Seismic Vulnerability Assesment of Tall RC Building with Friction Pendulum Bearing System

Rony Joy[1], C K Prasad Varma Thampan[2]

[1]*PG Student*, [2]*Professor, Department of Civil Engineering,*
Calicut University, NSS College of Engineering, Palakkad, India

Abstract

Seismic vulnerability analysis is a fertile area of research which needs more input from seismologists and engineers. This paper focuses on the development of fragility curves for a twelve-story reinforced concrete (RC) hospital building structure in India. Fragility curve is a statistical tool representing the probability of exceeding a given damage state to the earthquake intensity. A set of earthquake records were selected from PEER data base for the development of fragility curves. Incremental dynamic analysis is performed to analyse the structure subjected to different earthquake records with various intensities based on the scaling in terms of spectral acceleration in SAP 2000. Fragility curves are developed for the same structure with and without friction pendulum isolation system (FPS). Parametric study is also conducted by varying the radius of curvature and fragility curves have been developed for all the cases. These fragility curves are used to compare their seismic performance. The structure with FPS is found to be less vulnerable to seismic hazards as compared to the structure with fixed base.

Keywords— *Fragility Curve; Incremental Dynamic Analysis; Friction Pendulum Bearing System (FPS).*

I. INTRODUCTION

Recent studies shows that structural performance of Reinforced Concrete (RC) buildings always play crucial roles in terms of earthquake losses. Structures already built are vulnerable to future earthquakes. Damage to structures cause deaths, injuries, economic losses. Earthquake risk is associated with seismic hazard, vulnerability of building and exposure. Vulnerability assessment reveals the damageability of a structure under varying ground motion intensities. Vulnerability can be outlined as the sensitivity of the exposure to seismic hazard. The vulnerability of an element is usually expressed as a percentage loss (of strength, stability or serviceability) for a given seismic intensity level. The aim of a vulnerability assessment is to obtain the probability of a given level of damage of a given building type due to scenario earthquake. Tools specifically defined for crisis administration and seismic danger moderation arrangements must be defined. Vulnerability Index and Fragility Curves are two such tools which are used, to study the vulnerability and possible retrofitting for building typologies. The outcome of this assessment can be used in loss estimation of losses which is essential in disaster mitigation emergency preparedness.

The main objectives of this study is to evaluate the seismic vulnerability of a reinforced concrete structure by the development of fragility curves and to determine the improvement in the seismic performance of the structure by the addition of the friction pendulum bearing system by comparing the fragility curves for a fixed structure and structure with FPS. Parametric study, to understand the seismic behaviour of building with varying radius of the concave surface of FPS is also carried out.

II. THEORETICAL BACKGROUND

Earthquakes cause economic losses apart from the torturous pain of loss of lives. Seismic risk assessment is the first step within the disaster prevention strategy and in reducing the associated risks of infrastructures. The comprehensive study of seismic risk are often divided into 3 components- Hazard, Vulnerability and Exposure. Hazard is that the event capable of inflicting harm whereas Vulnerability represents the degree of loss of a component ensuing from a hazard. Exposure is that the amount of parts (population, the economic activities, and therefore the constructions and structures) exposed to a hazard. It’s well understood that it's not the earthquake that kills however the failure of the buildings exposed to those earthquakes. So understanding the behaviour of the buildings throughout Earthquake may be a growing space of research. Assessing the vulnerability of the structures as seismic performance are often useful for risk mitigation and emergency response coming up with.

A. Fragility Curve

A fragility analysis is an effective tool for risk assessment and vulnerability of structural systems. Fragility curves can be developed either for a specific system or component for a class of systems and components. Fragility curves provide the likelihood of surpassing a given damage state as a function of an engineering demand parameter that represents the ground motion. That is, it is the graph of intensity measure (IM on X axis) and % of damage on Y axis. In this work, the maximum inter-story drift ratio of the structure has been considered as a damage measure (DM) and 5% damped first mode spectral acceleration as an intensity measure (IM).

Fragility curves are functions that describe the probability of failure, conditioned on the full range of loads to which structure might be exposed. Fig 1 shows a typical fragility curve with IM along the x-axis and probability of failure along y-axis. Each point in the curve represents the probability of exceedance of the damage parameter, which can be inter-storey drift, lateral drift, base shear, etc., over the predefined limiting value, at a given ground motion intensity parameter. For an IM of say = x, the fragility curve gives the corresponding probability of exceedance of limiting damage parameter as = p%'. It can be interpreted that if 100 earthquakes of IM = x occur, p times the damage parameter will exceed the limiting value for which the fragility curve is developed. The information can be used to analyze, evaluate and improve the seismic performance of both non-structural and structural elements.

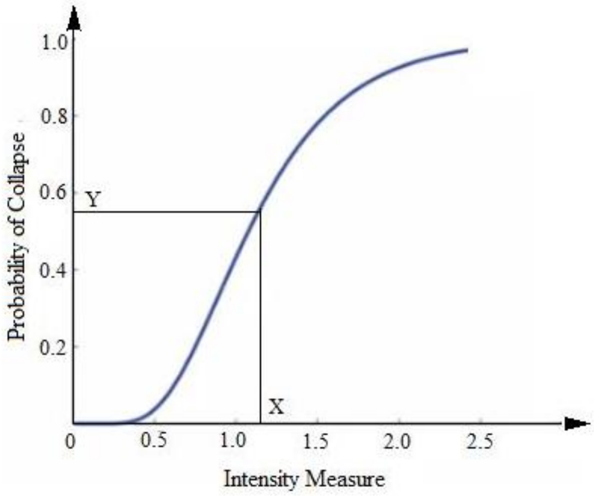

Fig. 1 Fragility Curve

B. Friction Pendulum Bearing System

The friction pendulum bearing system (FPS) is becoming a widely used technique for seismic protection and retrofitting of bridges, buildings, and industrial structures because of its remarkable features such as the stability of physical properties and durability with reference to the elastomeric bearings.

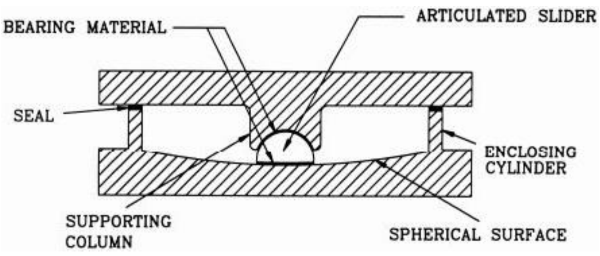

Fig. 2 Friction Pendulum Bearing

Friction pendulum Bearings work on a similar principle as a simple pendulum. Once activated during an earthquake, the articulated slider moves on the concave surface, inflicting the structure to move in small simple harmonic motions. Almost like a simple pendulum, the bearings increase the structures, natural period by inflicting the building to slide on the concave inner surface of the bearing. The bearings, separate out the imparting earthquake forces through the frictional interface. This frictional interface additionally generates a dynamic friction force that acts as a damping system during an earthquake. This lateral displacement greatly reduces the force transmitted to the structure, even during strong magnitude earthquakes. This sort of system additionally possesses a recentering capability, which permits the structure to centre itself, if any displacement is happening during a seismic event which is due to the concave surface of the bearings and gravity.

III. FRAGILITY ASSESSMENT

The seismic fragility of a structure is the probability of failure for a given seismic hazard level. It's measured as the probability of exceedance of a specific limit state of the selected (DM) damage measure for a given (IM) intensity measure. Over the last couple of years, the incremental dynamic analysis or 'IDA' has become the popular alternative for developing the seismic fragility curves for a given structure. An IDA consists of a series of nonlinear time-history analysis of the mathematical model of a structure subjected to incremented intensity measures of a ground acceleration data. A multi-IDA, where a large number of ground acceleration records are used to obtain multiple IM vs. DM 'IDA curves', are generally used in a seismic fragility analysis. For a specific IM, the variation in DM are treated as random samples in calculating fragility. Typically, log-normal distributions are used to model the distribution of DM at every hazard level. The parameters of those lognormal distributions vary over hazard levels. Fragility curves are obtained from the multi-IDA data, using the traditional fitting technique.

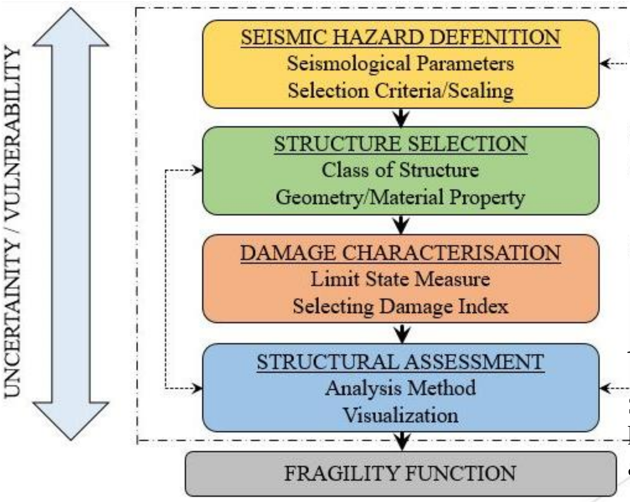

Fig. 3 Fragility Assessment - Methodology

A. Configuration & Structural Details of Example Building

The (G + 12) RCC hospital building with a storey height of 3m in each floor has 6 bays in X – direction and 3 bays in Y – direction forming a plan dimension of 36m x 12m. The building is kept symmetric in both mutually perpendicular directions in plan to avoid torsional effects. The orientation and size of column is kept same throughout the height of the structure. The building is considered to be located in seismic zone V as per IS: 1893-2002. Structural details of the building such as grade of concrete, grade of steel, beam sizes, column sizes and all the other parameters are assumed as per Table I.

Table. I Description of Building Model

No	Building Details	
1	Grade of concrete	M40
2	Grade of steel	Fe 415
3	Floor to floor height	3.0 m
4	Parapet height	1.2 m
5	Slab thickness	150 mm
6	External wall	230 mm
7	Internal wall	150 mm
8	Column	450 X 450
9	Beam	300 X 500
10	Live load	3 kN/m^2
11	Floor finish	1 kN/m^2

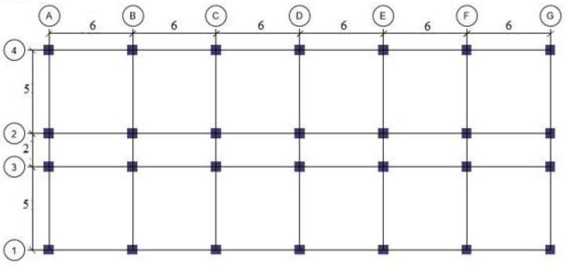

Fig. 4 Beam Column Layout

B. Properties of Friction Pendulum Bearing System

The design properties of Friction Pendulum System (FPS) isolators for the 13 storey RCC hospital symmetric building are as shown in Table II and Table III.

Table. II Properties of Link for Elastic Analysis

Direction	Stiffness (kN-m)	Effective Damping
U_1	29000000	0.10
U_2	1450	0.10
U_3	1450	0.10

Table. III Properties of Link for Non Linear Analysis

Direction	Stiffness (kN-m)	Rate Parameter	μ	R (m)
U_1	29000000	----	----	---
U_2	29000	40	0.08	1.00
U_3	29000	40	0.08	1.00

C. Finite Element Model

A three dimensional finite element modelling of the structure was carried out using the SAP 2000 v 16 [8]. Beam and columns were modelled with nonlinear frame elements characterized by plastic sections. Whereas the slab was modelled as a thin shell element which combines both membrane and plate bending action. A rigid floor diaphragm constraint was provided so that all the constrained joint act as a planar diaphragm. A 3-D discrete model of the friction pendulum isolation system was modelled as a link element. Which is a two noded element which are connected by six springs to represent the mechanical behaviour in each of the six directions i.e. three translation and three rotations. Material non-linearity was modelled in SAP 2000 v 16 by the incorporation of plastic hinges in the model. Plastic hinges structural modelling is based on the assumption that the plasticity zone is concentrated or distributed over a particular length within the structural elements, with corresponding plastic hinges formation. These Plastic hinges were assigned to all the beams and columns by using the auto hinge property of SAP 2000. Incremental dynamic analysis which includes a series of nonlinear time history analyses under a suite of multiple scaled accelerogram records of earthquake ground motion acceleration was performed to estimate limit-state capacity and seismic demand of the above structure.

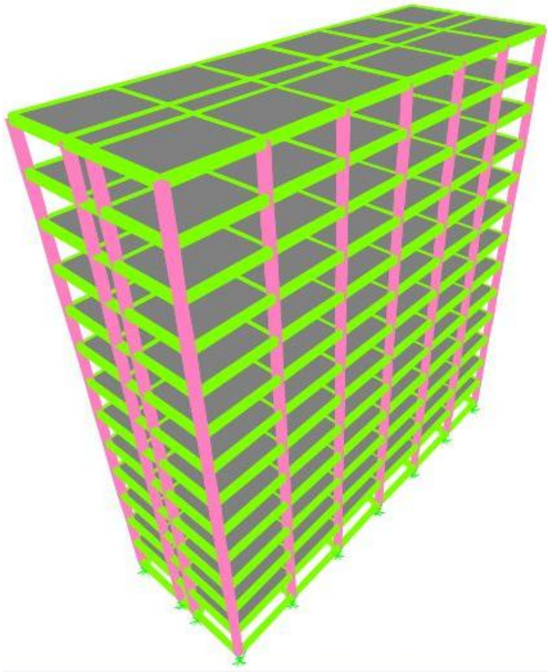

Fig. 5 Three Dimensional Model of the Building

D. Ground Motion Data

The task of selecting and scaling a proper real set of ground motion is very important for seismic design and analysis and also this is a complex task because each of them has differences in their characteristics and accordingly their effects on structural response will be different. Moreover, the accuracy of IDA results are depends on the number of chosen accelerogram records. For the present study twenty five ground motions records were selected from Pacific Earthquake Engineering Research center, (PEER, 2010) based on the following criteria.

The lowest magnitude of the selected earthquake was chosen to be 6.5. PGA and PGV for each earthquake were greater than 0.2g and15 cm/Sec, respectively. Source to site Distance should be at least 10 km. All NEHRP soil types of selected ground motion records came under C and D sites categories. Soil shear wave velocity for the selected earthquakes were greater than 180m/s in upper 30m of soil. Spectral shape was not considered in selecting records. Ground motion records were chosen to be free-field without any consideration of station housing.

Table. IV Selected Earthquakes

RSN	*Event*	*Year*	*Station*
6	Imperial Valley	1940	El Centro Array # 9
721	Superstition Hills	1987	El Centro Co
725	Superstition Hills	1987	Poe Road
766	Loma Prieta	1989	Gilroy Array # 2
767	Loma Prieta	1989	Gilroy Array # 3
783	Loma Prieta	1989	Oakland - Harbour
784	Loma Prieta	1989	Oakland - Title
802	Loma Prieta	1989	Saratoga - Aloha
803	Loma Prieta	1989	Saratoga - W Valley
828	Cape Mendocino	1992	Petrolia
848	Landers	1992	Cool Water
864	Landers	1992	Joshua Tree
900	Landers	1992	Yermo Fire Station
960	North Ridge	1994	Canyon Country
963	North Ridge	1994	Castic Old Ridge
987	North Ridge	1994	LA Centinela
993	North Ridge	1994	LA Fletcher
1006	North Ridge	1994	LA UCLA
1082	North Ridge	1994	Sun Valley
1111	Kobe	1995	Nishi Akashi
1116	Kobe	1995	Shini Osaka
1148	Koceli	1999	Arcelik
1158	Koceli	1999	Duzce
1602	Duzce	1999	Bolu
1787	Hector Mine	1999	Hector

E. Ground Motion Data

Four different structural limit states are considered in the current study, corresponding to slight damage, moderate damage, extensive damage and complete damage. They are related in terms of maximum inter-story drift ratio and cover the whole range of structural from serviceability to life safety, and finally to the onset of collapse. The permissible values of the maximum drift ratio corresponding to these different damage states are described in Table V are adopted and the fragility curves are developed accordingly.

Table. V 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 Damage	ID > 2.5%

F. Developing Fragility Curve

To develop the analytical fragility curve for the given structure Incremental Dynamic Analysis (IDA) was carried out. It fundamentally takes the old concept of scaling accelerogram records and use it in such a way that estimate precisely the full range of structural behavior, from elasticity to collapse. In IDA procedure, a set of chosen ground motion records is applied to a structure, each of those scaled to multiple levels of intensity [11]. Finally, by summarizing IDA envelops, defining limit-states on them and obtaining the results with fragility curves of probabilistic structural damage, the aims of performance-based earthquake engineering can be reached.

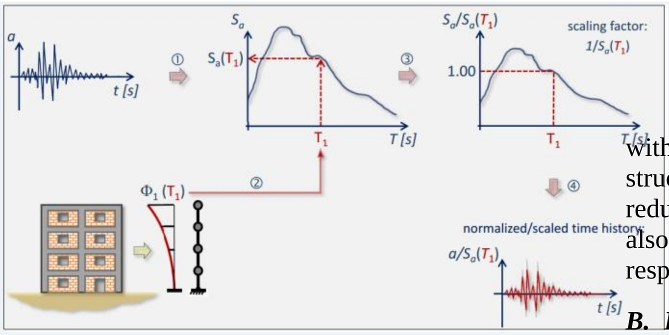

Fig. 6 Scaling Technique (NORSAR)

Lognormal cumulative distribution function is usually fit to this IDA data, to provide a continuous estimate of the probability of collapse as a function of *Sa* based on the following equations.

$$P(C/Sa = X) = \varphi\left(\frac{\ln X - \mu}{\beta}\right)$$

μ & β are parameters that define the fragility function and are to be estimated. β represents the steepness or the slope of the curve. The parameters estimated should be such that it has highest probability of having produced the observed data. When fitting a lognormal distribution to the observations, the goal is to identify the lognormal distribution parameters (μ and β) so that the fitted distribution predicts probabilities that are most consistent with the observed fractions of ground motions.

$$P(C/Sa = X_j)_{observed} = \frac{\text{Number of Collapse Sa} = X_j}{\text{Number of Ground Motions}}$$

More appropriate fitting technique can be obtained by using the method of maximum likelihood. Although this proposed method is slightly more complicated, it can be coded easily using Microsoft excel.

IV. RESULT AND DISCUSSION

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

A. *Time Period*

Fundamental time period of fixed base structure and base isolated structure using Friction Pendulum System (FPS) isolators are compared. First mode period both in X & Y direction for both the cases was compared and shown in Table no VI.

Table. VI Time Period

Direction	**Time Period**	
	Fixed Base (s)	**FPS (s)**
X	1.91	3.29
Y	1.87	3.25

Time period of the base isolated structures with FPS increases as compared to the fixed base structure. This lengthening of the first mode period reduces the earthquake induced forces. With FPS it is also possible to attain a reduction in structural response by energy dissipation.

B. *IDA Curves and Capacity*

An IDA curve is the plot of Damage Measure (Peak interstory drift ratio %) versus the intensity measure. These curves demonstrate the state of the damage measure parameter at different intensity measure levels of input record. In order to develop the IDA curves series of Nonlinear Direct Integration Analysis has been applied under a set of ground motions scaled to a specific level of intensity and thus IDA curves for each earthquake have been derived.

The IDA curve for the structure with fixed base and those with FPS with varying radius of concave surface is shown in the Fig 7 & Fig 8.Based on IDA conducted using 25 earthquakes the multi record IDA curves were developed. Consequently, by summarizing the multi record IDA into their 16%, median and 84% percentiles, it is possible to evaluate the capacities of the building for each limit state. The summarized IDA curve for the structure with fixed base and those with FPS with varying radius of concave surface is shown in the Fig 9 & 10.

Table. VII Capacity - Fixed Building

Case	**S_a (T_1, 5%)(g)**			**Max Drift Ratio**		
	16%	**50%**	**84%**	**16%**	**50%**	**84%**
Slight	0.126	0.181	0.271	0.005	0.005	0.005
Extreme	0.461	0.610	0.746	0.015	0.015	0.015
Moderate	0.502	0.630	0.768	0.025	0.025	0.025

Table. VIII Capacity - FPS Building

Case	**S_a (T_1, 5%)(g)**			**Max Drift Ratio**		
	16%	**50%**	**84%**	**16%**	**50%**	**84%**
Slight	0.167	0.271	0.352	0.005	0.005	0.005

Extreme	0.493	0.675	0.830	0.015	0.015	0.015
Moderate	0.604	0.850	1.025	0.025	0.025	0.025

It can also be seen that the capacity of the isolated system has enhanced as compared to the conventional fixed base structure.

C. Fragility Curve

Fragility Function which gives the relationship between shaking intensity (or the system demand) and the conditional probability of exceeding a response limit state was developed from the IDA results based on the concept of probability. The fragility curve for the structure with fixed base and those with FPS are shown in the Fig 10 and Fig 11. Fragility curves derived for the structure with FPS reflect the inherent characteristics of this structural form. When compared with the curves of regular moment frames of similar structural class, it is observed that the building with friction pendulum bearing system are less vulnerable to seismic hazard because of their energy dissipation property.

The fragility curve for building with fixed base and the one with FPS are developed and their comparison shows that the curve for isolated building tend to shift rightward as compared to curve for fixed case. From Fig 10 and Fig 11 it's inferred that for a particular value of intensity measure the probability of exceedance of limit state is relatively high for the building with fixed base than FPS. This clearly shows that the seismic capacity of the structure has improved significantly by the addition of FPS and is mainly due to the lengthening of first mode time period and energy dissipation characteristics of the friction pendulum bearing system.

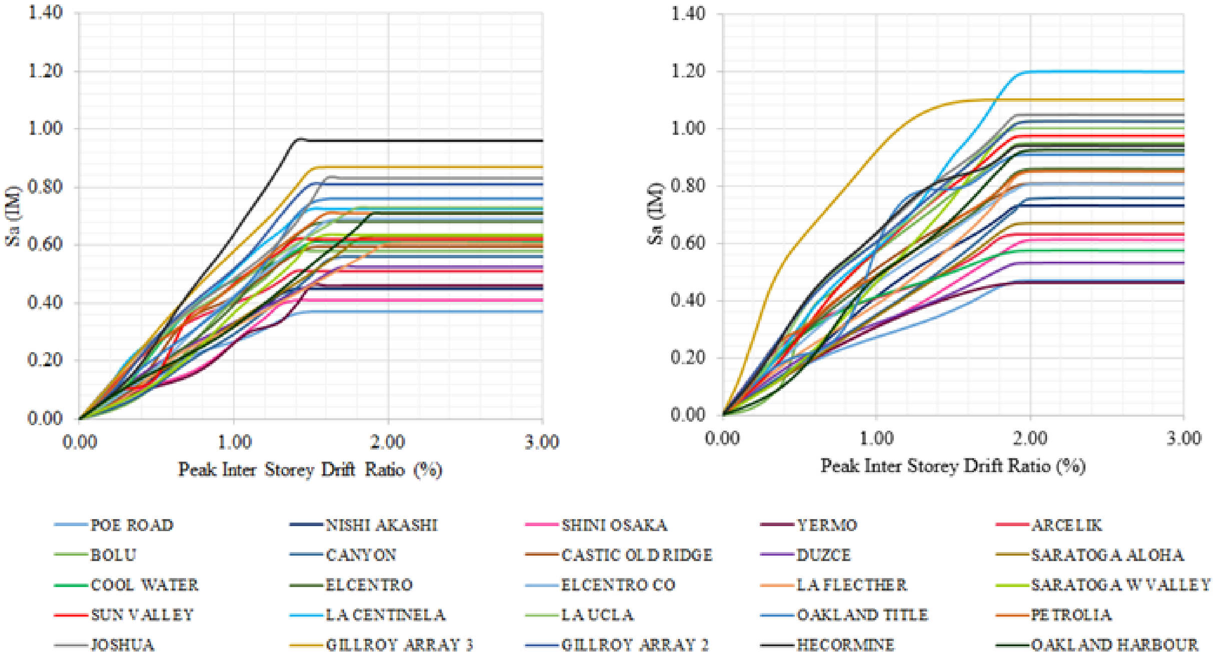

Fig. 7 Multi Record IDA Curve for Fixed and FPS Building

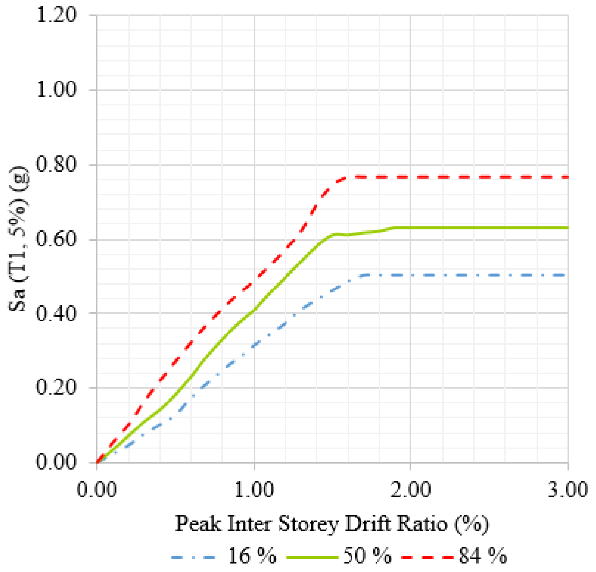

Fig. 8 Summarized IDA Curve - Fixed Building

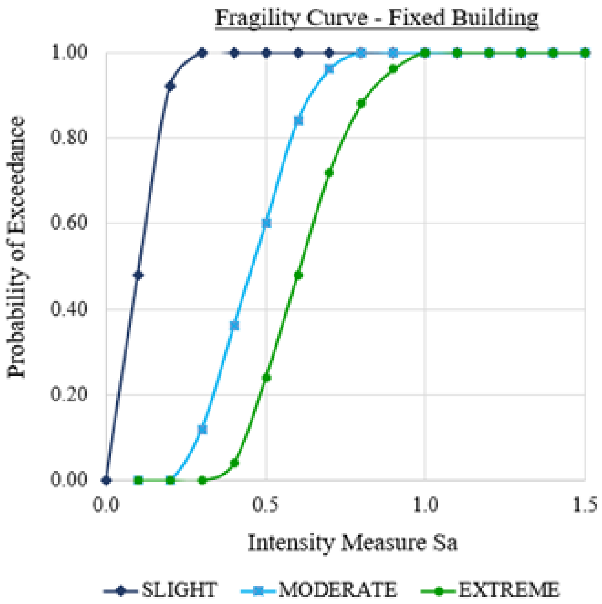

Fig. 10 Fragility Curve - Fixed Building

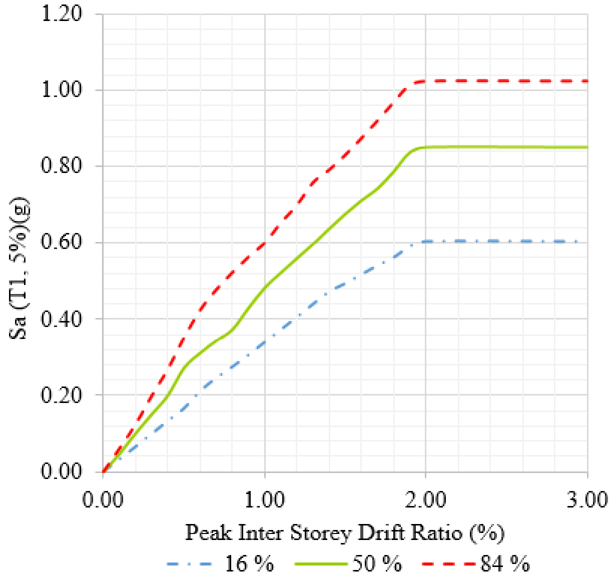

Fig. 9 Summarized IDA Curve - FPS Building

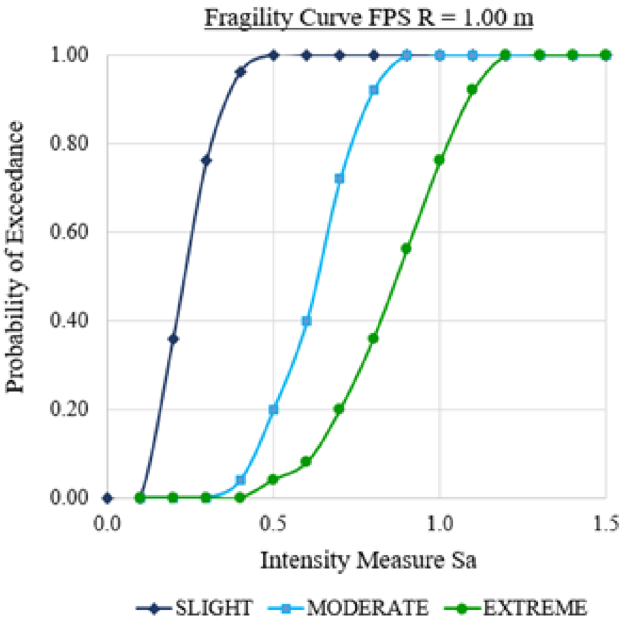

Fig. 11 Fragility Curve - FPS Building

V. SUMMARY AND CONCLUSION

By analyzing the above results it is possible make the following conclusions:

It can be seen that the addition of friction pendulum bearing systems to the building can largely improve the seismic performance of the building. This improvement was due to the fact that the lengthening of the first mode period reduces the earthquake induced forces. Additionally with FPS it is also possible to attain a reduction in structural response by energy dissipation. Results shows that storey drift considerably reduced by using FPS devices over the conventional structure. Permitting a structure sliding over its foundation distracts earthquake-induced forces from the structural system. All these, points out the fact that the structure with FPS is less vulnerable to earthquakes compared to the fixed building.

This study can be extended to study the seismic performance of building due to change in coefficient of friction and radius of concave surface of FPS. Further research could be conducted to study the effect of different aspect ratio, and varying heights and establishing the effects of aspect ratio on the fragility of structures. This study could also be extended to the performance of non-structural members when the limit states are defined. Additionally this idea could be stretched out to different sorts of structures with irregularities in plan and elevation. The optimum placement of FPS in irregular building is likewise a state of exploration. Fragility curves could also be developed for other types of structures, including steel, masonry, composite and other concrete structures.

REFERENCE

[1] Ashish R Akhare, Tejas R.Wankhade, "Seismic Performance of RC Structure Using Different Base Isolator," IJESRT International Journal of Engineering Sciences & Research Technology, pp. 724-729, May 2014

[2] Chopra AK. Dynamics of Structures: Theory and Applications to Earthquake Engineering. Prentice Hall: Englewood Cliffs, NJ, 1995

[3] FEMA. Prestandard and commentary for the seismic rehabilitation of buildings. Report No. FEMA-356, SAC Joint Venture, Federal Emergency Management Agency, Washington DC, 2000

[4] Marco Vona, " Fragility Curves of Existing reinforced concrete Buildings Based on Specific Structural Performance Levels" Open Journal of Civil Engineering, pp. , 120-134, August 2014

[5] N.R.Chandak, "Effect of base isolation on the response of reinforced concrete building", Journal of Civil Engineering Research, vol. 3(4), pp. 135-142, 2013

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

[7] S Aiswarya, Nandita Mohan, "Vulnerability analysis by the development of fragility curves," IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE), pp. 33-40, May 2014

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

[9] Shome N, Cornell CA. 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 1998; 1–12

[10] Shome, N., & Cornell, C. A. (1999). Probabilistic seismic demand analysis of nonlinear structures. Report No. RMS-35, RMS Program, Stanford University, Stanford, http://pitch.stanford.edu/rmsweb/Thesis/NileshShome.pdf.

[11] Vamvatsikos, D., & Cornell, C. (2002). Incremental dynamic analysis. Submitted to Earthquake Engineering and Structural Dynamics, John Wiley & Sons, Ltd.