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PROBABILISTIC DEMAND ASSESSMENT OF SEISMIC BASE-ISOLATED STRUCTURES IN OMMEDIATE OCCUPANCY PERFORMANCE LEVEL

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ABSTRACT

Evaluation of isolated structures in the form of Performance-Based design framework would make greater understanding of behavior such these structures and give a quantitative idea about regulation's adequacy in preparing safety margin under extreme loadings especially in performance objects with lower damage states. Seismic demand analysis of Base-Isolated special moment steel Structures has been investigated in this paper. 4-, 6- and 8-storey of three dimensional designed structures has been modeled in OpenSees Platform. The structures were Analyzed and Designed based on ASCE 7-2010 standard, ANSI/AISC 360-10 and ANSI/AISC 341-10 Specifications and some two dimensional frames were adopted from these archetypes for Evaluation of the performance objective. Various Source of Nonlinearity such as Material and Geometric Nonlinearities have been Intended in Finite Element Models. To consider the uncertainty in one hand and create comprehensive fragility curve on the other hand, Incremental Dynamic Analysis (IDA) using Far Field Ground Motions Set has been utilized. The structure performance would be presented in terms of "fragility curves" and "limit state frequencies" for immediate occupancy performance object. Results show that the mean annual frequency of models are much lower than the Fixed-base ones. It can be observed that the ASCE 7-2010 Standard can provide a uniform risk in models with various type of configuration too.

INTRODUCTION

Application of seismic isolation to protect the structure against earthquake's threats has been increasingly prevalent during recent years. Implementation of this technology plays a significant role in mitigating the damage and loss caused by earthquake in structural and non-structural components, and demonstrates the performance compared to fixed-base structures. Therefore international loading standards have attempted to define the relevant frameworks required for design of these systems. While the event life cycle risk at isolated structures is proved to be less than conventional fixed-base ones, the higher initial construction and cost as well as the maintenance fee have made the isolated structures feasible mostly in highly seismic zones and in structures with Important occupancies. These factors, combined with outstanding uncertainties, have made today's loads and modern design regulations and standards apply more strict criteria for design engineers. Although design requirements and monitoring criteria defined in regulations relating to earthquake-resistant systems are emphasized to provide life safety and prevent lateral collapse level, they also take into account other performance levels such as immediate occupancy performance state (IO). This performance level is important because the isolated structures are generally so significantly important that a stop in their operation would cause great damage not only to the isolated system itself, but also to surrounding environment or part of a society.

Today's modern Regulations analyse performance of structures at levels similar to lateral collapse by following design concepts in the existing standards such as FEMA P-695; however, defining structure's performance, particularly in lower performance levels is also among influential factors on analysis relating to decision making process for construction of structures. Therefore in this study, considering evaluation of structure's performance based on engineering framework introduced by Pacific Earthquake Engineering Research Center (PEER), the objective performance level is studied. Performance evaluation of this limit state for base-isolated buildings will increase the current knowledge about their seismic response and degree of conservatism that regulations have been considered and Risk assessment. Evaluating the earthquake-induced risks and study the responses of models in a probability framework are employed to clarify the extent to which design requirements of modern building codes are successful in maintaining in their occupancy. It should be note that by using total probability theorem and utilizing PEER framework, Risk evaluation will presented in "Fragility curves and "Mean Annual Frequency (MAF)" format for code-conforming structures.

Instead of designing buildings simply for the single limit state, PBEE focuses on the design or evaluation of buildings that will perform efficiently under numerous earthquake intensities, without having to follow prescriptive code-based design. A comprehensive study in the form of incremental Dynamic analysis (IDA) is going to be utilized in order to predict the structures Immediate Occupancy limit state in a reliable manner and consider the effect of the inherent variability in seismic response analysis of structures

PERFORMANCE EVALUATION METHODOLOGY

At the first step some three dimensional models were designed based on latest Design Load standard which considered as ASCE 7-2010 in this study. Once the structure is designed, a detailed mathematical model of the structure is going to be constructed. Two-dimensional models are considered in this paper. The model should capture all nonlinear effects, including geometric nonlinearity, and Nonlinearities associated with steel material that capture strength and stiffness degradation. After completing the models, the next step is to select and scale ground motions. Frequency content of these features will effect on Performance limit state during dynamic analysis of corresponding records. Accordingly, in this study 22 pairs of acceleration records related to far-field ground motions which listed in Appendix "A" FEMA P-695 (2009) is used. These records are normalized first and then scaled so that the median spectral acceleration of the record suite matches the spectral acceleration at the fundamental period, T, in the direction of the analysis of the index archetypes. In the next step, Incremental Dynamic Analysis (IDA) which introduced by Vamvatsikoset. al. (2002) is performed by scaling each ground motion. In order to consider the uncertainty in prediction of seismic intensity, a record of earthquakes scaled in a way to cover a wide range of seismic intensity. Also, considering the uncertainty of the spectral content and frequency of earthquakes, acceptable number of earthquake records have been used. IDA Procedure is capable to find the median capacity of the system. This median capacity is defined as the spectral intensity at which half of the ground motions have caused the structure to that performance object.

Probabilistic seismic demand analysis (PSDA), is the method used to calculate the mean annual frequency (MAF) of certain amounts of structural seismic damage state. In summary, PSDA combines seismic hazard curves for spectral acceleration of the structure, with the results of applying the nonlinear dynamic analysis of structures under a set of ground motions. This method is an application of the Total Probability Theorem. If the Engineering demand Parameter (EDP), representing the structural demand and Intensity Measure (IM), representing the intensity of the earthquake, PADA could be presented in the form of a mathematical formula as given in equation (1)

$$a_{DM}(y) = \int a_{DM|IM}(y \mid x) * \mid d a_{im}(x) \mid \tag{1}$$

Which $\mid d a_{im}(x) \mid$ is differential of seismic hazard function at x based on specific IM. In other words, this value is the probability of a certain Intensity of earthquake $G_{DM|IM}(y \mid x)$ Indicates the possibility of exceedance in demand index value, Say "y" if the Intensity Measure is equal to an specific value, Say "x". This amount is calculated based on non-linear dynamic analysis.

Morgan and Mahin (2011) has introduced limit state for immediate occupancy performance. This study also uses the same mentioned factors. Since no moat wall is assumed to exist in modellings and design, therefore story's drift and story's maximum acceleration were considered as the defining EDPs in immediate occupancy performance object. Table 1 indicates the quantity value of these parameters.

Table 1. IO Performance Limit State

Performance Index	Performance limit state
Maximum Interstory Drift Ratio	0.8%
Maximum Story Acceleration	0.5g

Next, by calculating failure possibility, fragility curves were plotted. These curves define the possibility of transition for different IMs. By exiting the Mean spectral acceleration of IO performance target and its standard deviation, the lognormal distribution is conducted as fragility function. Then based on equation (1) the MAF of models calculated.

ARCHETYPE DEVELOPMENT

Three samples of 4, 6 and 8-story steel structures which possess special ductility property according to ASCE 7-2010 standard is selected for this study. The models are located in San Diego, California, United States with Longitude and Latitude 32.715 and -117.1625 degree, respectively. Information of seismicity, the coefficients of the spectral acceleration, and maximum credible earthquake (MCE) and design earthquake (DE) response spectra and other factors are likely related to ASCE7 (2010) has been extracted. The structures occupancy assumed to be official. Their "risk category" and "seismic design category" of them are equal to "3" and "D" respectively.

ASCE 7-2010 restricted the Response modification factor of base isolated systems between 1 and 2. Therefore this numerical coefficient for studied models considered to be equal to 1.0 and the superstructure for each one is designed according to AISC 360-10 and AISC 341-10 in a three dimensional mode. According to the standards, their Risk Category classification and type of occupancy considered as 3 and buildings with office use respectively.

Isolator used in the models is assumed to be elastomeric rubber isolator with lead core (LRB) for which the manufacturer's specifications are presented in tables 2 and 3. Present study has been modelled based on experimental data of Bridgestone seismic isolation related product line-up. It should be note that two types of base isolations have been equipped. Type 1 which modelled below the interior columns of non-Seismic frames and Type 2 of isolations that utilized under perimeter columns of moment frames. These types are presented in Table 2. And Table 3.Respectively.

Table 2.Manufacturer's specifications of Type 1 LRB Isolations

No.	Number of Stories	Area of Rubber (m^2)	Total Thickness of Rubber (m)	Shear Modulus Of Rubber $(\frac{N}{m^2})$	Area of Lead Plug (m^2)	Yield Stress of Lead Plug $(\frac{N}{m^2})$	Shear Modulus Of Lead Plug $(\frac{N}{m^2})$	ratio of initial stiffness to yielding stiffness
1	4	0.2207	0.24	385000	0.00651	7967000	583000	13
2	6	0.1964	0.256	385000	0.00568	7967000	583000	13
3	8	0.1386	0.252	385000	0.00374	7967000	583000	13

Table 3.Manufacturer's specifications of Type 2 LRB Isolations

No.	Number of Stories	Area of Rubber (m^2)	Total Thickness of Rubber (m)	Shear Modulus Of Rubber $(\frac{N}{m^2})$	Area of Lead Plug (m^2)	Yield Stress of Lead Plug $(\frac{N}{m^2})$	Shear Modulus Of Lead Plug $(\frac{N}{m^2})$	ratio of initial stiffness to yielding stiffness
1	4	0.1662	0.24	385000	0.00478	7967000	583000	13
2	6	0.1453	0.248	385000	0.0041	7967000	583000	13
3	8	0.0908	0.248	385000	0.0027	7967000	583000	13

The structures modeled in OpenSees Platform by PEER. Figure 1.And Figure 2.Shows structural plan view and 4-storey building view in height, respectively. Span length and storey height of models assumed to be 5.0 meter and 3.0 meter, respectively. First floor height is assumed to be equal to 4.0 meter. Perimeter frames designed as Special Moment Frame (SMF) and internal frames are modeled as frames which can just handle weight loads and can't be able to carry out any seismic forces. In order to consider the effect of these weight-carrying frames and P-Delta phenomena in seismic resisting SMFs, Leaning-Column technique is used and modeled as can be seen in Figure 2.

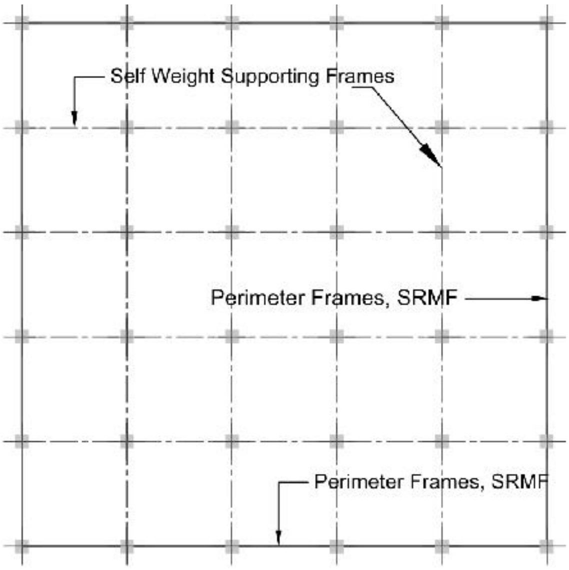

Figure 1. Plan View of Models

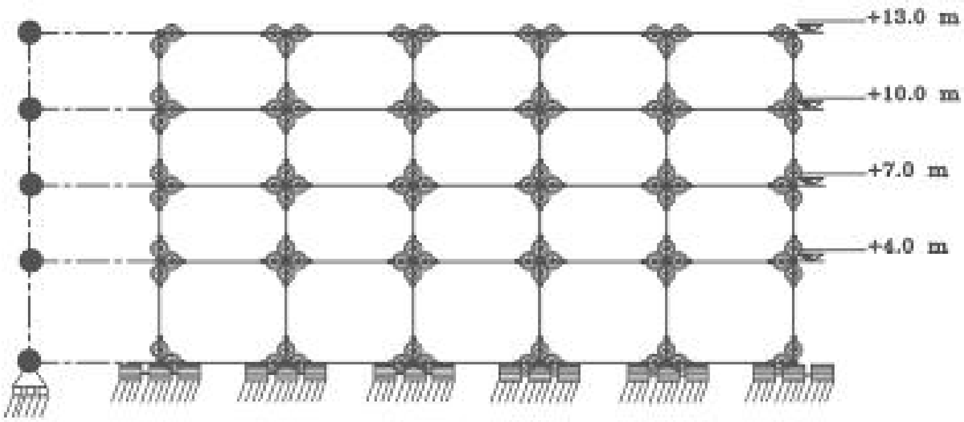

Figure 2. Elevation View of 4-Storey model

Contrary to most previous elements developed in this platform which were only capable of modelling bilinear behaviour, this element is able to include hardening effects at high strains and interaction of isolator's axial force on shearing capacity. Other structural properties including structures' period at design basis earthquake (DBE) level and maximum considered earthquake (MCE) are listed in table 4.

Table 4. Developed Archetype Properties

No.	Number of Stories	Transformed Period at MCE Earthquake (sec)	Transformed Period at DBE Earthquake (sec)	$R_{Isolated}$
1	4	3.342	3.092	1.0
2	6	3.236	3.00	1.0
3	8	3.193	2.95	1.0

Figure 3.Shows seismic hazard curve of area for Transformed Period at MCE Earthquake.

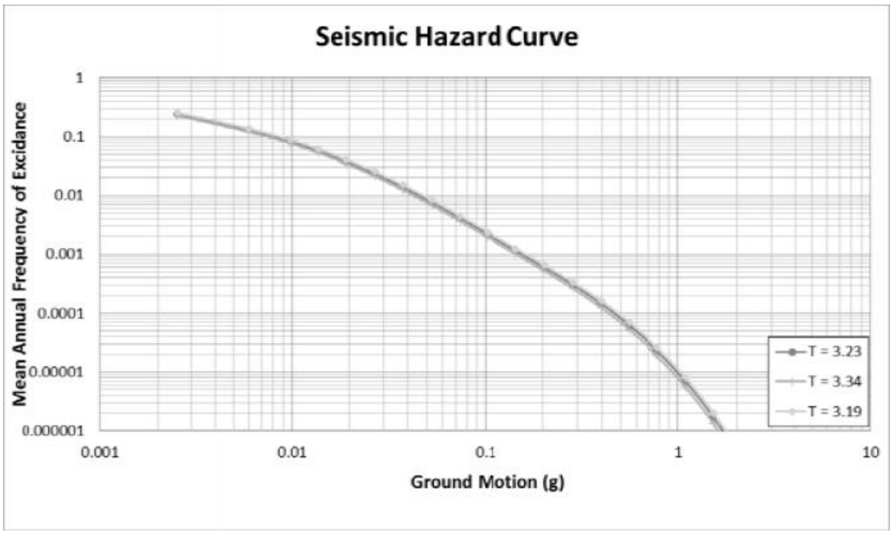

Figure 3. Seismic Hazard Curve of San Diego City

Furthermore columns and beams of the archetypes modeled as Box shape and Wide flange respectively. ASTM A36 type of steel assigned to the type of material for these sections. In addition two types of beam sections assumed in each storey level. Internal beams and external beams and only one type of column were assumed in lieu of each storey of models. Table 5. Presents related beam and column sections for 4-, 6- and 8- storey models. Dimensions of Column presented in millimeter.

Table 5. Beams and Columns of archetypes

6-storey Model			
Storey	Exterior Beam	Interior Beam	Column
Ground Floor	W21x201	W21x201	-
1st Floor	W24x84	W24x76	BOX45x4
2nd Floor	W24x94	W24x76	BOX35x4
3rd Floor	W24x84	W24x68	BOX35x3
4th Floor	W24x62	W24x55	BOX30x4
5th Floor	W18x50	W18x50	BOX30x3
6th Floor	W12x30	W12x30	BOX25x2.5

4-storey Model			
Storey	Exterior Beam	Interior Beam	Column
Ground Floor	W21x101	W21x101	-
1st Floor	W18x55	W18x50	BOX40x3
2nd Floor	W18x65	W18x50	BOX30x3
3rd Floor	W18x46	W18x40	BOX25x3
4th Floor	W10x26	W10x26	BOX20x3

8-storey Model			
Storey	Exterior Beam	Interior Beam	Column
Ground Floor	W21x201	W21x201	-
1st Floor	W24x103	W24x103	BOX55x3.5
2nd Floor	W24x103	W24x103	BOX50x3
3rd Floor	W24x94	W24x94	BOX45x3
4th Floor	W24x94	W24x94	BOX40x4
5th Floor	W24x76	W24x76	BOX35x3.5
6th Floor	W24x68	W24x68	BOX30x4
7th Floor	W18x55	W18x55	BOX30x3.5
8th Floor	W12x30	W12x30	BOX30x3

A comprehensive nonlinear modeling technique is developed and implemented and these nonlinear effects are included in both steel’s geometry and material in order to detect the behavior of structural responses more accurately. P-Delta effect of nonlinear geometry is applied to the members and the effect of nonlinearity in material is modeled by Lumped Plasticity considering hysteretic behavior in the form of plastic hinges at the both ends of each element. For this purpose hysteretic behavior obtained from Lignos (2008) is used. Besides modeling zero length plastic hinges that investigate the nonlinearity, an elastic element is modeled between these hinges of the elements. According to Zareian (2009) the ratio of initial stiffness in hysteretic curve to initial stiffness of elastic elements are considered equal to 1.0. An example of the cyclic behavior of a Wide Flange profile is shown in Figure 3.

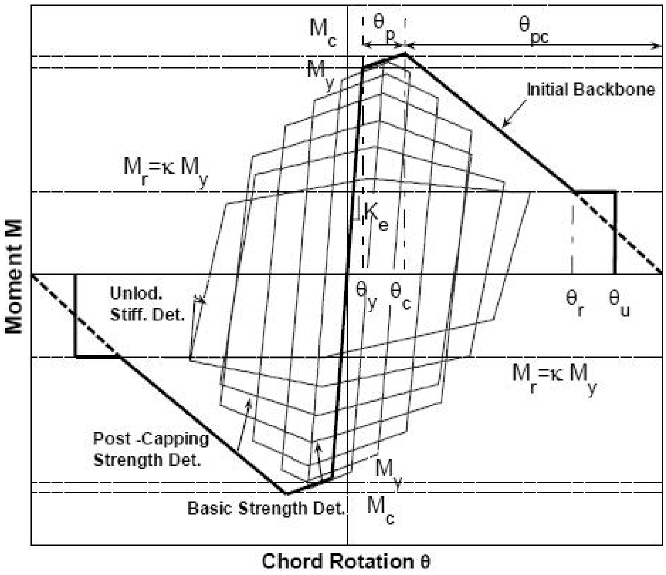

Figure 4. schematic curve of Steel sections hysteretic behavior

INCREMENTAL DYNAMIC ANALYSIS

Vamvatsikoset. al. (2002) presented an approach to identify structural response under various range of intensities for several ground motion records. This procedure presented as Incremental Dynamic Analysis (IDA). Each records scaled such that cover a wide range of earthquake magnitude, Frequency contents and spectral shapes. In order to perform IDA analysis, appropriate parameters is needed to reflect the response and earthquake intensity as accurate as possible. The selection of these parameters is very important. Because the choice of an appropriate parameters would reduce degree of in the responses. In this study Spectral Acceleration of effective period of seismically isolated structure at the Maximum displacement (Sa (T=TM)), is considered as an appropriate intensity. Figure 5, Figure 6. And Figure 7.Shows IDA curves of 4, 6 and 8-storey models. The median value of Target spectral acceleration calculated according these curves.

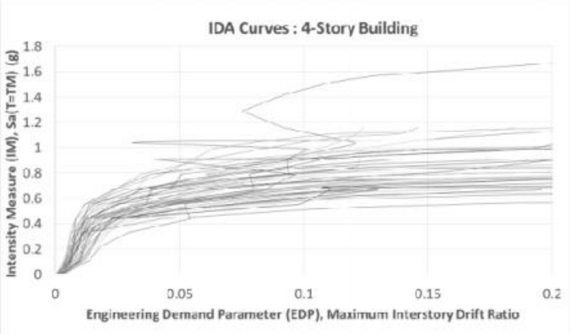

Figure 5. IDA Curve of 4-Storey Model

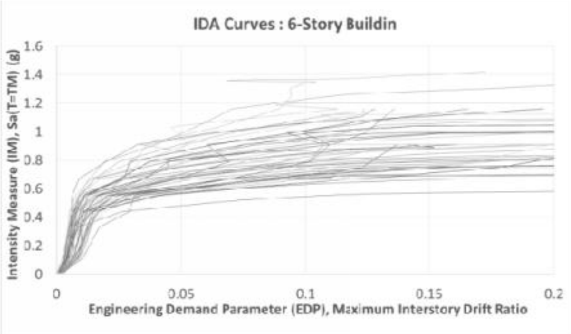

Figure 6. IDA Curve of 6-Storey Model

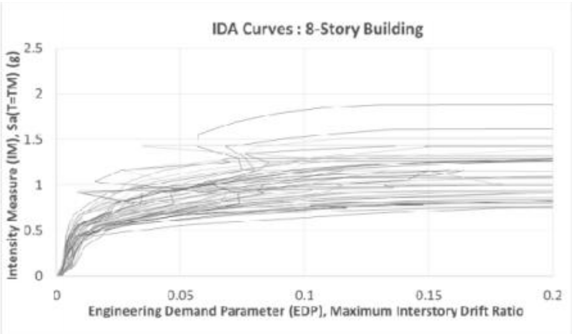

Figure 7. IDA Curve of 8-Storey Model

IMMEDIATE OCCUPANCY PERFORMANCE ASSESSMENT

Calculating Median Spectral Accelerations on one hand and specifying total uncertainty, log-normal probability distribution corresponding to each model will be available. Figures 8, Figure 9. And Figure 10. Also provides the structural fragility curves for four, six and eight Storey models.

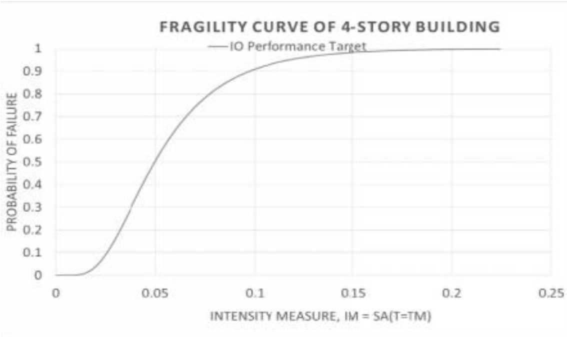

Figure 8. Fragility Curve of 4-Storey Model

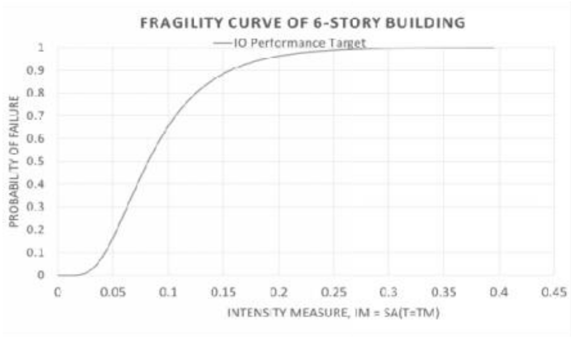

Figure 9. Fragility Curve of 6-Storey Model

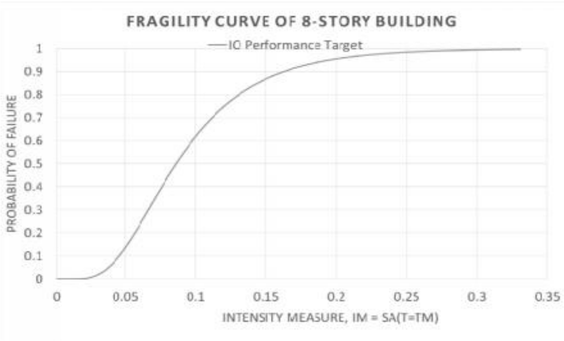

Figure 10. Fragility Curve of 8-Storey Model

This distribution indicates the conditional probability and could be used in equation (1) to calculate Mean Annual Frequency value.Figure 11.Provides these values for models. As it can be seen seismic risk which induced by various models provided a same range.

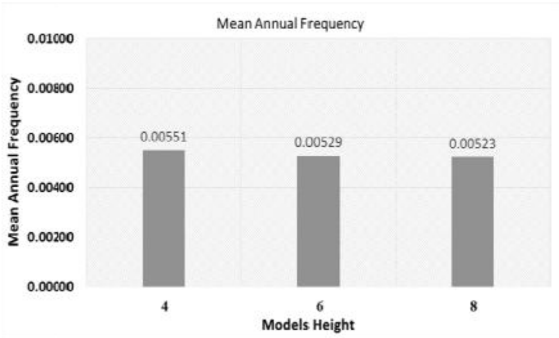

Figure 11. Mean Annual Frequency of Models

CONCLUSIONS

The Results confirm that application of isolators have significant effect in decreasing possible damage corresponding to IO level in the form of possible risk and Mean annual frequency. In another words, application of seismic isolator systems increases range of immediate occupancy performance and improves seismic behavior, and therefore current modern standards are able to meet prerequisites for preparation of IO level. Based on MAF results, a uniform risk is obtained for these archetypes which means variation in height doesn't affect the seismic risk of models. Therefore IO performance object has same efficiency in the models. During analyzing the results found that Acceleration Limit Sate plays an important role in this performance target and whatever the structure height becomes more, Interstory drift will have more share in reaching limit state criteria.

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