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PERFORMANCE EVALUATION OF LEAD RUBBER POLYMER BEARINGS AS LATERAL LOAD RESISTING SYSTEMS IN RC FRAMES EXPOSED TO DIFFERENT GROUND MOTION INTENSITIES

S Siva Bhanu Sai Kumar[1], G V Rama Rao[2]
[1] Research scholar, Department of Civil Engineering, Andhra University College of Engineering, Visakhapatnam, India
[1] Department of Civil Engineering, MVGR College of Engineering, Vizianagaram, India
[2] Department of Civil Engineering, Andhra University College of Engineering, Visakhapatnam, India

ABSTRACT

Purpose – Base isolation has been a popular and frequently used technique to extend seismic resistance to the structure and a proven to be effective for low-rise buildings with firm support. This study is intended to meter the effectiveness of the lead rubber polymer base isolation technique when the RC structure is exposed to the different magnitude of earthquake forces. Effectiveness is measured directly by quantifying the potential of damage caused to the structure.

Design/methodology/approach – Three response spectrums are developed by scaling at least two of ground motions from each of moderate, strong and major earthquake categories. The non-linear time history analysis is conducted on a reinforced concrete frame. Response of this structure is recorded in each time history analysis. Again, the time history response of the structure is recorded by applying base isolation to the structure using a lead rubber base isolator. Probabilities of damage of the structures with and without base isolators are calculated based on Hazus-MH 2.1 (***Hazus ®-MH 2.1 Technical Manual***) **[11]**

Findings – The probability damage curves predicted the severity of damage of the structure for a given spectral displacement. The efficiency of the base isolators in reducing the response of the structure is calculated and damage is assessed subsequently. Through the response plots, the compatibility of base isolators for different classes of earthquake scenarios is evaluated.

Practical implications – This non-linear dynamic analysis of the structure with and without base isolators using ETABS can be used as an alternative for experimental modelling to study the nonlinear response of the structure. The fragility curves are useful in gauging the extent of damage that occurs.

Originality/value – Most of the previous studies considered reinforced concrete structures subjected to one ground motion only. However, in the study presented in this paper, various seismic parameters for an RC structure subjected to various sets of ground motions were determined to assess influence of magnitude of ground motion and the efficiency of base isolation on structural response. This study is useful in assessing the performance and suitability of the base isolation technique. Given the assessment, it will be useful in designing more efficient and economical structures.

INTRODUCTION

Seismic forces are inherently random and unpredictable. Hence structures have to be analysed under the influence of these forces. Seismic loads need to be properly devised to gauge the actual performance of structures with a comprehensive interpretation of the damage. The hysteresis energy distribution study carried by **(Faghihmaleki, Abdollahzadeh and Esmaili, 2018)[09]** on buildings with different heights and **(Apostolopoulos, Drakakaki and Basdeki, 2019)[03]**on a column (at element level) has again impressed upon the need for lateral load resistance systems and techniques at elemental and structural levels. Enormous loss cognate with earthquake forced to think about innovative techniques and methods to protect the structure. This led to the concept of base isolation in 1923. Base isolators will resist the seismic forces and make the structure stay stable. Later various methods are developed to isolate buildings and structures from seismic forces. As the superstructure is less exposed to seismic forces the cost for the isolation will be less compared to the traditional structure for the same intensity of an earthquake. These base isolators are designed in such a way that they absorb the energy and dampen the structural system which reduces the seismic response of the building. These are suitable for any type of building i.e., low rise to mid-rise buildings which rest on hard ground but are not suitable for high rise buildings and soft soils. **(Barbat, Pujades and Lantada, 2008)[04]** studied the concept of seismic vulnerability, damage and risk assessment along with a brief overview of the most commonly used method for assessment of structure’s vulnerability to earthquakes and then the seismic fragility curves are discussed. Capacity curves for buildings are developed using non-linear structural analysis tools, as well as a simple procedure that enables the development of probability damage curves are explained. **(Su, Ahmadi and Tadjbakhsh, 1992)[32]** modelled and analysed an RC structure with its base isolated using laminated rubber bearing with and without lead plug and several frictional base isolation systems. It is concluded that all base isolation systems performed almost similarly. The ArcView tool was also used to create a Geographic Information System (GIS) to organise the data and reduce seismic risk occurrences that cause major building vulnerability; thus, despite the region's low-to-moderate seismic hazard, the projected seismic risk is large. **(Khechfe *et al.*, 2002)[18]** Investigated the seismic performance of secondary systems with isolated base. Different base isolation systems are used to determine which system is the most effective in protecting the non-structural systems. Out of all energy absorbing systems base isolation system is the most effective in controlling the displacement and minimizing the increase in the accelerations. (Matsagar and Jangid, no date)**[23]** have utilized isolation devices, elastomeric bearings and sliding frameworks in the retrofitting works and inferred that seismic base isolation lowers the seismic response by a component going from 0.3 to 0.8 in the superstructures, and controls the distribution of these responses, the seismic reaction of the retrofitted structures is decreased when contrasted with the conventional designs and both isolation systems are found to be effective. **(Losanno *et al.*, 2021)[22]** an original minimal expense fibre-reinforced elastomeric isolators (FREIs) created with the recycled rubber (RR) and 3D FEA are done on the rigid-base and isolated-base setups of the model structure exposed to a group of recorded strong ground motions. The mathematical model of the unreinforced masonry building was created and the hysteretic behaviour of infills and RR-FREIs are simulated. Their outcomes showed a critical decrement in both the storey accelerations and the inter-story drifts. **(Lin, Chan and Tagawa, 2020)[21]** linked a base isolator with the Earthquake Early Warning (EEW) and proposed a new seismic-risk mitigation strategy. They've developed a smart system that locks the base isolator with shear keys till there's no earthquake risk and unlocks it once the seismic activity is detected by the EEW system. On a shake table subjected to past earthquakes, a 6-story test frame is aroused. The proposed technique appears to be beneficial in decreasing seismic responses on the building, according to the findings. It's an earthquake-risk mitigation system that uses the Internet of Things.**(Pourmasoud *et al.*, 2020)[26]** MDSI (Multi-Directional Seismic Isolation) systems with an isolation unit and a Super-High-Damping-Rubber (SHDR) device are used to alter vertical stiffness without impacting horizontal displacements. Under ten distinct combined vertical-horizontal earthquake excitations, the proposed system was utilised for 3, 5, 8, and 12-story steel frames. MDSI can minimise maximum vertical and horizontal accelerations by up to 55 and 25 per cent respectively relative to existing base isolation systems. **(Rastgoo Moghadam and Konstantinidis, 2015)[28]** observed the rotational effect on the horizontal behaviour of rubber isolators using 3D FEA. Four boundary conditions are considered: (1) no rotation at the bottom and top, (2) rotation only at the top, (3) rotation only at the bottom, and (4) rotation at both top and bottom of the bearing. It was demonstrated that the finite element model can reliably assess the rotational effect on the horizontal behaviour of the bearing. Also, rotation is applied to the top of another and it was shown that applying rotation and axial load causes an initial lateral displacement with an increment in the average stress vertically for a given rotation the value of initial lateral displacement also increases. **(Kelly and Van Engelen, 2015)[17]** has proposed a mono series solution for the compression modulus of the rectangular fibre-reinforced elastomeric isolator, alternative for steel–reinforced elastomeric bearing. A G+10 RC structure is considered performance was assessed. And concluded that proposed model has performed nearly as steel–reinforced elastomeric bearing. **(Zhao *et al.*, 2019)[36]** studied the effect of tuned mass damper introduced into the friction pendulum system in reducing the structural responses and concluded that this system is more effective in reducing the structural response and produced greater attenuation relative to the other base isolation systems. **(Sasaki *et al.*, 2012)[31]** analysed a G+5 multi-storied structure base isolated with triple-friction-pendulum bearings (TPB), with a combination of lead-rubber bearings (LRB) and cross-linear bearings (CLB) and base fixed subjected to near-fault and long duration sub-duction ground motions. It was found that TPB provided greater attenuation of structural responses relative to LRB-CLB system. **(Ramallo *et al.*, 2004)[27]** devised a smart base isolation system for six degree freedom system, subjected to three different ground motions and their structural responses are compared with those of the same system isolated with lead rubber bearing system. It is observed that smart isolation mitigated majority of structural response compared to other isolation systems.

From the review of previous studies on Performance of reinforced concrete structures with base isolators subjected ground motion, it can be observed that most of the previous studies considered reinforced concrete structures subjected to one ground motion only.

However, the possibility of a structure being subjected to same ground motion for which it is designed for is rare. So it is desirable to study the seismic performance of RC structures subjected to various ground motions and design it for the most critical response. Various seismic parameters for an RC structure subjected to various sets of ground motions can be determined to assess influence of magnitude of ground motion and the efficiency of base isolation on structural response. This study is useful in assessing the performance and suitability of the base isolation technique. Given the assessment, it will be useful in designing more efficient and economical structures.

OBJECTIVES:

- Assess the vulnerability of the RC structure by calculating the damage probability of the structure.
- To assess the compatibility and efficiency of the base isolation technique for RC structures in different classes of earthquake scenarios.

METHODOLOGY

A typical RC framed structure with and without base isolators is modelled and analysed using ETABS designing software (according to **(IS 456, 2000)[12]** and **(IS 1893, 2016)[15]**. **(Boukhalkhal *et al.*, 2020)[06]** compared Non-linear dynamic analysis with static non-linear analysis (*Dynamics of Structures by Anil K. Chopra*.)[05] and concluded that the error in the structural responses are nominal but non-linear dynamic analysis provides the more accurate simulation of the dynamic forces compared to static non-linear analysis at it provides few characteristics of dynamic analysis. **(Yang *et al.*, 2021)[35]** adopted vertical mode decomposition response spectrum method and the time history analysis method to assess the vertical seismic action and concluded time history analysis is more precise and **(Zorić *et al.*, 2022)[37]** have used lead rubber base isolators and measured the structural response of the structure by carrying the time history analysis. So time history analysis is carried out for all the RC frames and structural responses are recorded. Here in this study fragility analysis is performed to obtain damage probabilities (Siva *et al.*, 2016)[03] performed seismic fragility analysis to assessed the performance of the lateral load resisting systems in the structures. Probabilities of damage are calculated as per **(Hazus- MH2.1)[11]** developed by Federal Emergency Management Agency. The detailed methodology adopted is shown in the following flow chart (Figure-1).

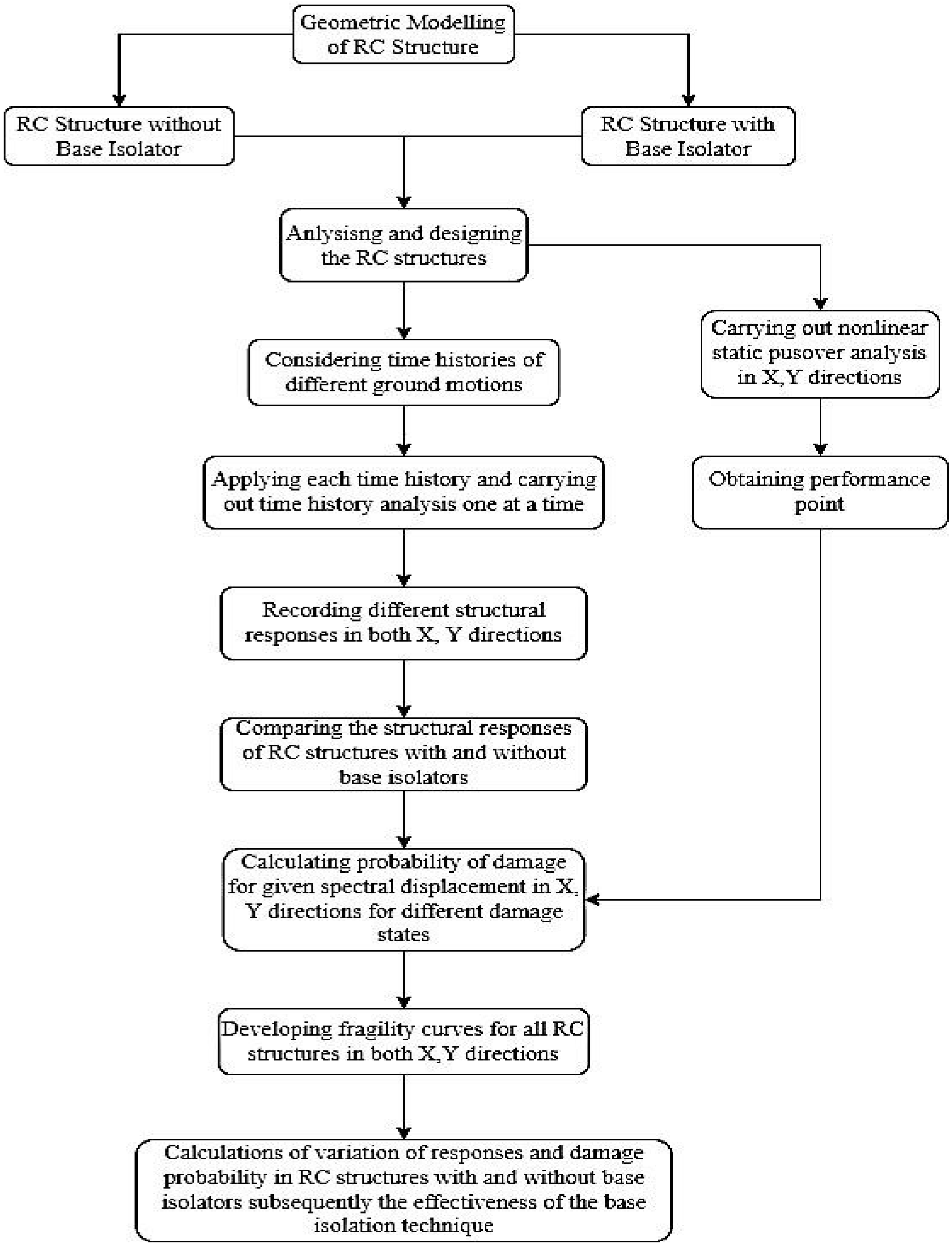

Figure-1 Flowchart describing methodology adopted

Calculation of Probability of damage of RC structure for given spectral displacements:

The probability of damage can be estimated as per clause No. 6.4.3.1 of the Hazus manual[11] given by FEMA

$$[P[\,dS/S_d] = \phi[(1/\beta ds)\; * \ln\,(S_d/S_{d,ds})]$$

Where,

$S_{d,\,ds}$ - The spectral displacement median value when the building reaches the threshold of the damage state.

βds - The standard deviation of spectral displacement's natural logarithm for damage state

ϕ - The normal cumulative distribution function.

Many formulae are in wide use to calculate the median value of spectral displacement. The following formulae in table-1 proposed by **(Barbat, Pujades and Lantada, 2008)**[04] using the capacity spectrum method in the evaluation of seismic damage of urban areas are considered, as the variables used are directly dependent on the parameters derived from the non-linear static pushover curve.

Table- 1 type of damage state and corresponding median value of spectral displacement

Type of Damage	Formula
Slight	$\left[S_{d,ds} = 0.7\mathrm{dy}\right]$
Moderate	$\left[S_{d,ds} = \mathrm{dy}\right]$
Severe	$\left[S_{d,ds} = \mathrm{dy} + 0.25(\mathrm{du} - \mathrm{dy})\right]$
Complete	$\left[S_{d,ds} = \mathrm{du})\right]$

LEAD RUBBER POLYMER BASE ISOLATOR:

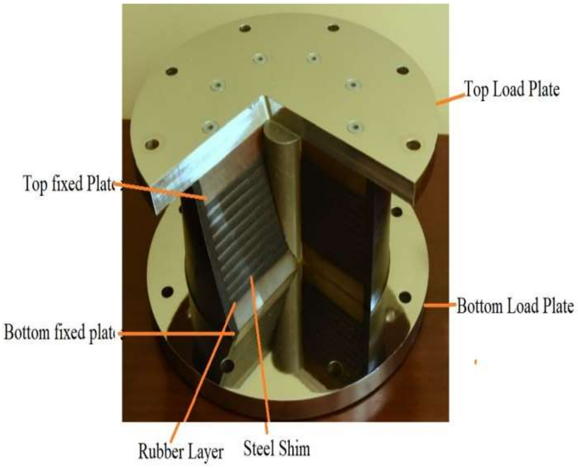

Figure 2 Lead Rubber Polymer Base Isolator(Source: https://www.berkeley.edu/)

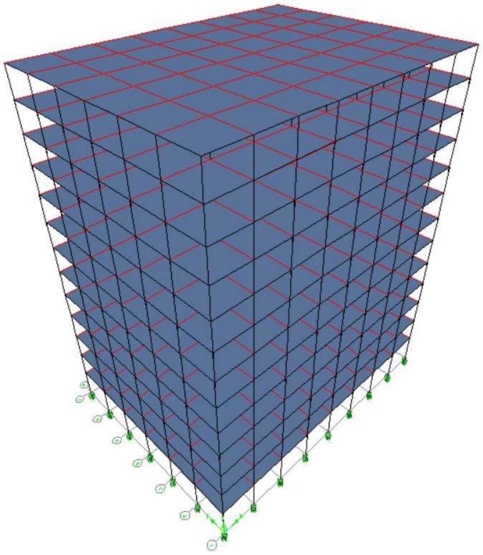

Figure 3 Model of the structure with base isolator

Lead Rubber Polymer Base isolators shown in figure-2 are most popular in constructions as they provide more flexibility and less deflection. These isolators consist of two thick steel plates, natural rubber layers and shims. By adding lead plugs in the holes made in the rubbers and steel shims damping is provided.

MODELLING:

Dimensions of the RC Frame:

Height =38.4 m
Length = 32 m
Width = 24 m

Number of bays

In X-direction = 8
In Y-direction = 6
Number of storey's in Z-direction = G+10
Height of each storey = 3.2m

Spacing of bays

In X-direction = 4 m
In Y-direction = 4 m
Length of each bay = 4 m

Thickness of walls and slabs

Slab = 0.125 m
External wall = 0.150 m
Internal wall = 0.100 m
Parapet wall = 0.100 m

Loads Considered

As per table-1 of (IS 875 : Part-1, 1987)[13]
Brick masonry's unit weight = 19 kN/m^3
Reinforced cement concrete's unit weight = 24 kN/m^3
As per table-1 of (IS 875 : Part-2, 2008)[14]
Average floor live load = 2.5 kN/m^2
Roof live load = 2 kN/m^2

Base Isolator properties

Vertical stiffness of the bearing (K_v) = 1500000 kN/m
Effective horizontal stiffness (K_{eff}) = 800 kN/m
Effective damping = 5%
Elastic stiffness (K_e) = 2500 kN/m
Yield force (F_y) = 80 kN
Post yield stiffness ratio = 0.1

Table-2 Properties of the isolator

Elastomer Properties (Materials)		Isolator Dimensions	
Shear Strain (%)	50	Shape	Circular
Shear Modulus (G)	0.707MPa	Diameter	800mm
Bulk Modulus (K)	1500 MPa	Thickness of Rubber Cover	10mm
Elastic Modulus (E)	2.63 MPa	No. of layers	18
Damping (%)	5	Thickness of each layer(t_r)	9mm
Lead Yield Strength (σ_{pl})	8MPa	Thickness of steel plate(t_s)	2mm
Material Constant (k)	0.7	No. of steel plates	17
		Lead Core Diameter	140mm
		Total Height	196mm

Table-3 Data of the ground motions considered and given notations (Source: PEER ground motion database)

Notation	Ground Motion	Year of Occurrence	Mechanism	Magnitude of Earthquake	Joyner-Boore Distance Rjb (km)	Radius of Rupture Rrup (km)	Vs30 (m/s)
G.M -1	Umbria-02	1979	Normal	3.7	4.11	6.25	678
G.M -2	9128775 highland baseline	1999	Strike-slip	3.81	0	1.81	335.43
G.M -3	El centro 07	1979	Strike slip	5.01	7.32	10.31	210.51
G.M -4	San Francisco	1976	Reverse	5.28	9.74	11.02	874.72
G.M -5	Tabas	1978	Reverse	7.35	0	13.94	302.64
G.M -6	Kern	1952	Reverse	7.36	81.3	82.19	514.99

Table-4 Classification of Earthquakes

S. No.	Earthquake	Class
1	G.M -1	Minor
2	G.M -2	Minor
3	G.M -3	Moderate
4	G.M -4	Moderate
5	G.M -5	Major
6	G.M -6	Major

Sample Scaled Ground Motions and Target Response Spectrum in X-Direction

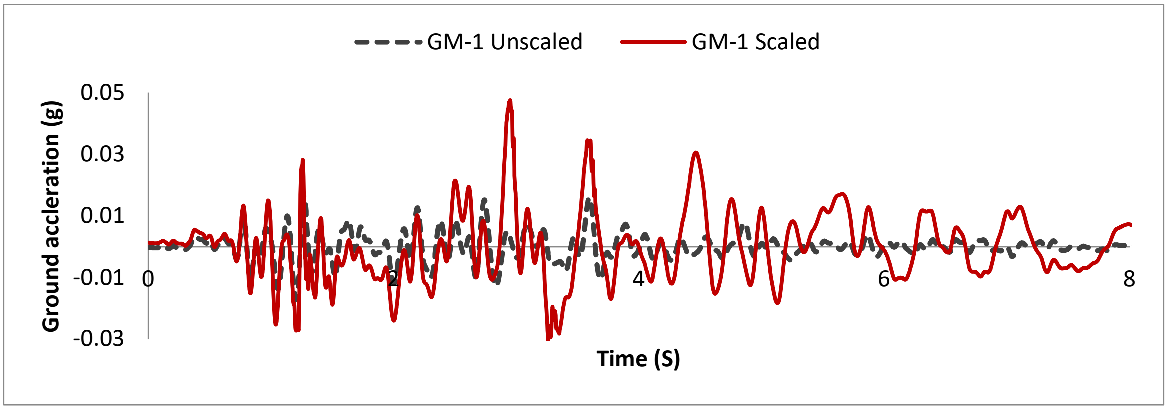

Figure 4 Scaled and Unscaled G.M-1 in X-Direction

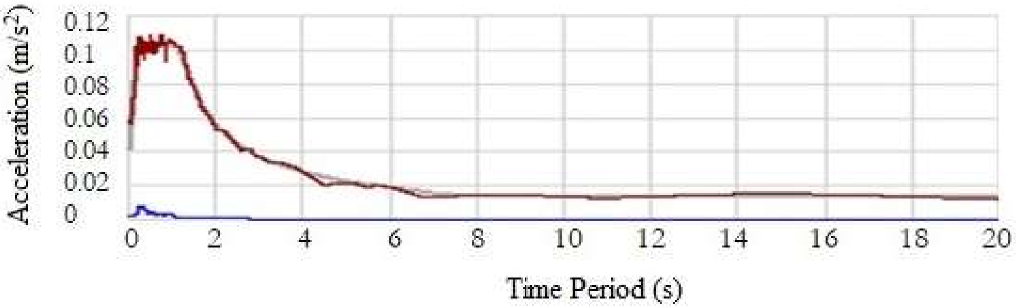

Figure 5 The target response spectrum of G.M-1 after scaling in X-Direction

RESULTS

Maximum Displacements:

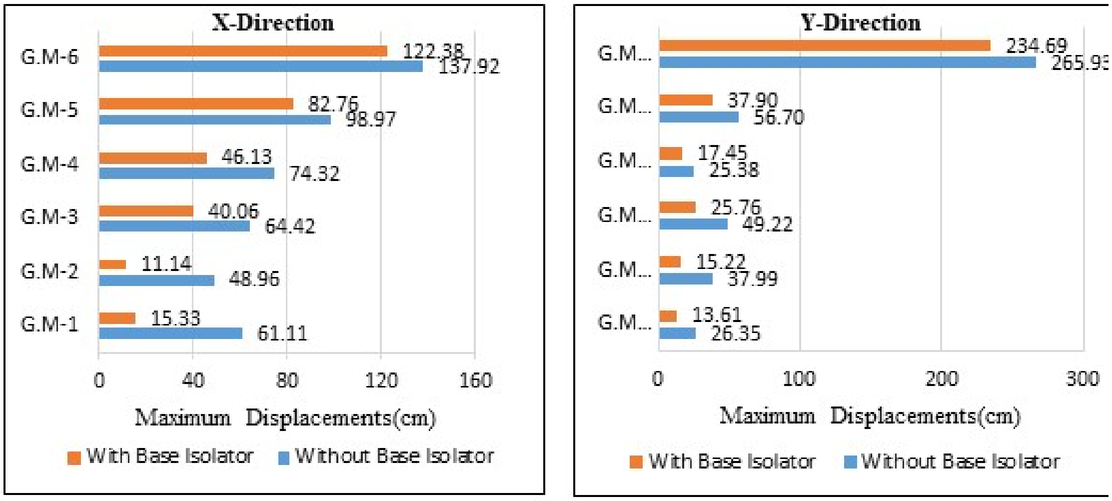

Figure 6 Maximum displacement values in X-direction and Y-direction

From the above figure it is observed that for minor earthquakes (G.M-1 and G.M-2) an average of 75.96%, 61.23% maximum displacement in the structure is reduced by using base isolator in X, Y directions respectively, that of moderate earthquakes (G.M-3 and G.M-4) is 37.87%, 42.07% in X and Y directions respectively and that of major earthquakes (G.M-5 and G.M-6) are 13.4%, 15.51% in X and Y directions respectively. And also, the percentage of reduction of displacement declined as the magnitude of the earthquake increased. This is maybe because of improvement in the force-displacement hysterical behaviour of the base isolator.

Maximum Accelerations:

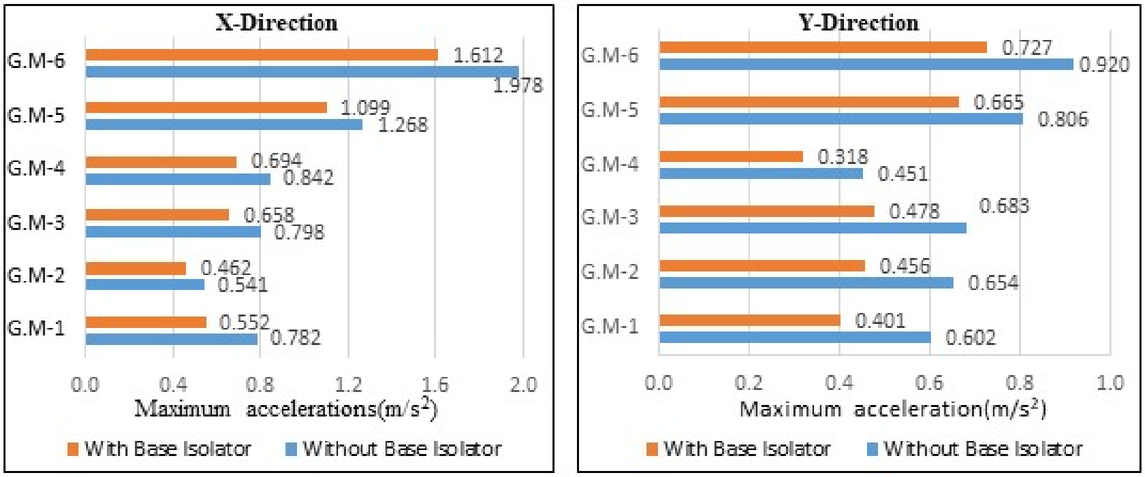

Figure 7 Maximum storey acceleration values in X-direction and Y-direction

The highest maximum storey accelerations in the structure in X, Y directions are observed when major earthquake ground motions G.M-5, G.M-6 are applied. The least maximum storey accelerations in X, Y directions are observed when ground motion G.M-2 and G.M-4 are applied. This is because the major component of G.M-2 is oriented towards the Y direction and that of G.M-4 is oriented towards the X direction. But the average reduction in maximum storey acceleration of the structure by using base isolation for minor earthquakes (G.M-1 and G.M-2) is 22.03%, 31.8% in X, Y directions respectively. That of moderate earthquakes (G.M-3 and G.M-4) are 17.53%, 29.77% in X, Y directions respectively, for major earthquakes (G.M-5 and G.M-6) they are 15.92% and 19.23% in X, Y directions respectively. A decremented trend was observed in the average reduction of storey acceleration in both X, Y directions as the magnitude of ground motion increased.

Maximum base shear:

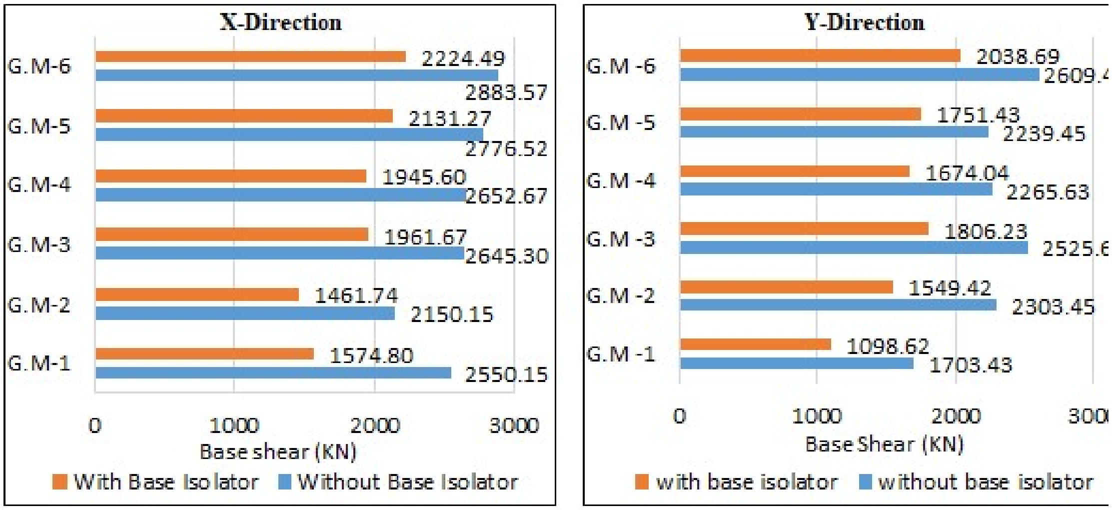

Figure 8 Maximum base shear values in X-direction and Y-direction

Average reduction of base shear in X, Y directions are more in base-isolated structure when it is exposed to minor earthquake ground motions than that of moderate and major earthquake ground motions are applied. The average reduction of base shear in X, Y directions are 35.13%, 34.12% for minor earthquake ground motions (G.M-1 and G.M-2) that of moderate earthquake ground motions (G.M-3 and G.M-4) are 26.25%, 27.29%, and major earthquake ground motions (G.M-5 and G.M-6) are 23.05%, 21.83%.

Maximum inter storey drift:

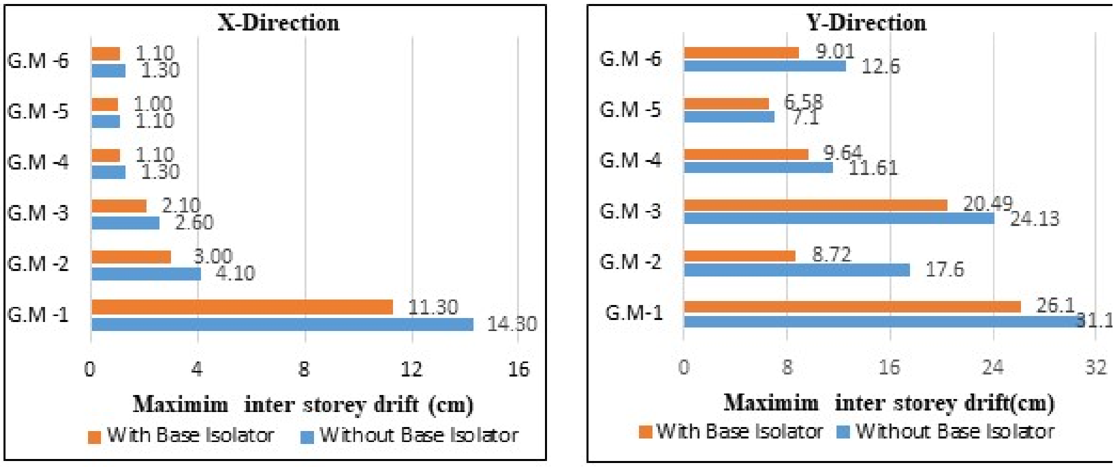

Figure 9 Maximum inter storey drift values in X- direction and Y-direction

Maximum inter storey drift is reduced in base-isolated structure compared to that of regular structure. But a nominal reduction is observed irrespective of the type of earthquake ground motion.

Fragility curves:

Following are the fragility curves developed and used to evaluate the probability of structural damage.

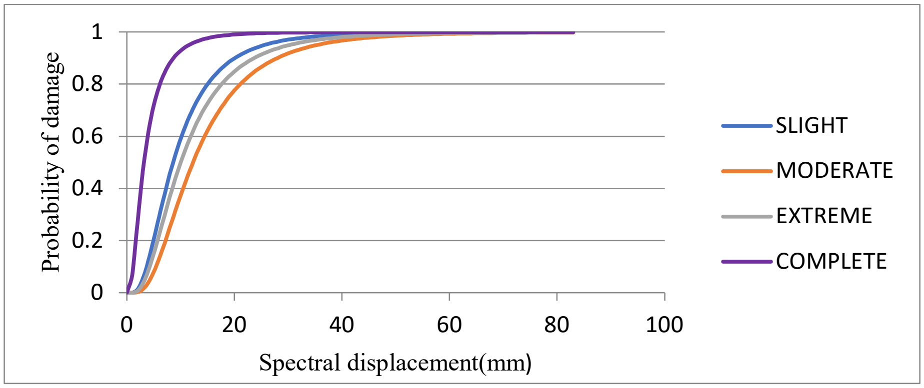

Figure 10 Fragility curve in X- direction

No significant reduction in the probability of a slight damage state is observed in the structure when it is subjected to minor, moderate, major earthquake ground motions. The average reduction in the probabilities is 4.27%, 4.2% and 0.87% for minor (G.M-1 and G.M-2), moderate (G.M-3 and G.M-4), major (G.M-5 and G.M-6) earthquake ground motions respectively.

For a moderate damage state, a considerable amount of damage probability is observed when the structure is exposed to minor earthquake ground motion. And that of the structure exposed to moderate and major earthquake ground motions are negligible. The average reduction in the probabilities is 24.9%, 5.16% and 1.32% for minor (G.M-1 and G.M-2), moderate (G.M-3 and G.M-4), major (G.M-5 and G.M-6) earthquake ground motions respectively.

Similarly, for extreme damage states, a considerable amount of damage probability is observed when the structure is exposed to minor earthquake ground motion. The average reduction in the probabilities is 29.8%, 6.4% and 2.17% for minor (G.M -1 and G.M -2), moderate (G.M -3 and G.M-4), major (G.M-5 and G.M-6) earthquake ground motions respectively.

A significant amount of reduction in probability for complete damage state is found in the structure when it is subjected to minor, moderate, major earthquake ground motions. The average reduction in the probabilities is 38.58%, 16.82% and 12.81% for minor (G.M-1 and G.M-2), moderate (G.M-3 and G.M-4), major (G.M-5 and G.M-6) earthquake ground motions respectively.

Y-Direction:

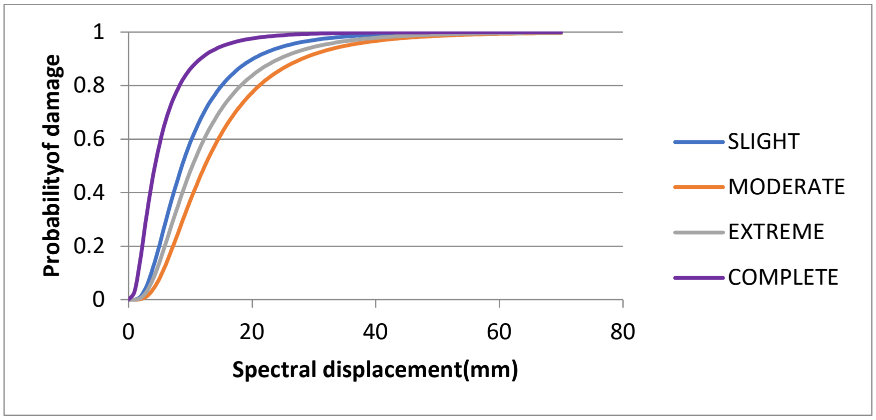

Figure 11 Fragility curve in Y- direction

The average reduction in the probabilities is 6.31%, 3.68% and 1.37% for minor (G.M-1 and G.M-2), moderate (G.M-3 and G.M-4), major (G.M-5 and G.M-6) earthquake ground motions. There is no significant reduction in the probability of a slight damage state is observed in the structure when it is subjected to minor, moderate, major earthquake ground motions respectively.

For a moderate damage state, a considerable reduction of damage probability is observed when the structure is exposed to minor earthquake ground motions only. The average reduction in the probabilities is 20.22%, 5.89% and 2.17% for minor (G.M-1 and G.M-2), moderate (G.M-3 and G.M-4), major (G.M-5 and G.M-6) earthquake ground motions respectively.

Similarly, for extreme damage states, a considerable amount of damage probability is observed when the structure is exposed to minor earthquake ground motions. The average reduction in the probabilities is 25.17%, 10.24% and 3.61% for minor (G.M -1 and G.M -2), moderate (G.M -3 and G.M -4), major (G.M -5 and G.M -6) earthquake ground motions respectively.

A significant amount of reduction in probability for complete damage state is found in the structure when it is subjected to minor, moderate, major earthquake ground motions. The average reduction in the probabilities is 30.41%, 18.38% and 13.91% for minor (G.M-1 and G.M-2), moderate (G.M-3 and G.M-4), major (G.M-5 and G.M-6) earthquake ground motions respectively.

DISCUSSION

In present study performance of LRB isolators under various seismic inputs is observed by applying different seismic intensities and all uncertainties in the seismic input intensity. Subsequently vulnerability of the structure is assessed by developing fragility curves. It is observed from the analysis that LRB isolators exhibited better attenuation towards minor ground motion intensities. A decrement in seismic impact magnitude in the structure is observed when minor ground motions are applied as a consequence of increase in specific periods of natural oscillations of the system. An improved seismic resistance in structure is observed when moderate and major ground motions are applied. Present study contributes for the comprehensive understanding of behaviour of the LRB isolated structure subjected to ground motions of different intensities.

CONCLUSIONS

It is conclusive that lead rubber polymer base isolators are more suitable for minor earthquake ground motions relative to moderate and major ground motions. As displacement ductility demand is disproportionately large in moderate and major ground motions there is lesser reduction in the structural responses. Even though reduction in structural response is less in moderate and major ground motions improvement in lateral load resistance is observed due to a stable rollover configuration of the isolator up to design displacement limit. Lead rubber Polymer base isolators can improve the flexibility of the structure to the extent it prevented the structure from complete damage but no significant reduction in slight, moderate, severe damage probabilities where higher flexibility demand is required. And from the findings we can conclude that lead rubber polymer base isolators exhibited lesser attenuation in case of moderate and major earthquakes relative to other base isolation methods.

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