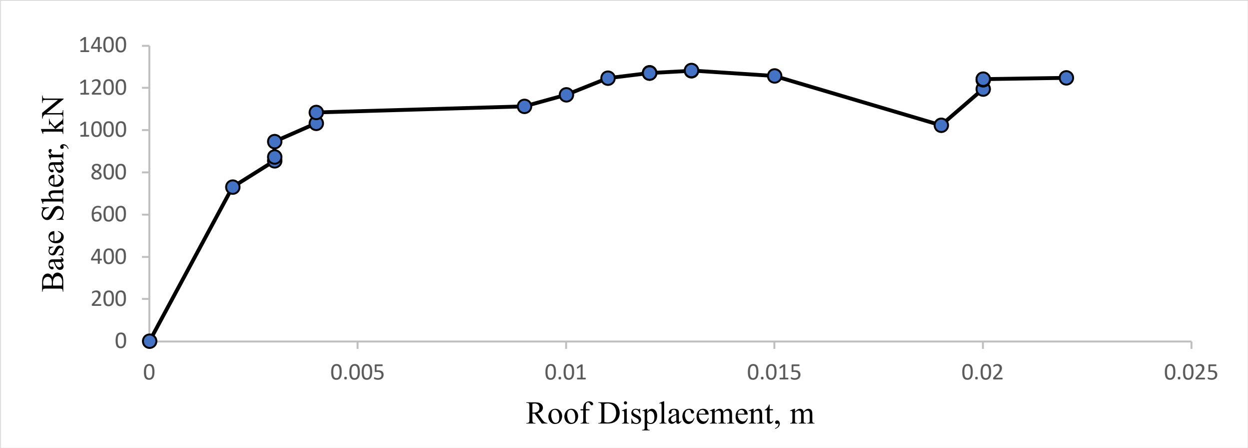


Figure 6: Pushover Capacity Curve (V_b vs δ_{roof}).

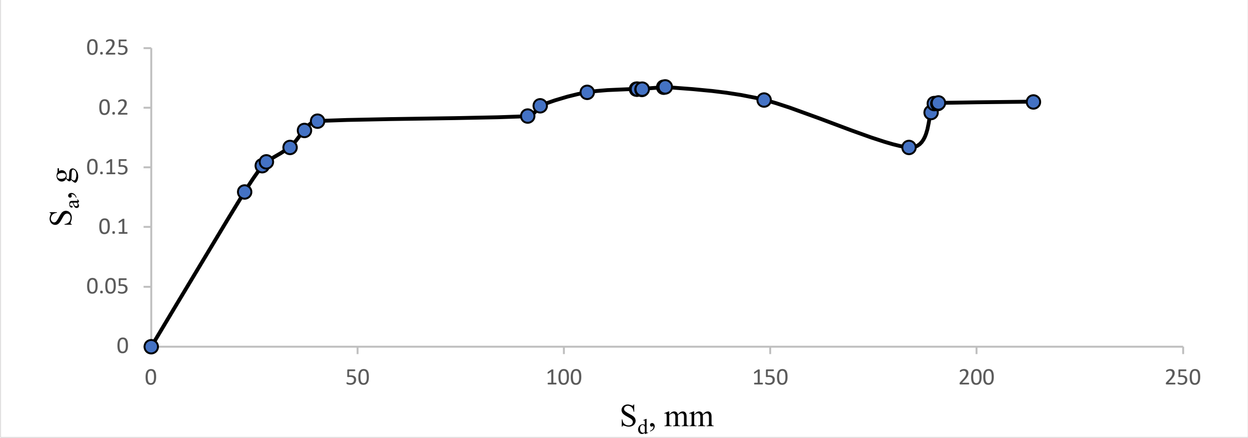
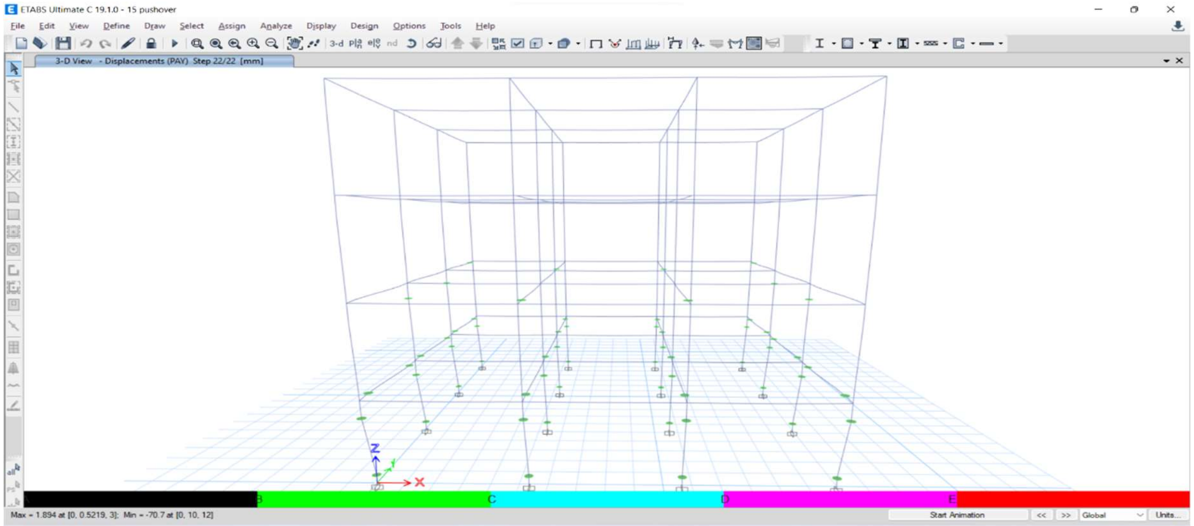


Figure 7: Pushover Capacity Curve (S_d vs S_a).

The lateral loads are applied in stages in a Pushover study. Plastic hinges begin to emerge as the number of steps increases. All of the hinges in this study were created in the BC region of fig:4 or the green region (BC) of fig:8.



Max = 1.894 at [0, 0.5219, 3]; Min = -70.7 at [0, 10, 12]

Figure 8: Plastic hinge formations.

4.2. DEFINED DAMAGE STATES

HAZUS techniques are used to consider limit state functions. The structural fragility curve parameters are used to calculate the DS values for S_d (Table: 2).

Table 2: Damage states parameters as per HAZUS methodologies.

Spectral Displacements (inches)								
Damage State	Slight		Moderate		Extensive		Collapse	
Parameter	$\overline{S}_{d,\,ds}$	β_{ds}	$\overline{S}_{d,\,ds}$	β_{ds}	$\overline{S}_{d,\,ds}$	β_{ds}	$\overline{S}_{d,\,ds}$	β_{ds}
High-code Seismic design level	1.50	0.68	3.00	0.67	9.00	0.68	24.00	0.81
Moderate-code Seismic design level	1.50	0.69	2.60	0.69	7.00	0.69	18.00	0.90
Low-code Seismic design level	1.5	0.71	2.40	0.74	6.00	0.86	15.00	0.98

4.3. FRAGILITY CURVE COMPUTING

Finally, by graphing the risk of surpassing a damaged condition by the spectral displacement, the FC is represented as a lognormal cumulative distribution. The curves for each DS at each seismic level are shown below. Calculations are shown in appendix A.

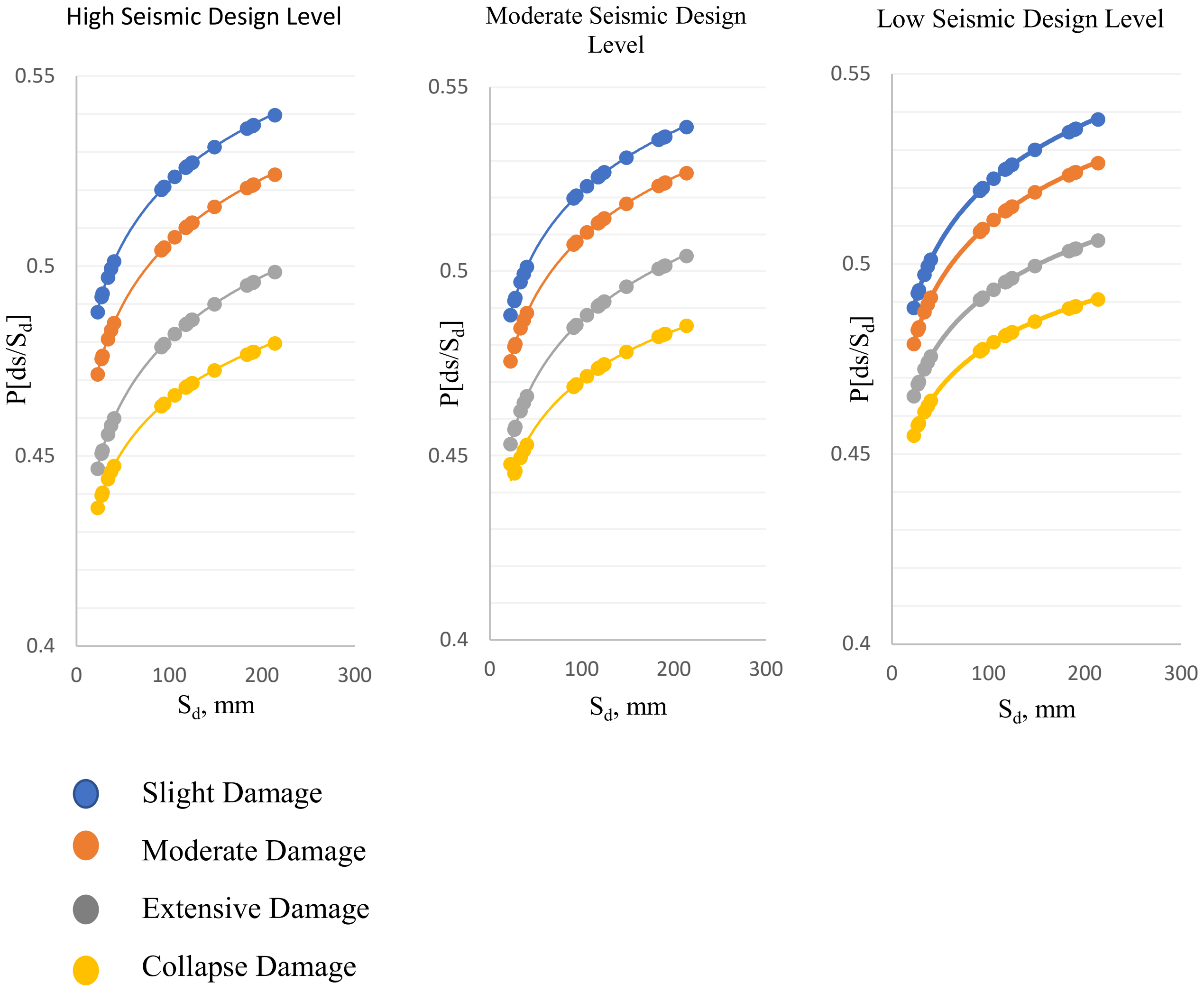


Figure 9: Fragility Curves obtained for different seismic design levels.

CHAPTER 5

DISCUSSIONS

5.1. GENERAL

Fragility curves are plotted for different limiting values for the damage parameter. The intensity measured here is the spectral displacement of the earthquake. As the limiting value increases the curve shifts towards the right and becomes flatter.

From the fig:9, it can be seen that at weak shaking the probability of exceedance for the limit state corresponding to slight damage is high, which means slight damage is sure, moderate, and extensive damages are likely to occur. Whereas if there is an earthquake of strong intensity the building is more likely to be crossed the damage states of slight and moderate. The exceedance probability for the extensive damage state is more than that of the collapse damage state.

Regions of various damage states such as slight, moderate, Extensive, and collapse damages are marked between each fragility curve. With the severity of the damage, the parameter defining the limit state of damage increases, and the exceedance probability decreases.

5.2. LIMITATIONS AND FUTURE SCOPES

The fragility curve for the damage states is displayed in this study based on FEMA rules. These damage states can also be determined using the response surface approach, which employs the principles of the structural reliability domain's first-order second-moment method. Large iterative simulations are required to investigate the relationship between the structure's resistance and the action taken. To minimize the variances in the correlation, superior computing abilities and licensed analysis tools are required.

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APPENDIX A: Probability of exceedance calculation.

The S_d values obtained from Etabs software were analyzed for cumulative lognormal distribution matching to DS, as well as their median and standard deviation data specified in HAZUS guidelines, in order to plot the fragility curve. Below are calculations for slight damage related to a high code seismic design level.

We need to find,

$$P[ds/S_d] = \phi\ [1/\beta_{ds} * \ln (S_d/S_{s,\ ds})]$$

S_d can be found from the pushover analysis results as shown in the table:3.

Table 3: S_d and S_a values obtained from pushover analysis results.

S_d, mm	S_a, g		S_d, mm	S_a, g
22.631	0.129671		118.872	0.215617
26.894	0.151541		118.901	0.215779
27.866	0.154753		124.14	0.217277
33.569	0.167025		124.54	0.217567
37.102	0.181098		148.425	0.206699
40.234	0.188891		183.576	0.166878
91.158	0.193111		188.933	0.196206
94.173	0.2017		189.672	0.203624
105.569	0.213052		190.537	0.203752
117.497	0.215776		190.681	0.204089
117.774	0.215785		213.684	0.205092

$S_{s,\ ds}$, and β_{ds} values are outlined in HAZUS guideline corresponding to high seismic design level and height of the building. Values assumed in this study are tabulated in table:4.

Table 4: S_{sd} and β_{ds} assumed as per HAZUS Manual.

HIGH CODE SEISMIC DESIGN LEVEL				
Damage sate	**$S_{s,d}$, in**	**$\beta_{ds, in}$**	**$S_{s,d, mm}$**	**$\beta_{ds, mm}$**
Slight	1.5	0.68	38.1	17.272
Moderate	3	0.67	76.2	17.018
Extensive	9	0.68	228.6	17.272
Complete	24	0.81	609.6	20.574

Calculations of the $P[ds/S_d]$ using the above equation, the exceedance probabilities are calculated and illustrated in table:5 for a slight damage state condition.

Table 5:Calculation of the probability of exceedance.

S_d, mm	**ln (S_d)**	**ln ($S_{s, ds}$)**	**ln ($S_d/S_{s,ds}$)**	**1/β_{ds}*ln ($S_d/S_{s, ds}$)**	**Norm.S. Dist** $P[ds/S_d]$
22.631	3.119321	3.640214	-0.520894	-0.03015827	0.48797041
26.894	3.291903	3.640214	-0.348311	-0.020166227	0.49195538
27.866	3.327407	3.640214	-0.312807	-0.01811064	0.49277529
33.569	3.513603	3.640214	-0.126611	-0.007330434	0.49707561
37.102	3.613671	3.640214	-0.026543	-0.001536788	0.49938691
40.234	3.694712	3.640214	0.054498	0.003155288	0.50125878
91.158	4.512594	3.640214	0.87238	0.050508336	0.52014135
94.173	4.545134	3.640214	0.904919	0.052392267	0.52089193
105.569	4.659365	3.640214	1.01915	0.059005934	0.52352631
117.497	4.766413	3.640214	1.126199	0.065203712	0.5259941
117.774	4.768768	3.640214	1.128553	0.065340045	0.52604837
118.872	4.778047	3.640214	1.137833	0.065877316	0.52626225
118.901	4.778291	3.640214	1.138077	0.065891439	0.52626787
124.14	4.82141	3.640214	1.181196	0.068387892	0.52726157
124.54	4.824627	3.640214	1.184413	0.068574147	0.5273357
148.425	5.00008	3.640214	1.359865	0.07873237	0.53137725
183.576	5.212629	3.640214	1.572414	0.091038355	0.53626894
188.933	5.241392	3.640214	1.601178	0.092703692	0.53693052
189.672	5.245296	3.640214	1.605082	0.092929712	0.5370203
190.537	5.249846	3.640214	1.609632	0.093193152	0.53712494
190.681	5.250602	3.640214	1.610388	0.093236892	0.53714232
213.684	5.364498	3.640214	1.724284	0.099831172	0.53976082

APPENDIX B: Pushover Capacity Curves obtained from Etabs.

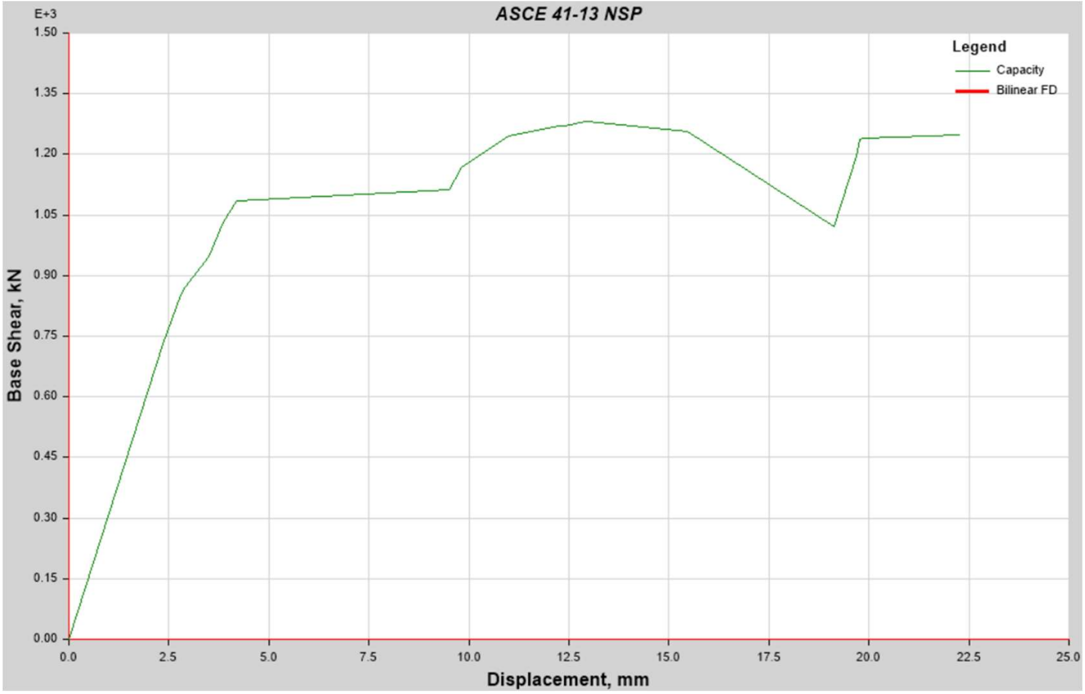

Figure 10: Capacity Curve obtained from Etabs.

Figure 11: Capacity and demand curves in terms of S_d and S_a

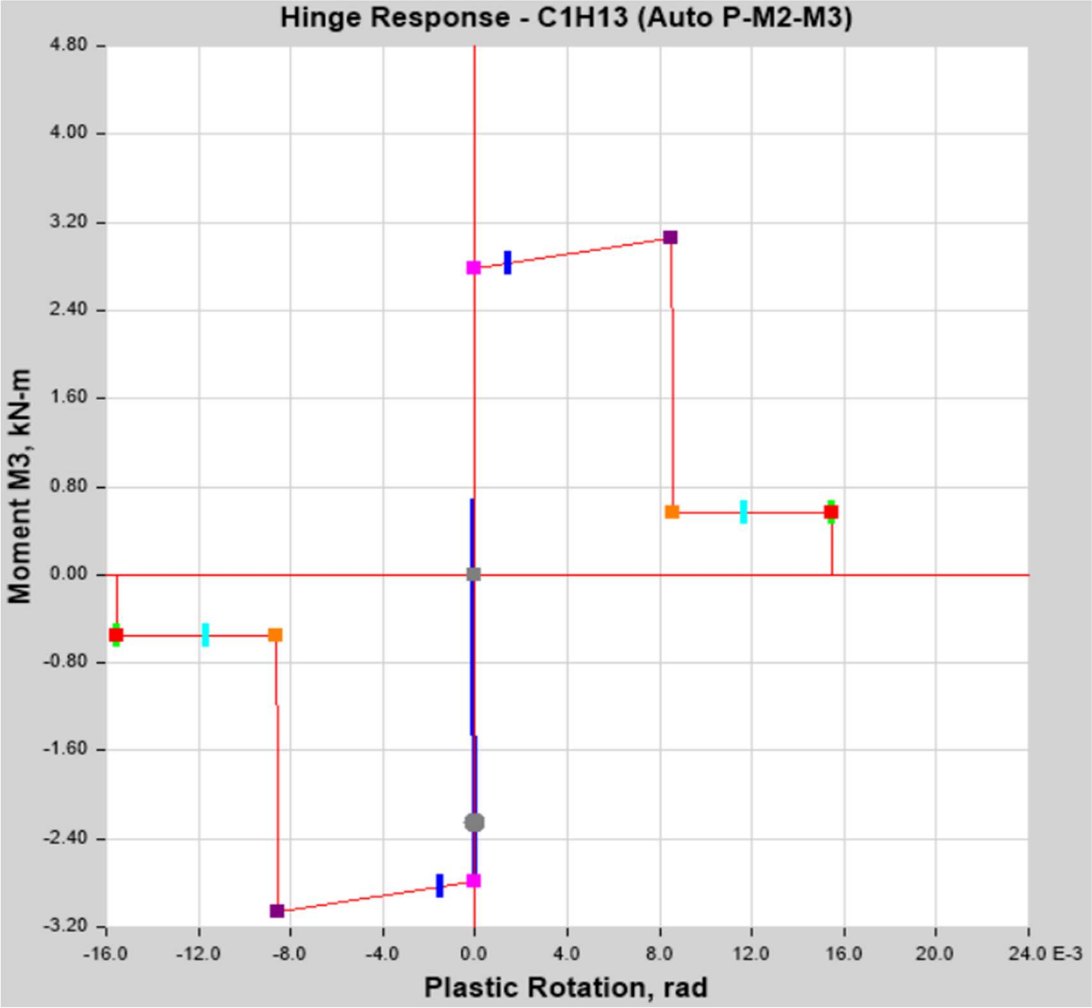

Figure 12: Hinge response.