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SEISMIC VULNERABILITY ASSESSMENT OF 125M HIGH RCC CHIMNEY UNDER INDIAN EARTHQUAKES

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ABSTRACT

Evaluation of seismic vulnerability of very flexible structures such as high-rise petrochemical and refinery stacks (chimney) and power plant chimneys are a challenging problem in earthquake engineering. Their equipment and structures are often considered as vital facilities and thus they must be fully functional after even very strong ground motions. From other point of view, numerical modelling of such mega-structures with numerous elements may not allow to consider all details of mechanical characteristics of consisting materials, particularly nonlinear performance of elements during large deformations. Therefore, a simplified model corresponding to dynamic characteristics of whole structure is substantially needed to investigate seismic performance and failure modes of these essential structures subjected to strong ground motions. The procedure for developing a 2-D simplified nonlinear model based on moment-curvature in some plane-sections of a 3-D sophisticated model but linear system having almost identical dynamic properties is discussed. However, basic dimensions of industrial RC chimney, such as height above ground, the diameter at top, etc., are generally derived from the respective national environmental provisions for where the structure is to be built. The objective of the present study is to investigate the vulnerability reinforced concrete chimney under various Indian earthquakes.

Keywords: Earthquake, Chimney, Vulnerability curve, Wind, seismic design

1. INTRODUCTION

Chimney is a structure that encloses the flue and along with it forms a system that provides ventilation for hot gases or smoke to the open-air atmosphere. To ensure smooth flow of gases and to draw air into the combustion, also known as stack effect or chimney effect, chimneys are typically vertical or close to vertical. Industrial chimneys that exist today in many parts of the world including India are predominantly built using Reinforced Concrete (RC).

The chimneys constructed during and before late seventies may be vulnerable to damage during earthquakes because of old construction techniques or inadequate seismic design. Previous codes do not cover sufficient seismic detailing compared to the current codes.

Due to the advancements in the design codes, it is deemed necessary to evaluate the design of the previously constructed chimneys using current codes to ensure their safety. This study emphases on the behaviour of the windshield of RC chimney, when subjected to seismic action and the response of structure under a given wind load. The response of the flue liner is not considered in the study.

RC concrete chimneys are subjected to various types of loads in both vertical and lateral directions. The primary loads that a concrete chimney generally experiences are pressure due to wind loads, the loads due to the seismic action, and temperature loads aside from self-weight of the structure and the loads imposed on the service platforms. The effects due to the action of wind on RC chimney plays an important role on its structural behaviour as concrete chimneys in most cases are very tall and slender structures. Earthquake is also a prime consideration for chimneys as seismic load is considered as a natural load and is dynamic in its nature. Code provisions advise to use quasi-static method for the evaluation of seismic loads. Chimneys – typically recognized as high and flexible structures – are subject to a large number of failure cases. The failure cases of 739 chimneys were statistically summarized in this paper, and a few statistical laws of chimney failure under many causes such as earthquake action, wind load and temperature stress were analysed. The results indicate that the failure of steel chimneys was mainly triggered by wind load, the damage to reinforced concrete chimneys were mainly caused by temperature stress and construction defect, while 90% of the failure cases of masonry chimneys are put down to earthquakes. Most failures are the consequences of earthquakes, followed by temperature stress. Moreover, were masonry chimney to be excluded, temperature stress becomes responsible for the most damage – accounting for about 50% and earthquakes; construction and wind load inclusive, account for nearly the same proportion. The severity of these causes is arranged in a descending order – wind, earthquakes, temperature and construction.

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Figure 1: Failure of Chimney

2. OBJECTIVE

- To mathematically model and study the dynamic responses of a Reinforced concrete chimney, under Indian seismic accelerations using SAP2000.
- The present study aims at the probabilistic seismic risk assessment of a Reinforced concrete chimney under Indian earthquakes by conducting a fragility analysis.
- To carry out the investigation for a large number of engineering demand parameters (EDPs) or DMs in order to identify the most sensitive DM, which can assist in the process of decision making for the design of Reinforced concrete chimney, under Indian seismic accelerations using SAP2000.
- To study the variation in the probability of exceedance for low, medium, and high levels of the PGA.
- To show the variation in the probability of exceedance under the Indian earthquakes for a Reinforced concrete chimney in the higher limit.

3. METHODOLOGY

The concept of fragility analysis in the field of earthquake engineering is first introduced by the research work of Kennedy and his co-workers (Kennedy et al., 1980) in the probabilistic seismic estimation of the nuclear power plant. With the development in the methodologies of seismic risk assessment, the fragility analysis has become an efficient tool for the risk assessment of the structures. Fragility is defined as the conditional probability of exceeding a specified limit state or threshold value of a structural member or system for a given intensity of ground shaking (Porter et al., 2007; Ramamoorthy et al., 2006; Reed and Kennedy, 1994). The lognormal probability distribution function is widely used to describe the fragility function.

Where, Pf = Probability of exceeding a particular damage state, DS, for a given level of intensity level, IM (e.g., PGA, PGV, Sa (T1), and IMm = Median threshold value of intensity measure required to cause ith damage state. Φ is standard cumulative probability function. where Fr = fragility function, Sd = structural demand, Sc = structural capacity and SM = earthquake severity measure.

To develop the fragility curves using the analytical method, a few popular simulation methods need to be applied. The assessment can be categorized into two main groups, namely, Nonlinear Static Analysis and Nonlinear Dynamic Analysis.

Nonlinear static analysis or pushover analysis (POA) is one of the methods used to develop fragility seismic curves. a capacity curve initially evaluated the appropriateness of POA in damage analysis, from which the fragility curve.

The capacity curves can represent mean or mean plus/minus with one/two/three times the standard deviation of capacity curves. From these capacity curves, the results can be compared with those of the Performance-Based Seismic Design (PBSD) in generating fragility curve.

It is important to choose a nonlinear analysis tool while considering its limitation. Such a toll can provide an accurate investigation and stable NTHA of the structure.

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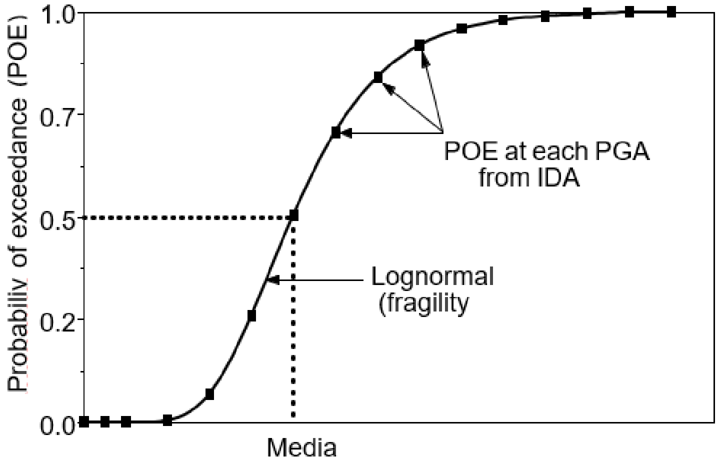

Figure 2: Vulnerability Curve

4. MODELING AND ANALYSIS

The chimney considered in this study is an industrial reinforced concrete chimney located in outskirts of Delhi region in India. The structure was designed using IS-4998 specifications 1992. A door of 2 × 0.8 m has been planned to be opened for a continuous emission measurement system on the chimney. In order to evaluate the effect of such an opening, this chimney was particularly selected for this study. There has been no damage occurred on the chimney during the earthquakes.

The structure is 125 meters tall and the outer and inner diameter at the base of the structure are 8.67 meters and 7.67 meters, respectively. The outer and inner diameter at the top of the structure is 3.97 meters and 3.47 meters respectively. The structure has two openings, one at the base of the structure as construction opening with a dimension of 1.83 meters in width and 3.96 meters in height and the second as flue opening at a height of 8.84 meter from base with a dimension of 5.2 meters in width and a height of 11.28 meters. The general view of the chimney elevation configurations analysed is presented in Figure 3-1(a) and the section cut elevation has been shown in Figure 3-1(b). The dead load of the structure has been calculated as 34265 kN. Table 3.1 tabulates material properties used in the modelling of the industrial chimney.

Table 1. Material properties Modelling Data

Property	Unit	Value
Concrete Compressive Strength fc	MPa	30
Modulus of Elasticity of concrete	GPa	27.3
Poisons ratio of concrete	-	0.2
Weight per unit volume concrete	kg/m^3	2400
Yield Strength of Steel fy	MPa	415
Minimum Tensile Strength fu	MPa	620
Modulus of Elasticity of steel	GPa	200
Weight per unit volume of steel	kg/m^3	7750

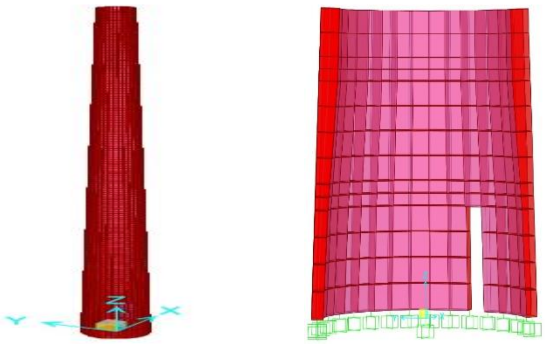

Figure 3: Finite Element Model of RC chimney

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Table 2. Mesh density analysis results for structural fundamental period

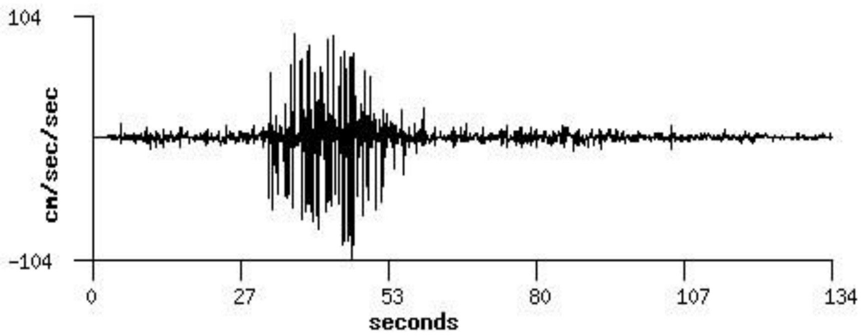
Mesh size		# of Nodes	# of Area Elements	Fundamental period (sec)
at base (m)	at top (m)			
1.05 × 0.991	**0.47 × 0.99**	**5021**	**4968**	**2.295520**
1.05 × 0.495	0.47 × 0.49	9878	9808	2.295522
0.53 × 0.49	0.47 × 0.49	11914	11808	2.304029

4.1 Ground motion selection

Time history method shall be based on an appropriate ground motion (preferably compatible with the design acceleration spectrum in the desired range of natural periods) and shall be performed using accepted principles of earthquake structural dynamics. For this study, the Time History acceleration data of 10 Indian Earthquakes has been adopted. The 2001 Bhuj earthquake, occurred on 26 January, India's 52nd Republic Day, at 08:46 AM IST and lasted for over 2 minutes. The epicentre was about 9 km south-southwest of the village of Chobari in Bhachau Taluka of Kutch District of Gujarat, India. The intraplate earthquake reached 7.7 on the moment magnitude scale and had a maximum felt intensity of X (Extreme) on the Mercalli intensity scale. The earthquake killed between 13,805 and 20,023 people (including 18 in south-eastern Pakistan), injured another 167,000 and destroyed nearly 400,000 homes. The details of each individual earthquake have been summarized in Table below. For assessing the structure using the time-history analyses, the mean spectrum of all these ground motions has to be more than 90% of the target demand spectrum (ASCE7-16) for a range a time period of the structure. The range of time period has been selected as 0.2T to 2T with the lower 0.2T again lowered to include 90% of mass participation in each principal direction of the building. The target response spectra here corresponding to Zone V MCE level hazard, considering 1.5 load factor for earthquake loading.

Table 3. Ground Motions

Indian Earthquake Records								
Serial number	Year	Earthquake	Mw	Station Component	PGA	Rjb	PGV	PGD
					(g)	(Km)	(cm/s)	cm
1	2001	Bhuj	7	Ahmedabad	0.106	239	11.2	18.6
2	1999	Chamoli	6.6	Ukhimath	0.09	35.6	6.8	18.1
3	1999	Chamoli	6.6	Ghansiali	0.084	75.3	5.01	43.6
4	1999	Chamoli	6.6	Tehri	0.062	89.7	6.15	33.1
5	1991	Uttarkashi	7	Barkot	0.09	55.8	7.4	84.4
6	1991	Uttarkashi	7	Bhatwari	0.25	21.7	16.8	60.3
7	1991	Uttarkashi	7	Tehri	0.073	50.6	4.65	25.3
8	1988	Ne-India	6.6	Hajadisa	0.099	205.2	7.78	197.2
9	1990	Ne-India	6.6	Laisong	0.062	210.1	2.63	1.5
10	1995	N.E. India	6.6	Diphu	0.1	227.3	4.7	23.4



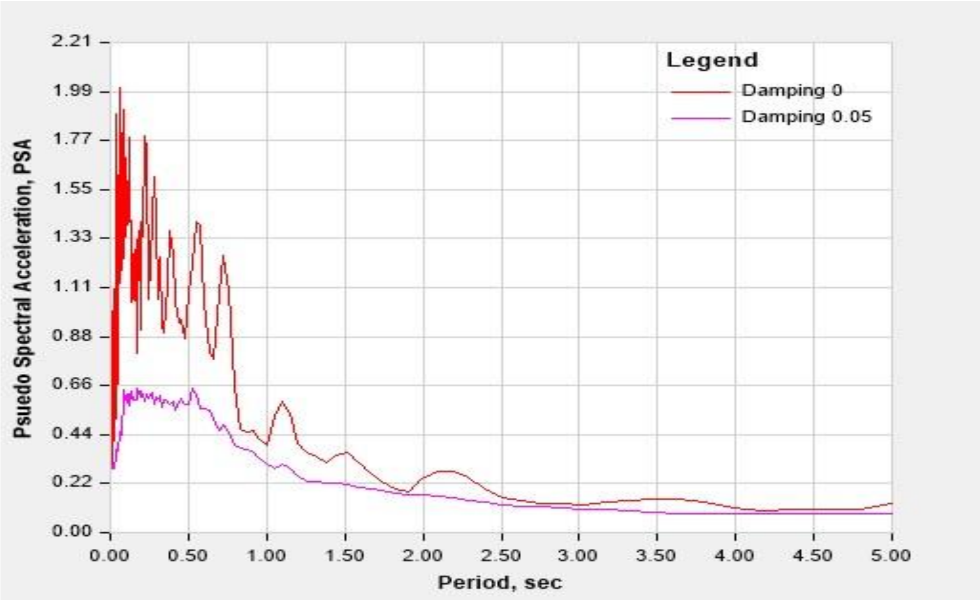


Figure 4: Time History and Pseudo Acceleration

Table 4. Damage state

Damage Measures	Damage States			
	-Structural (DS-1)	Slight (DS-2)	Ioderate (DS-3)	xtensive (DS-4)
Maximum Inter-storey drift ratio (MIDR)	0.05%	0.10%	0.20%	0.70%
Maximum base shear (MBS)	20%W	30%W	40%W	50%W
Maximum Strain (MSR)	0.002	0.003	0.004	0.005
Maximum top displacement (MTD)	200	300	400	500
Maximum top floor acceleration (MTA)	0.1g	0.2g	0.3g	0.4g

5. RESULTS AND DISCUSSION

Modal analysis, is the study of dynamic properties of a system in the frequency domain. It is performed to evaluate the mode shapes due to free-vibration of the structure and to depict the displacement patterns of the structure. Mode shapes describe the pattern into which a structure will naturally displace without the influence of any external applied force. All vibrational modes do not equally contribute in the modal response of a structural system, hence only those modes are considered that contribute to the higher mass participation ratios.

Table 5. Modal Period and Frequencies

Modal Periods and Frequencies					
Output Case	**Step Num**	**Period**	**Frequency**	**Circ Freq**	**Eigen value**
Text	Unitless	Sec	Cyc/sec	rad/sec	rad^2/sec^2
MODAL	1	2.381991	0.419816788	2.637786677	6.957918551
MODAL	2	2.381991	0.419816788	2.637786677	6.957918554
MODAL	3	0.627438	1.593782748	10.01403234	100.2808438
MODAL	4	0.627438	1.593782748	10.01403234	100.2808438
MODAL	5	0.271498	3.68326662	23.14264671	535.5820966
MODAL	6	0.271498	3.68326662	23.14264671	535.5820966
MODAL	7	0.161527	6.190930354	38.89876264	1513.113735
MODAL	8	0.153206	6.527174136	41.01144463	1681.938591
MODAL	9	0.153206	6.527174136	41.01144463	1681.938591
MODAL	10	0.124542	8.029451029	50.45052873	2545.255849

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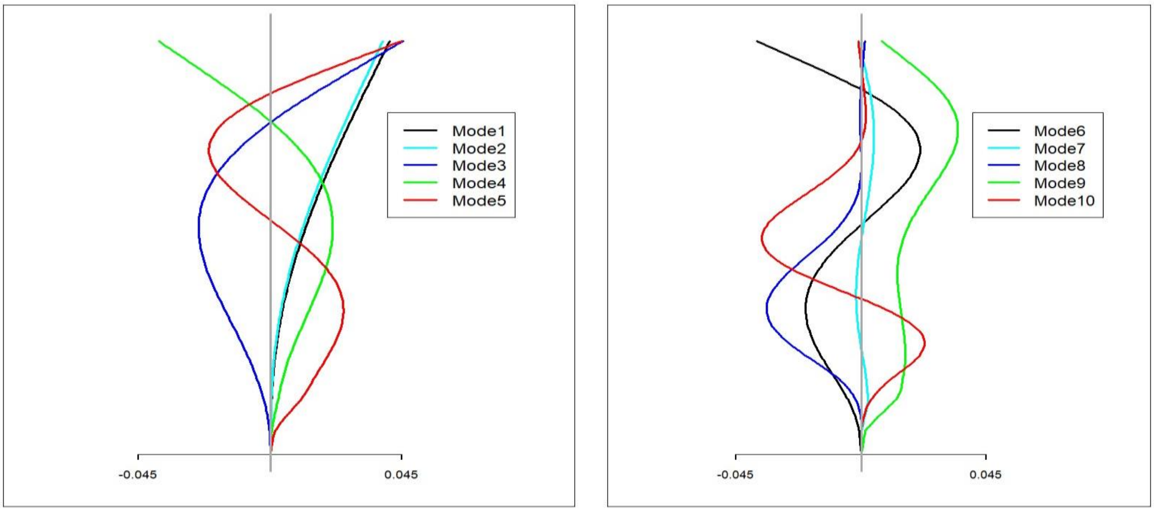
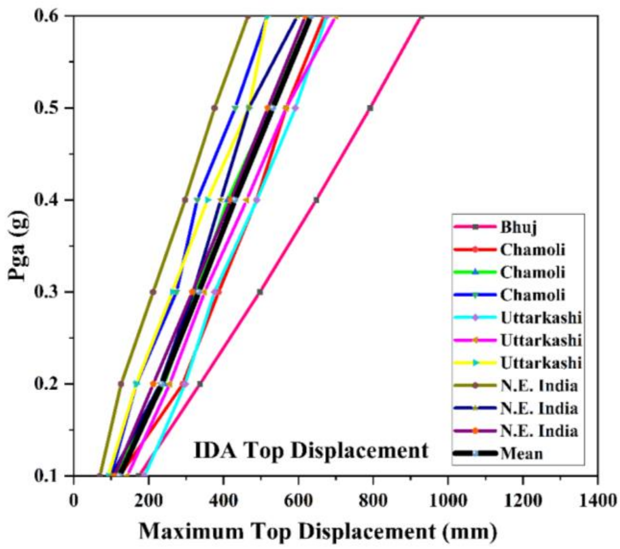
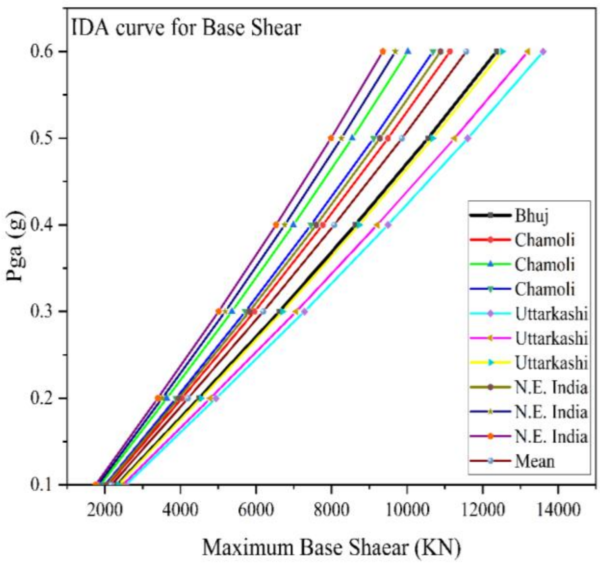


Figure 5: Mode shapes of chimney

Table 6. Base Reactions

Base Reactions						
OutputCase	**GlobalFX**	**GlobalFY**	**GlobalFZ**	**GlobalMX**	**GlobalMY**	**GlobalMZ**
Text	KN	KN	KN	KN-m	KN-m	KN-m
DEAD	1.326E-10	2.281E-10	23283.835	-2.171E-08	1.561E-08	1.048E-10
MODAL	230.252	45.594	-0.00001688	-3957.2154	19985.9277	0.00003706
MODAL	45.594	-230.252	-0.000008744	19985.9277	3957.2154	-0.000005525
MODAL	2417.556	570.542	-0.00009593	-20936.5047	88679.0567	-0.0017
MODAL	570.542	-2417.556	0.00002009	88679.0557	20936.5061	0.0011
MODAL	6238.784	6979.091	-0.008959	-155813.708	139306.5593	0.0376
LINING	3.357E-11	4.785E-11	4525.875	-4.641E-09	3.994E-09	1.995E-11
EQX	-869.535	-6.706E-08	-9.497E-09	0.000006707	-74171.5785	6.507E-08
EQY	-0.000000105	-1304.302	-2.908E-09	111257.3677	-0.00001028	9.761E-09
RSX	808.108	375.067	0.0005383	12604.6338	36829.4436	0.0015
RSY	414.388	892.829	0.0005791	40690.595	13926.0875	0.002
dl+0.25ll	1.661E-10	2.759E-10	27809.71	-2.635E-08	1.961E-08	1.248E-10





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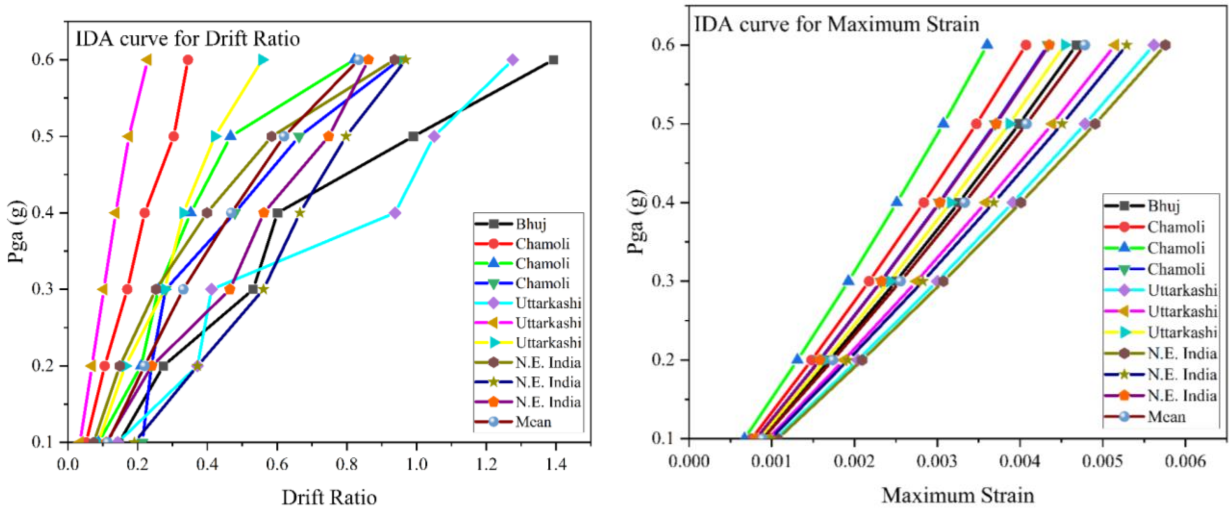

Figure 6: Incremental Dynamic Analysis curves

In this study, the seismic fragility is presented in the damage probability curve (fragility curve). All set of fragility curves were plotted.

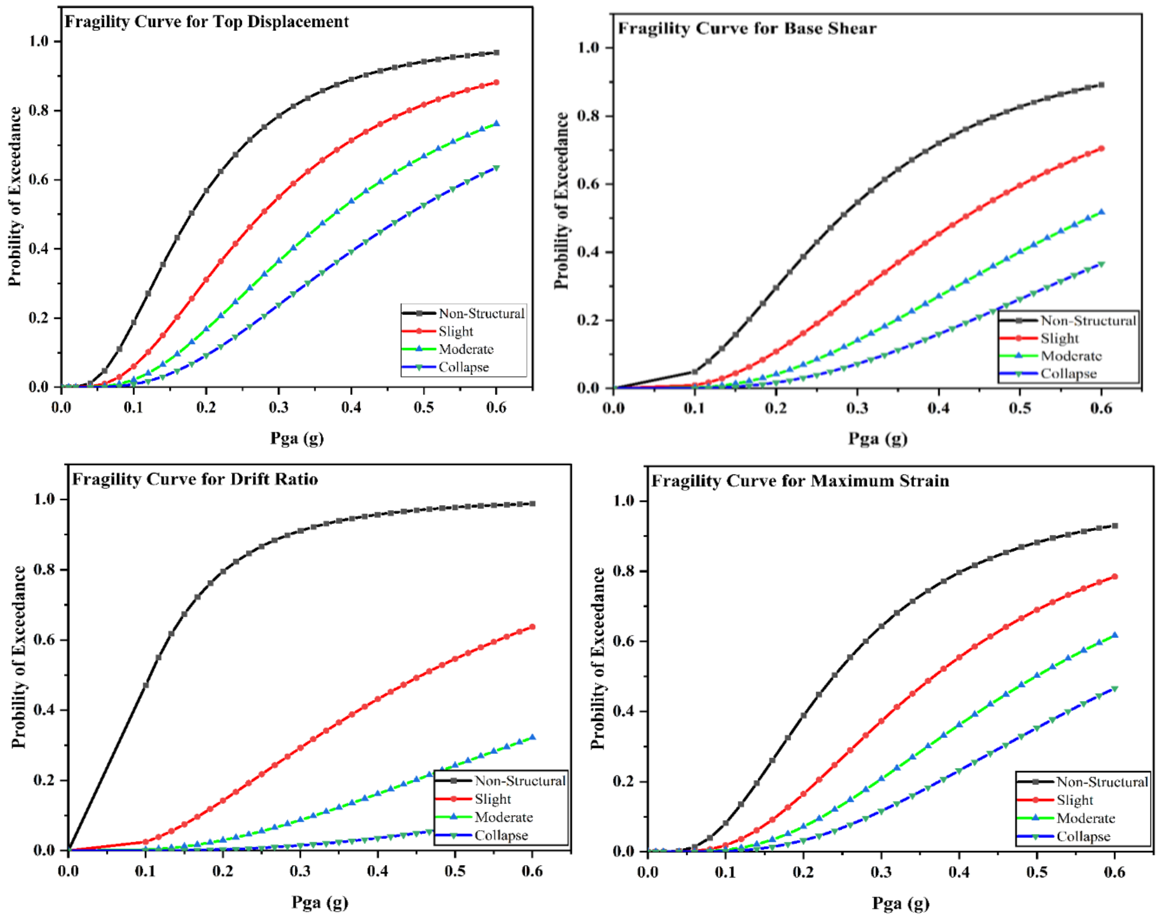

Figure 7: Fragility Curves for different damages

6. CONCLUSION

Linear time history analysis of the building has been done using the acceleration data of Indian earthquake. Present study focused on the vulnerability of chimney under Indian earthquake scenario. The tip deflection of the chimney was calculated for each load condition. Indian code for earthquake loading gives the highest top displacement of 0.451 m which corresponds to 0.3% drift ratio. From this study it can be concluded that.

- The Reinforced concrete chimney is highly vulnerable to Indian earthquakes.
- Tall reinforced concrete chimneys respond in a complex manner under earthquake excitation. The structure can be thought of as a highly tuned profiled cantilever which is ‘whippy’ in nature and dominated by higher mode effects.

- The inelastic response of a chimney cannot be readily predicted using linear static or nonlinear static procedures such as a simple static push over analysis or by a single degree of freedom substitute structure.
- The chimney responds inelastically with the development of multiple plastic hinges in the higher Pga levels. Higher mode effects dominate the response with significant inelastic deformations typically concentrated over the region between 30–80% of the chimney height.
- A moderately ductile chimney, which responds inelastically through the formation of multiple plastic hinges, can sustain earthquake ground shaking at a level at least four times greater than the motion needed to cause the elastic moment demand to exceed the ultimate moment capacity, assuming uncracked section properties. This result is significant as it implies that a chimney designed elastically using uncracked section properties can survive an earthquake scaled by at least a factor of four
- There is much less variability of POE in the slight damage state for different types of earthquakes, and this variability increase significantly with increases in damage states associated with all damage measures.

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