Earthquake Vulnerability Assessment of Irregular RC Building with Friction Pendulum System Bearing

Nalina Kishore, C K Prasad Varma Thampan

Abstract— Earthquakes (EQ) are found to be the most hazardous disaster that generally strikes structures. Earthquake vulnerability analysis is a must in order to ensure safety of the structure analysis and to evaluate the quantum of loss. This paper focuses on the development of fragility curves for twenty-story irregular RC building structure in India with fixed base and Friction Pendulum bearings. Fragility curve is a tool representing the conditional probability of exceeding certain damage level. For fragility curve development, 20 earthquake records were selected from PEER data base. Incremental dynamic analysis was performed to analyze the building subjected to different earthquake records. The EQs were scaled in terms of spectral acceleration. Building modeling and analysis was done in SAP2000. Fragility curves are developed for irregular building with and without friction pendulum system (FPS). Vulnerability of these buildings was compared. The building with FPS is found to be less vulnerable to seismic hazards as compared to the building with fixed base both symmetric and irregular types.

Index Terms— Base Isolation, Fragility Curve, Friction Pendulum System Bearing (FPS), Incremental Dynamic Analysis, Non linear Dynamic Analysis, Seismic hazard, Vulnerability Assessment.

1 Introduction

EHARTHQUAKES are one of the most hazardous natural disasters that strike structures and cause large damages and loss of lives, especially in regions which are defined as high-seismic zone by geologists. Majority of human beings live in earthquake prone areas. To ensure safety, various seismic analysis approaches were proposed including both static and dynamic methods. Although seismology branch has been continuously advancing during the century, it is impossible to predict future earthquakes' severity and time of attacking. Therefore previous earthquake data are still widely used to analyse buildings resulting in designed buildings for resisting future earthquakes. Already constructed buildings may collapse under future earthquakes.

Due to the difficulties in predicting earthquakes and its random nature, various probabilistic analyses were proposed in analysing for seismic responses of building. In addition to uncertainties in seismic loads, uncertainties associated with building material, design process, building geometry, and construction will also lead to the use of probability to predict building responses.

Fragility analysis is a probabilistic method which shows the probability of exceeding a certain damage level. This technique is commonly used in order to evaluate the earthquake vulnerability assessment of various structures. Fragility curve is a statistical tool used for the vulnerability assessment and it gives the probability of building damage level under different ground motion intensities. This assessment is generally used in disaster mitigation fields.

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The main objective of this paper is to evaluate the EQ vulnerability of irregular RC building with the help of fragility curves. Also evaluates the seismic performance of building with the addition of Friction Pendulum System Bearing.

2 Theoretical Background

Earthquake effects of general type buildings are predicted with the help of some functions such as loss and damage functions. But these functions may not be useful for some kind of specific buildings. The development of the above mentioned functions are easy only if the user is an engineer experienced in non- linear analysis field. In disaster mitigation field, user must create various functions that can be used for both specific and individual type building.

2.1 Fragility Curve

A fragility analysis is widely used for hazard assessment and earthquake vulnerability assessment of various structures. The fragility curve is a statistical tool showing the probability of exceeding certain damage state as a function of intensity measure (IM). It is developed from multi record IDA curves. Commonly used IMs are Spectral acceleration (Sa), Spectral displacement (Sd), Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV) etc. Figure 1 shows a typical fragility curve with PGA along x-axis and probability of failure along y-axis.

A point in the curve represents the exceeding probability of damage state at a given intensity measure. These damage states can be lateral drift, base shear, story drift etc. The function, which is used to generate fragility curve for a building, is generally found to be log-normal functions. In this study, 5% damped spectral acceleration is considered as an Intensity Measure (IM) and maximum inter-story drift ratio as damage state (DS).

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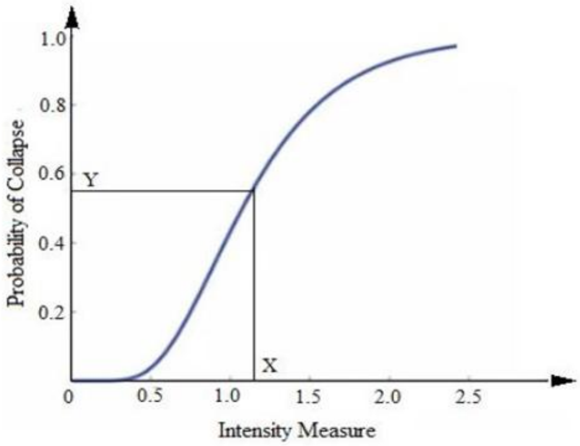

Fig 1: Fragility Curve

2.2 Incremental Dynamic Analysis (IDA)

IDA is a computational analysis method of earthquake engineering to study the behaviour of structure under seismic loads. Simulated building seismic responses obtained from IDA are represented by IDA curves that require a series of non- linear time history analysis with a suite of ground motions, during which the ground motion intensities are increased using a specified scale factor. Therefore, IDA provides the building's seismic behaviour for the whole range from elastic to collapse.

Three steps were used to perform IDA and develop IDA curves, namely, pre- process, process and post- process as described in figure 2.

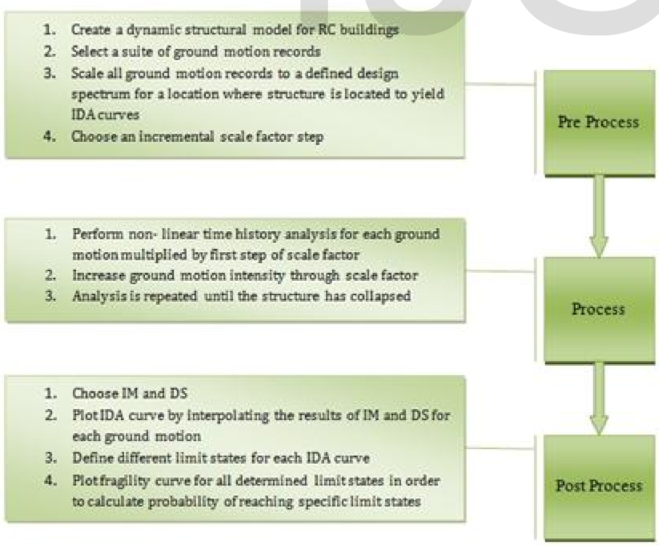

Fig 2: Steps to perform IDA

2.3 Friction Pendulum System (FPS) Bearing

Friction Pendulum Bearing is a sliding device which is commonly used now-a-days. FPS has the ability to combine the sliding with pendulum action. It consists of an articulated slider on spherical concave surface. The slider is covered with Teflon as polished bearing material. The friction coefficient between the surfaces is 0.1 at high velocity sliding and 0.05 at low velocities. Friction pendulum system gets activated when EQ forces exceeds the static friction value. The restoring force in FPS is proportional to the weight supported by the bearing and inversely proportional to the radius of curvature of spherical sliding surface. The schematic layout of FPS bearing is shown in figure 3. Due to numerous advantages, FPS was chosen for this study.

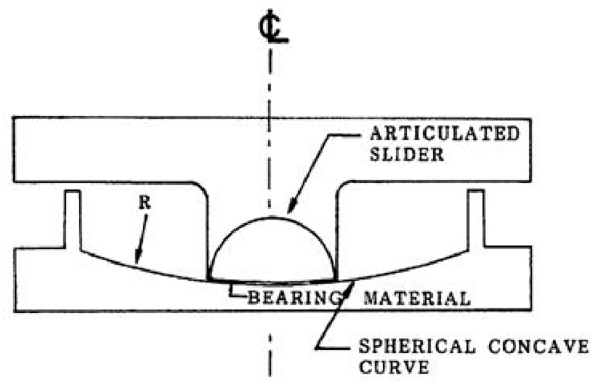

Fig 3: Friction Pendulum System Bearing

3 Fragility Assessment

In the early stages, vulnerability assessment techniques were using the predetermined EQ data for estimating the damage of a building. But with the rapid advancement of computation and easy data collection techniques, more comprehensive methods were proposed. In general, the assessment methods are grouped into four types namely, Expert opinion method, Empirical method, Hybrid method and Analytical method.

Even though Expert opinion method is earliest method, it is only useful where damage data from previous earthquake is not available at all or for some intensity it's not available. In Empirical method, the 'predetermined EQ data' are extrapolated to evaluate the city based damages. They are largely dependent on the observed post-earthquake damage data. Hybrid methods combine expert opinion and post-earthquake damage data with analytically derived damage from a mathematical model of a building typology. Among the four, Analytical methods are considered to be more efficient. It deals with nonlinear analysis of structures, probabilistic modelling of earthquake, and generalizing results of smaller area to a region or other cities etc. In this study, analytical fragility curve method was used to develop fragility curves using IDA.

3.1 Building Configuration & Strutural Details

A G+20 irregular RC building located in Zone IV is considered for the study. Building is having a storey height of 3m in each floor has 6 bays in X – direction and 3 bays in Y – direction forming a plan as shown in figure 4. Structural details of the building are assumed as per table 1 and link properties as per table 2.

3.2 Finite Element Model

A 3D modelling of case study building was done using SAP2000 v 19. Beam and columns were modelled with non-linear frame elements characterized by plastic sections where-as, the slab was modelled as a thin shell element which combines both membrane and plate bending action. A 3D discrete model of the friction pendulum isolation system was modelled as a link element. Plastic hinge properties were assigned to each beam and column using auto hinge property of SAP2000. IDA was conducted to generate multi record IDA curves and thereby generate fragility curves.

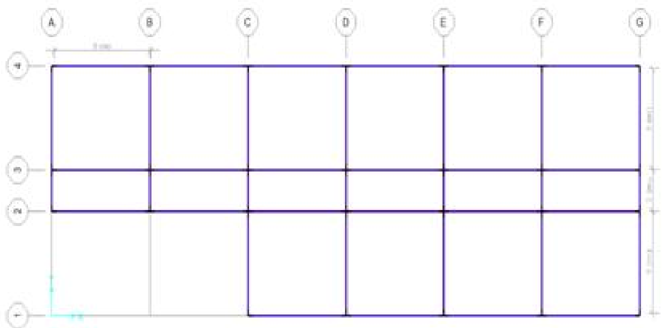

Fig 4: Plan view of Irregular Building

TABLE 1
BUILDING DETAILS

Grade of Concrete	M 40
Grade of Steel	Fe 415
Floor to floor height	3 m
Parapet height	1.2 m
Slab thickness	150 mm
External Wall	230 mm
Internal Wall	150 mm
Column	600 x 600 mm
Beam	300 x 600 mm
Live load on each floor	3 kN/m^2
Floor finish	1 kN/m^2

TABLE 2
LINK PROPERTIES

Properties	FPS
Vertical Stiffness (U1)	51663 kN/m
Linear Stiffness (U2 & U3)	2044 kN/m
Non Linear Stiffness (U2 & U3)	1013 kN/m
Damping	0.10

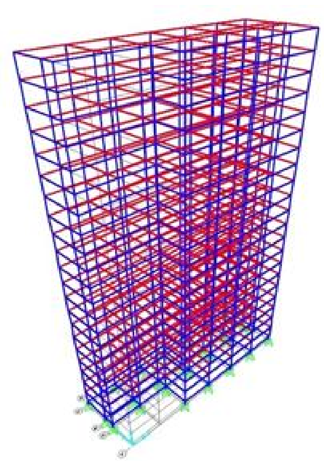

Fig 5: Three dimensional model of Building

3.3 Ground Motion Selection

A set of ground motion records needs to be selected from PEER database to perform IDA analysis and obtain reasonable results. According to research done by Shome and Cornell (1999), 20 ground motion records are required to estimate the limit state capacity and seismic demand of buildings. The following criteria listed in table 3 were used to select 20 ground motion records given in Table 4 for the present study.

TABLE 3
CRITERIA CONSIDERED FOR SELECTING THE GROUND MOTION

Criteria	Value or Type
Magnitude	Greater than 6.5
Soil class	Class D (As per NEHRP)
Source type	Strike-slip, Reverse, Reverse oblique
Source distance	More than 10 km
PGA	More than 0.2 g
PGV	More than 15 cm/sec

TABLE 4
SELECTED EARTHQUAKES

RSN	Station	Event	Year
6	El Centro Array # 9	Imperial Valley	1940
721	El Centro Co	Superstition Hills	1987
725	Poe Road	Superstition Hills	1987
766	Gilroy Array # 2	Loma Prieta	1989
767	Gilroy Array # 3	Loma Prieta	1989
783	Oakland – Harbour	Loma Prieta	1989
784	Oakland – Title	Loma Prieta	1989
802	Saratoga – Aloha	Loma Prieta	1989
803	Saratoga - W Valley	Loma Prieta	1989
828	Petrolia	Cape Mendocino	1992
848	Cool Water	Landers	1992
864	Joshua Tree	Landers	1992
900	Yermo Fire Station	Landers	1992
960	Canyon Country	North Ridge	1994
963	Castic Old Ridge	North Ridge	1994
987	LA Centinela	North Ridge	1994
993	LA Fletcher	North Ridge	1994
1006	LA UCLA	North Ridge	1994
1082	Sun Valley	North Ridge	1994
1111	Nishi Akashi	Kobe	1995

3.4 Damage State (DS) selection

Damage State (DS) is a measure of structural responses to the lateral loads effect such as base shear, top drift, maximum inter-story drift, and so on. Selecting DS depends on the purpose of the analysis. This study uses maximum inter-story drift ratio in percentage (ID) as the DS to compare the structural damage of the case study buildings.

Four structural limit states are considered for the present study. These are related to maximum inter-story drift ratio. The permissible values of the maximum inter-story drift ratio corresponding to these limit states are shown in table 5.

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TABLE 5
DAMAGE STATES

Performance level	Transient drift
Slight damage	0.2% < ID < 0.5%
Moderate damage	0.5% < ID < 1.5%
Extensive damage	1.5% < ID < 2.5%
Complete collapse	> 2.5%

3.5 Intensity Measure (IM) selection

IM is a scalar which increases monotonically with IDA scale factor. IMs of earthquake are the Richter scale or Modified Mercalli scale that can be expressed as Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV) or 5% damped first-mode spectral acceleration Sa (T1, 5%) for engineering purposes. For moderate period buildings and no near-fault ground motions, Sa (T1, 5%) is more suitable and efficient IM than PGA [13]. In addition, Sa (T1, 5%) gives more consistent results than PGA. Therefore Sa (T1, 5%) was adopted in this study as the IM**.**

3.6 Development of Fragility curves

In order to develop fragility curves, IDA was performed on the building under case study. The following procedure was used to generate fragility function and thereby to create fragility curves.

1. Analyse the building models using the IDA and create IDA curves for 20 ground motions in both x and y direction by increasing the intensities using scale factors. Scale factors used for the present study are in the range of 0.51 to 2.83. Determine the value of IM (Sa (T1, 5%)) of the building response from the IDA curve of 20 ground motions and these are used as the ground motion parameter in the fragility curve (i.e. horizontal axis).
2. To obtain fragility curve assumptions, natural logarithmic shall be taken ln(x) for ground motion parameter.
3. Calculate mean and standard deviation for ln(x) using the equation shown below.

$$\lambda = \frac{1}{n}\left(\sum_{i=1}^{n} \ln(x_i)\right)$$

$$\beta = \sqrt{\frac{1}{(n-1)}\left[\sum_{i=1}^{n} (\ln(x_i) - \lambda)^2\right]}$$

Where

n = number of ground motions considered

λ = Mean

β = Standard Deviation

4. Calculate standard normal, s of lognormal data using the equation

$$s = \frac{\ln(x) - \lambda}{\beta}$$

5. Apply the standard normal distribution for the probability function and CDF which is denoted as φ using the equation

$$P(C/\,S_a = x) = \varphi\left\{\frac{\ln(x) - \lambda}{\beta}\right\}$$

6. Plot fragility curve between probability as vertical axis and spectral acceleration, Sa (IM) as horizontal axis.

4 RESULT AND DISCUSSION

In this study, the seismic behaviour of building with fixed base and the one with FPS were compared. Parameters such as time period and peak storey drift in both the cases were compared. EQ vulnerability of those buildings was investigated by the development of fragility curve.

4.1 Time Period

Modal analysis is performed to determine the fundamental period of these buildings. Mode shapes are determined by Ritz vector analysis and from that the time period corresponding to the fundamental mode shape is taken as fundamental time period. Fundamental time period of the buildings obtained are tabulated in table 6.

TABLE 6
TIME PERIOD FOR G+20 BUILDING

Direction	Fixed Base	Base Isolated
X Direction	2.31 sec	4.56 sec
Y Direction	2.49 sec	4.75 sec

The time period of base isolated building is found to be lengthened when compared to that of a fixed base building. This long time period reduces the earthquake induced forces on the building.

4.2 Multi Record IDA curves and Fragility curves

Multi Record IDA curve for fixed base and FPS with R=1.0 m are shown in figure 6 & 7. From summarized IDA curves (figure 8 & 9), it is possible to evaluate the capacities of the buildings into their 16 percentile, median and 84 percentiles. Capacities are shown in table 7.The seismic forces were applied both x and y directions.

Fragility curve for fixed base and FPS with R=1.0 m are shown in figure 10 & 11.

5 SUMMERY AND CONCLUSION

The conclusions from the studies are described below:

Time period of fixed base building is found to be less when compared to FPS isolated building. This lengthening of time period reduces the seismic induced forces hitting on the building. From the multi record IDA curves, the peak inter-story drift ratio is found to be decreased from fixed base building to FPS isolated building. Also in each building model, the drift value corresponding to X-direction is found to be slightly smaller than Y-direction. While evaluating the summarized IDA curves, it is found that the capacity of the structure is increased by the use of FPS over fixed base building. In each building model, X-direction is having slightly higher capacity when compared to Y-direction.

While observing the fragility curves, it is understood that

FPS isolated building are less vulnerable to earthquake hazard because of its energy dissipation property in both directions. Considerable reduction in vulnerability is obtained for un-symmetrical building also.

TABLE 7
CAPACITIES OF BUILDING

Limit States	Case	Sa (g)			Max. Drift Ratio		
Fixed Base Building							
		16%	50%	84%	16%	50%	84%
Immediate Occupancy	X	0.1218	0.1562	0.2360	0.5	0.5	0.5
	Y	0.1097	0.1428	0.2070			
Life Safety	X	0.2532	0.4343	0.5076	1.5	1.5	1.5
	Y	0.2332	0.4174	0.4890			
Collapse Prevention	X	0.2532	0.4400	0.5776	2.5	2.5	2.5
	Y	0.2332	0.4240	0.5596			
FPS with Radius = 1.0 m							
Limit States	**Case**	**Sa (g)**			**Max. Drift Ratio**		
		16%	50%	84%	16%	50%	84%
Immediate Occupancy	X	0.1557	0.1967	0.2635	0.5	0.5	0.5
	Y	0.1144	0.1781	0.2505			
Life Safety	X	0.5404	0.6812	0.7874	1.5	1.5	1.5
	Y	0.5323	0.6611	0.7635			
Collapse Prevention	X	0.5532	0.7500	0.8796	2.5	2.5	2.5
	Y	0.5432	0.7300	0.8592			

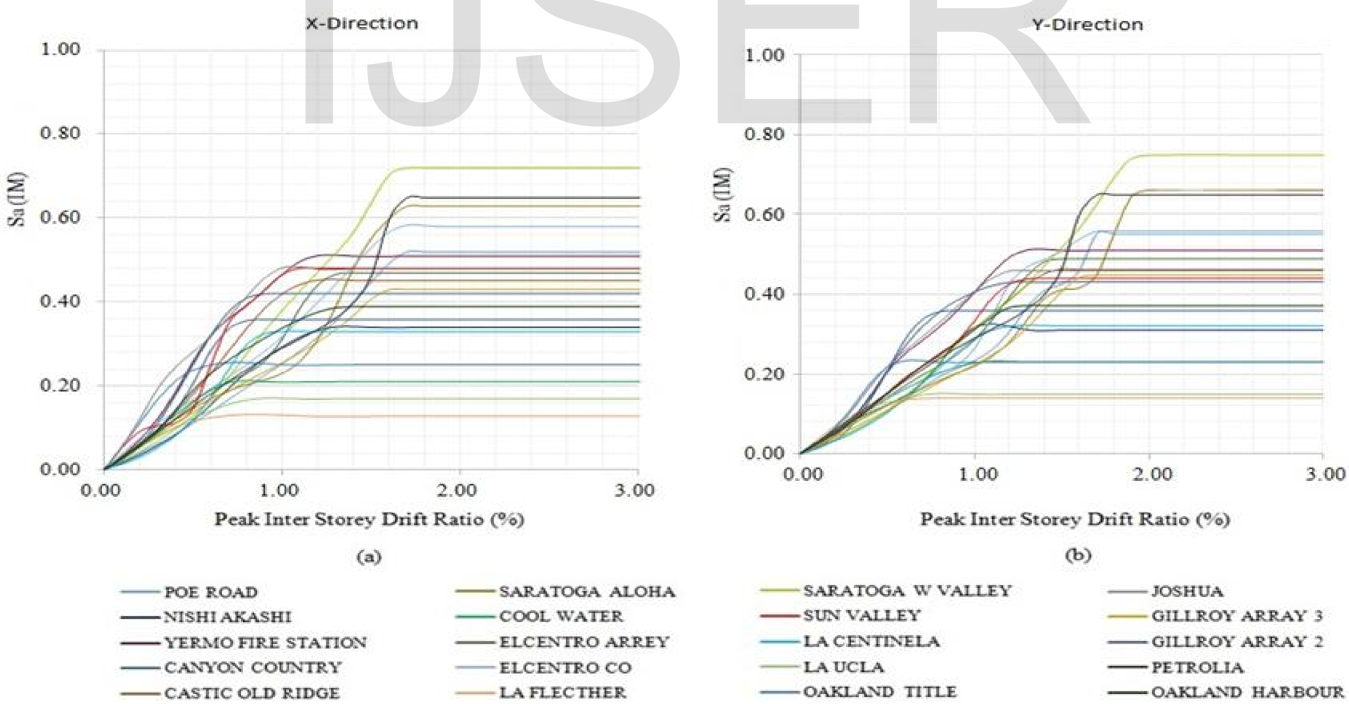

Fig 6: Multi record IDA curves for Fixed base building

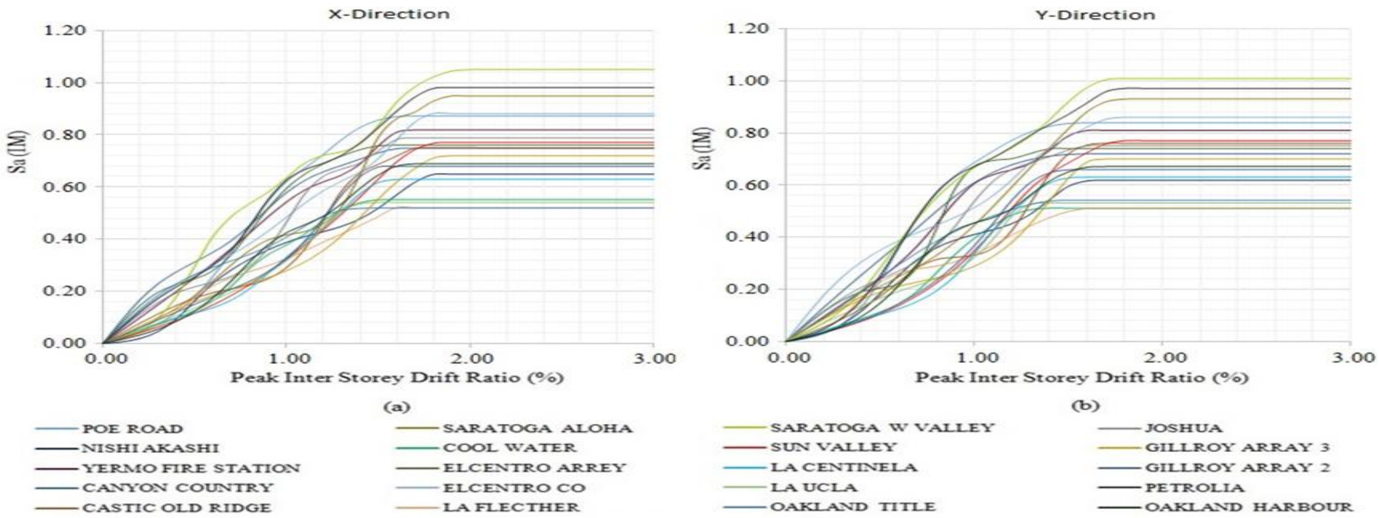

FIG 7: Multi record IDA curves for FPS isolated building (R= 1.0)

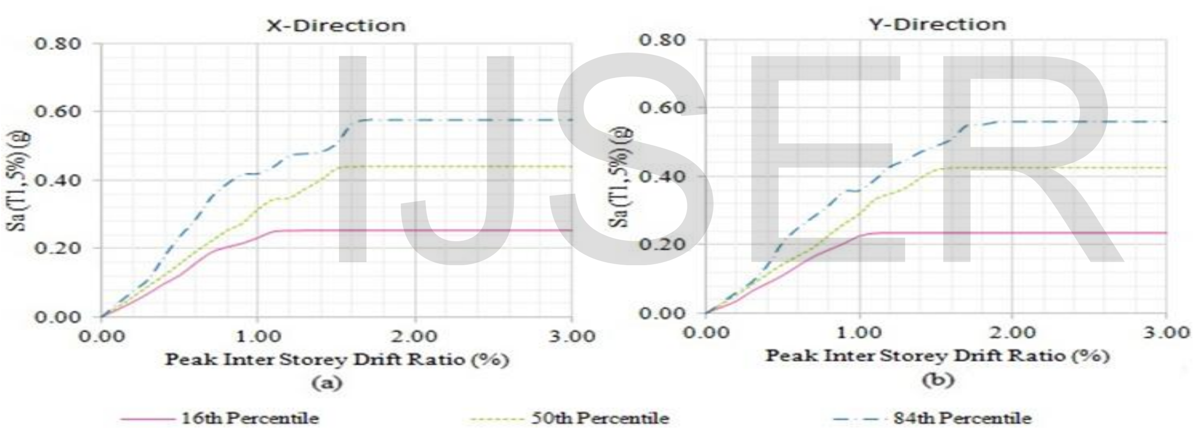

FIG. 8: Summarized IDA curves for Fixed base building

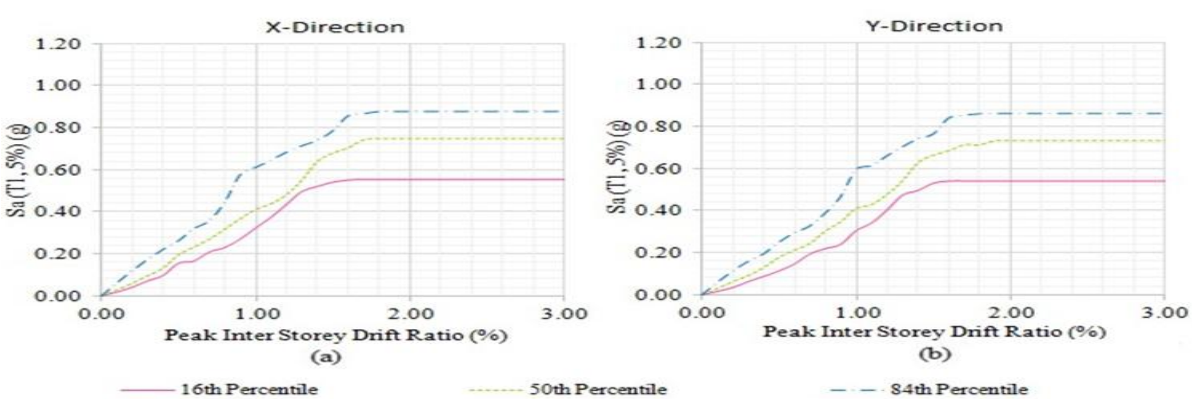

Fig. 9: Summarized IDA curves for FPS isolated building (R= 1.0)

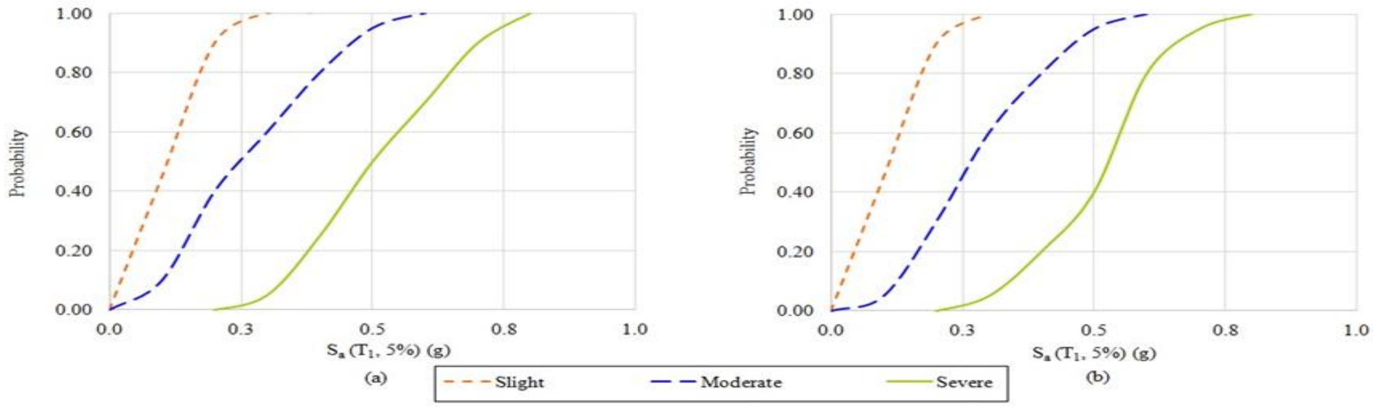

Fig. 10: Fragility curves for Fixed base building (a) X Direction (b) Y Direction

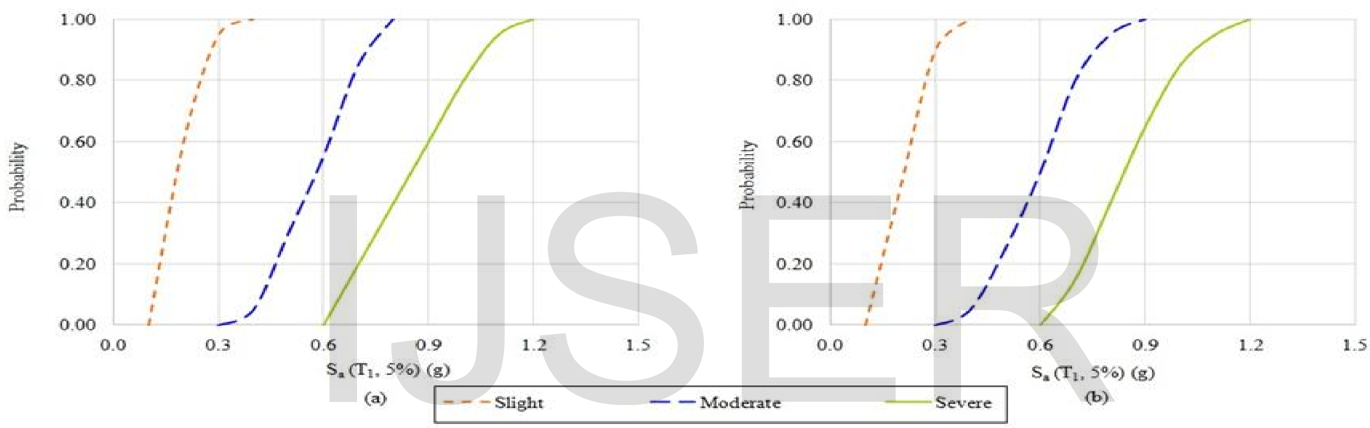

Fig. 11: Fragility curves for FPS isolated building (R= 1.0) (a) X Direction (b) Y Direction

REFERENCES

[1] Anil K Chopra, *Dynamics of Structures,* Engelwood Cliffs, New Jersey: Prentice Hall, 1995.

[2] Aiswarya S, Nandita Mohan (2014), "Vulnerability Analysis by the Development of Fragility Curves", *", IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE),* Vol.2, pp. 33-40.

[3] Ashish R. Akhare, Tejas R.Wankhade (2014), "Seismic performance of RC structure using different base isolator", *IJESRT International Journal of Engineering Sciences & Research Technology,* pp. 724-729.

[4] Calvi G. M et.al (2006), "Development of Seismic Vulnerability Assessment Methodologies over the past 30 years", *ISET Journal of Earthquake Technology,* Paper No. 472, Vol. 43, pp. 75-104.

[5] Chandak N. R (2013), "Effect of base isolation on the response of RC Building", *Journal of Civil Engineering Research, Vol. 3,No. 4, pp. 135-142*.

[6] Federal Emergency Management Agency (FEMA), NEHRP Guidelines for the Seismic Rehabilitation of Buildings (273), Washington D.C, 1997.

[7] Murat Serdar Kircil, Zekeriya Polat (2006), "Fragility analysis of mid-rise R/C frame buildings", *Engineering Structures*, 28, 1335–1345.

[8] PEER (2010). *Technical Report for the Ground Motion Database web*, California Pacific Earthquake Engineering Research Center. http://peer.berkeley.edu/peer_ground_motiondatabase.

[9] SAP 2000. (2007), *Analysis Reference Manual*, Version 8. Berkeley, California; Computers and Structures, Inc.

[10] Seismic Vulnerability Assessment of Building Types in India (2013), Technical Document (Tech-Doc) on Seismic Vulnerability Assessment Methods for Buildings, *Submitted to National Disaster Management Authority, Government of India.*

[11] Shome N, Cornell CA (1998), "Normalization and scaling accelerograms for nonlinear structural analysis", Proceedings of the 6th U.S. National Conference on Earthquake Engineering, paper 243. EERI, El Cerrito, CA: Seattle, Washington, 1–12.

[12] Vamvatsikos D, Cornell C. A (2002), "Incremental Dynamic Analysis", *Submitted to Earthquake Engineering and Structural Dynamics*, John Wiley & Sons, Ltd.

[13] Vamvatsikos D, Fragiadakis M. (2010), "Incremental dynamic analysis for estimating seismic performance sensitivity and uncertainty". *Earthquake engineering & structural dynamics*, 39(2), 141-16