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Seismic Assessment of Steel-frame Buildings Mounted with Base-Isolated System

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Abstract

A multi-Storey steel frame building against earthquakes has always been a challenge for structural engineering and researchers. Many seismic protection systems have been investigated overtime where the Base Isolation system has widely been used and implemented. It works on the principle of dissociation of substructure to the superstructure. In the present paper, different multi-storey steel frame buildings are evaluated, which are mounted with Lead Rubber Bearing (LRB) as a base isolator. LRB has been designed in compliance with the FEMA and ASCE guidelines. Further, a relative study is presented for evaluating the traditional fixed-base structure with a base-isolated building by performing a time history analysis. Base shear, inter-storey drift, acceleration, and displacements are examined as a result of the study. The outcome shows significant contributions towards reducing acceleration, inter-storey drift and base shear distributed over the floors. Moreover, LRB not only absorbs the seismic energy but also substantially decreases the destructive effect during an earthquake.

Keywords: Time History Analysis, Base Isolation, Lead Rubber Bearing, Storey Drift, Displacement

1. Introduction

A building has to be safeguarded from all the adverse conditions induced on it like earthquakes. Due to the shaking of the ground, inertia forces are caused, which are proportionate to the product of ground accelerations and building mass. With the increase in ground accelerations, strength and stiffness of the structures should also be enhanced to prevent structural damage [1].

Several seismic designs were made in the last few decades to make structures resistible during earthquake shaking, where the structure should not sustain much deterioration of structural elements and little deterioration of non-structural components under-occupancy level as defined by FEMA 356 [2]. Special techniques need to be implemented in designing these structures so that they remain undamaged even under major earthquake [3]. The primary aim of any structural designer in a building would be to minimize floor acceleration and inter-storey drifts [4, 5]. If the structure is too stiffened, it reduces the inter-storey drifts. It boosts the floor acceleration, directing to the damage of structural as well as non-structural equipment, whereas by making the structure more flexible, reducing the floor acceleration and increasing the inter-storey drifts. Thus, base isolation helps to lower both floor accelerations and inter-storey drifts at the same time [6-9]. Base isolation is accepted as one of the most trustful technique to secure the structures from strong ground motions techniques [10, 11]. The basic idea of base isolation is to separate the superstructure from the substructure by inserting a device in between them which increases dampness, provides flexibility and energy dissipation ability to the building as shown in Fig. 1 [12]. Base Isolation is a method for reducing earthquake motions to keep buildings safe from hazards. In the base isolation system, to absorb seismic energy, isolators are established in the building structure’s foundation. Thus, restricting the transfer of seismic energy directly to the superstructure and allowing minimum damage to structure [13, 14]. The concept is dated back in early 1909 when a British medical doctor from Scarborough worked on separating a building from the ground by a layer of tale powders for a patent [1].

As per the references, the first modern technique of base isolators was carried out in 1969 in a school building by using rubber isolators in Skopje, Macedonia [1, 15]. But, in the last few decades, the base isolation concept has rapidly gained visibility across the globe, resulting in, development of various isolation systems [16].

In the current scenario, various base isolation devices are being used i.e. High Damping Rubber Bearing, Friction Pendulum Bearing, Lead Rubber bearing with their combination actuated in parallel to each other [17, 18]. LRB is the most common used isolator, where various research has been conducted under strong earthquakes. Jangid investigated the effect of multi-storey buildings isolated with LRB under near-fault motions [19]. Shoaei and Mahsuli presented the reliability-based approach of steel moment frame structures mounted with LRB considering target base

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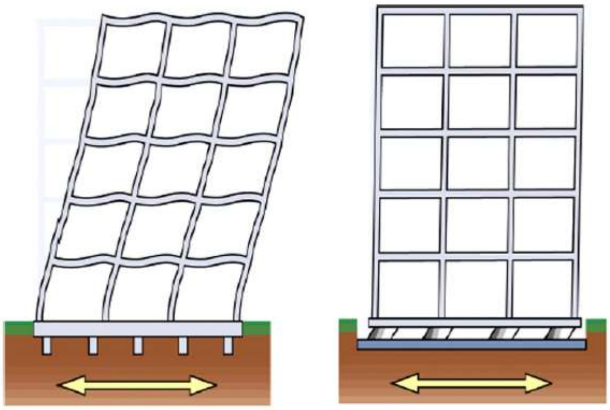


Conventional Structure   Base – Isolated Structure

Fig. 1. Description of Base-Isolation System [12]

displacement and natural period of the superstructure as critical parameters. A regression equation has been proposed, which predicts the optimal design variable of base-isolated systems [20].

In this study, the seismic response of base-isolated buildings with fixed-base buildings is presented. Two prototype models containing four and eight-storey buildings are taken into account, which illustrates low- and medium-rise buildings accordingly, with and without base isolation system. LRB is considered as an isolator in this paper, and its dynamic behaviour has been investigated using time history analysis where Imperial Valley and Northridge ground motions are being considered as shown in Table 1. Several parameters, such as inter-storey drift, base shear, maximum accelerations, and maximum displacements, are explored.

2. Modelling of Steel-frame buildings

All structural building are designed in conformity with Indian codes guidelines [21-23], to validate the design process of base isolation systems under Earthquake events. 4-, and 8- storey steel frame buildings are assessed, which indicate low and medium-rise buildings. They were presumed to be present on the medium soil site in zone V as per Indian code IS: 1893(2016) [24].

Table 1. Seismic characteristics of the considered accelerograms used for Time History Analysis

Earthquake Name	Imperial Valley	Northridge
Date of Occurrence	May 18, 1940	January 17, 1994
Recording Station	El Centro	Sylmar Converter Station
Component	00	360
PGA (g)	0.341	0.827
Duration	53.76	60

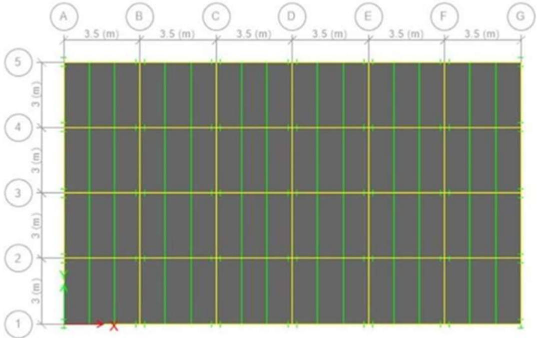


Fig. 2. Typical Floor Plan for both 4- and 8- storey Buildings

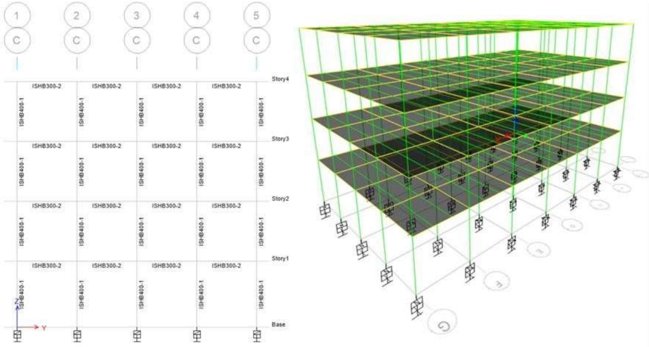


Fig. 3 Elevation and 3D view of G+3 Steel building

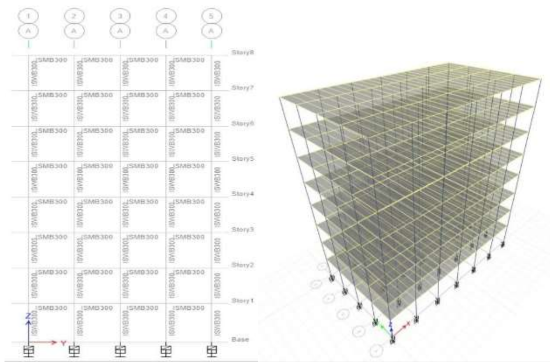


Fig. 4 Elevation and 3D view of G+7 Steel building

To examine the effect of Earthquake characteristics, in this paper, two earthquake motions, namely Imperial Valley and Northridge, have been considered as shown in Fig. 5. Both the earthquake motions have been taken from recording stations El Centro and Sylmar Converter station having the Peak Ground Acceleration (PGA) value of 0.341g and 0.827g respectively. Table 1 provides the salient features of these ground motions. The target spectrum taken from Indian Code IS: 1893(2016) and the mean matched spectrum of earthquake ground motions for 5% damping are matched with the help of seismomatch software [25]. 30% tolerance level has been considered.

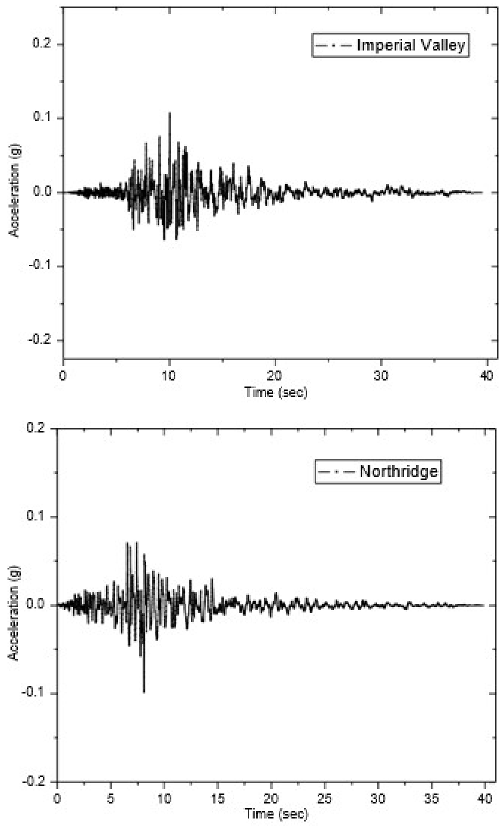
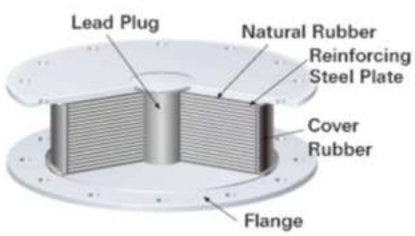


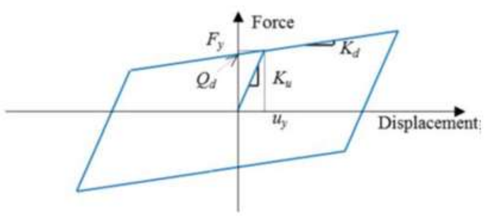
Fig. 5. Recorded Ground Motion data for Imperial Valley and Northridge

3. Mechanical Properties of LRB

The LRB consist of alternate layers of rubber and steel shims along with lead plug which is "force-fitted into pre-formed hole" bonded together to form a unit as shown in Fig. 7 [26-28]. The major function of lead-core is to provide rigidity and energy dissipation under service and high lateral loads [29]. An attempt has been made to design LRB, based on the recommendations of the FEMA, Indian Code and ASCE [1, 24, 30].



(a) Detailing of LRB



(b) Bi-linear force-displacement behaviour

Fig. 6. Mechanical Description of LRB [28]

The design calculation of LRB for asymmetrical regular shape building is carried out as follows:

STEP 1. LRB Isolators are designed based on the vertical load (W_i) at each isolator locations with the assumption of design displacement (d_{bd}) at the target design period (T_b).

STEP 2. Effective stiffness of the bearing (K_{eff}):

$$K_{eff} = \left(\frac{Wi}{g}\right)\left(\frac{2\pi}{T_b}\right)^2 \quad (1)$$

g = Gravitational Force

STEP 3. Design displacement:

$$d_{bd} = \frac{C_v}{B}\left(\frac{g}{4\pi^2}\right)\mathrm{T} \quad (2)$$

Where, $C_v = \frac{S_a}{g}$ from the demand spectra for period = 1 sec, B = Damping coefficient,

$$\frac{1}{B} = 0.25\left(1 - l_n\varepsilon_{eff}\right) \quad (3)$$

Where, $\varepsilon_{eff} = Effective\ Damping$

STEP 4. Global Dissipated energy per cycle at the design displacement:

$$E_D = 2\pi K_{eff}(d_{bd})^2\varepsilon_{eff} \quad (4)$$

Where, ε_{eff} = Effective Damping, d_{bd} = Design Displacement

Also, $E_D = 4F_o\ (d_{bd} - d_{vd})$ for $(d_{bd} \gg d_{vd}), d_{vd}$ = Yield Displacement

$$d_{vd} = \frac{F_o}{K_e - K_r}, (K_e \approx 10K_r) \quad (5)$$

STEP 5. Force at zero displacement under cyclic loading:

$$F_o = \frac{E_D}{4d_{bd}} \quad (6)$$

STEP 6. Stiffness of lead core of LRB:

$$K_{pb} = \frac{F_o}{d_{bd}} \quad (7)$$

STEP 7. Stiffness of rubber in LRB:

$$K_r = K_{eff} - K_{pb} \quad (8)$$

STEP 8. Total thickness of LRB:

$$t_r = \frac{GA_r}{K_r} \quad (9)$$

Where, G = Shear Modulus, A_r = Plan area of rubber

Total thickness, t_r should not be less than $\frac{d_{bd}}{\gamma}$

STEP 9. Diameter of lead rubber bearing:

$$D_{bearing} = \sqrt{\frac{K_r t_r}{400\pi}} \quad (10)$$

STEP 10. Total loaded area calculation (A_L):

- $A_L = Total\ loaded\ area$

A_L= Force-free area – Area of Lead Core (11)

- $A_{ff} = force\ free\ area$

$$A_{ff} = \frac{\pi}{4} \times (D_{ff})^2 \quad (12)$$

- $A_{pb} = area\ of\ lead\ core\ in\ LRB$

$$A_{pb} = \frac{\pi}{4} \times (D_{pb})^2 \quad (13)$$

- $D_{pb} = diameter\ of\ lead\ core\ in\ LRB$

$$D_{pb} = \sqrt{\frac{4f_o}{400\pi}} \quad (14)$$

- $D_{ff} = diameter\ of\ force\ free\ section$

$$D_{ff} = D_{bearing} - 2t_r \quad (15)$$

STEP 11. Circumference of force free section:

$$C_f = \pi \times t \times D_{ff} \quad (16)$$

STEP 12. S_i = Shape Factor

$$S_i = \frac{loaded\ area}{circumference\ of\ force\ free\ section} \quad (17)$$

STEP 13. H= height of LRB

$$H = (N \times t) + (N-1)t_s + 2t_{ap} \quad (18)$$

Where,

N = No. of Rubber layer

t = Single Rubber layer thickness

Table 2 – Summary of LRB characteristics

LRB Properties	Models	
	G+3	G+7
K_{eff} (kN/m)	804.86	650.18
ε_{eff}	15%	15%
d_{bd} (m)	0.244	0.244
d_{vd} (m)	0.00835	0.00853
K_e(kN/m)	6152.2	4945.20
K_r(kN/m)	615.22	494.52
F_o (kN)	51.37	43.00
T_b (sec)	2.0	2.56

To obtain the thickness of each layer (circular) can be obtained from

$$S = \frac{loaded\ area}{load\ free\ area} = \frac{\pi d^2/4}{(\pi d)t} = \frac{d}{\pi t} \quad (19)$$

t_s = thickness of steel lamination

t_{ap} = laminated anchor plate thickness

STEP 14. Design Check

The designed isolator must also be checked to satisfy the vertical stiffness:

$$K_v = \frac{E_c A_r}{T_r} \quad (20)$$

Where, E_c is the compression modulus. It is evaluated as:

$E_c = \left(\frac{1}{6GS^2} + \frac{4}{3K}\right)^{-1}$ for circular isolators.

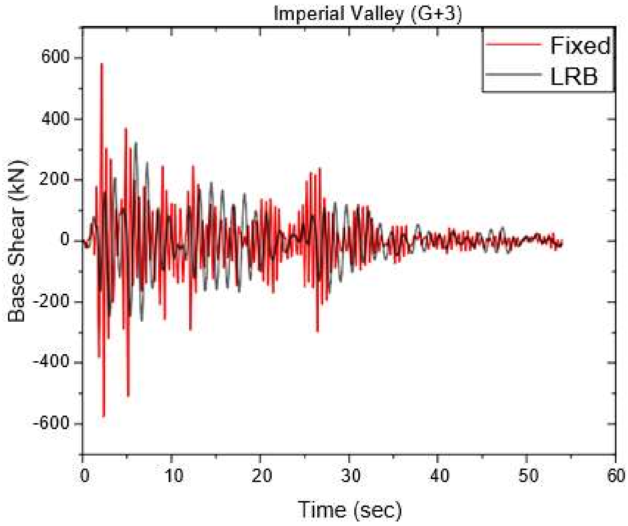
Table 2 summarizes the properties of Lead Rubber Bearing for G+3 and G+7 floor buildings designed by the given procedure.

4. Results & Interpretation

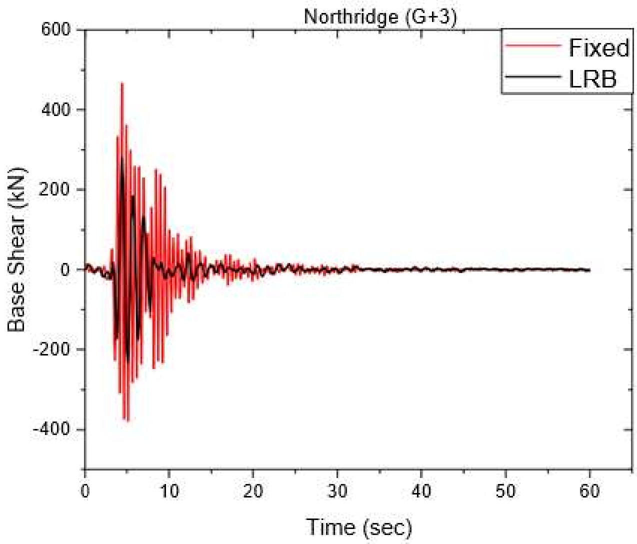
The maximum base shear response of the isolated and the fixed base has been portrayed in Table 3. From Table 3, it can be noted that the maximum base shear value of fixed-base building is comparatively higher than base-isolated building for both G+3 and G+7 floors structure. It can also be seen that the decrease of base shear for Imperial Valley ground motion is 45% and 49% respectively for 4- and 8-storey building, whereas the reduction is around 40 to 43% for Northridge ground motion. Thus, increasing the no. of floors of the buildings enhances the maximum base shear for both ground motions. Also, a comparison has been done of

Table 3 – Maximum base shear response for G+3 and G+7 storey buildings: -

Earthquake Records	G+3 Steel Building		
	Fixed	LRB	Reduction (%)
Imperial Valley	582	325	45
Northridge	466	279	40
	G+7 Steel Building		
Imperial Valley	1237	615	49
Northridge	1153	659	43



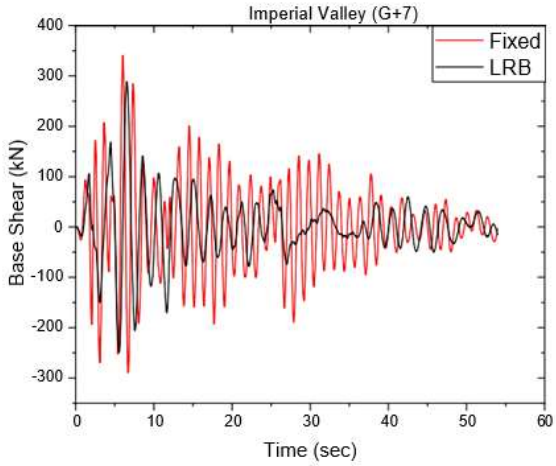
(a) Imperial Valley Earthquake



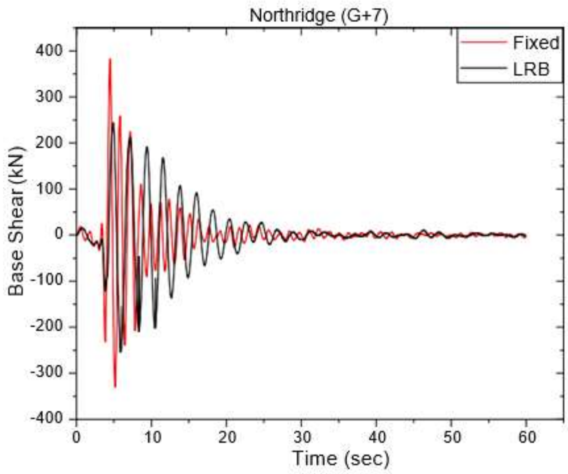
(b) Northridge Earthquake

Fig. 8. Base Shear of 4-Storey Building with LRB and the Fixed Base Structure

the base shear for G+3 and G+7 building using time history analysis and outlined in Fig. 8 and Fig. 9 for the structure with the base isolation system (LRB) and the fixed base structure (Fixed) for the given seismic records detailed in Table 1. With reference to the fixed-base structure, a significant reduction in the LRB damped structure's curve were observed.



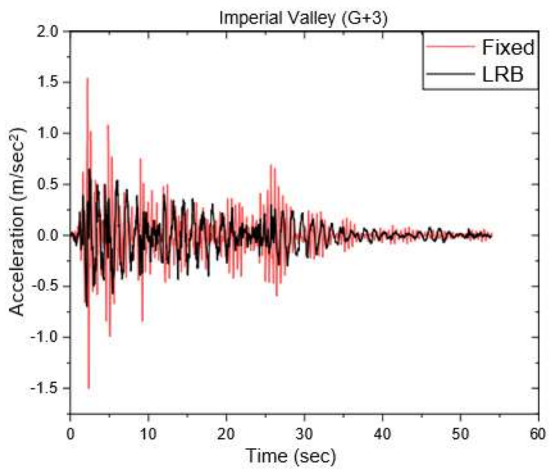
(a) Imperial Valley Earthquake



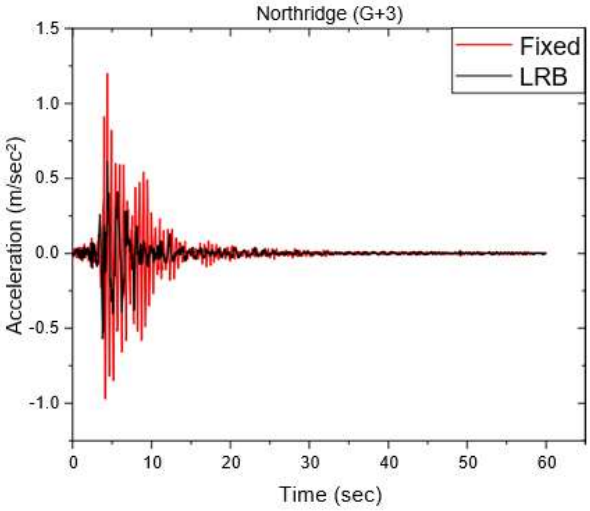
(b) Northridge Earthquake

Fig. 9 Base Shear of 8-Storey Building with LRB and the Fixed Base Structure

In the given study, the responses of LRB and fixed base structures are also investigated with acceleration as a parameter in assessing the effectiveness of buildings, as shown in Fig. 10 and Fig. 11. It is discovered that the LRB provides a sudden decrease of maximum base acceleration for

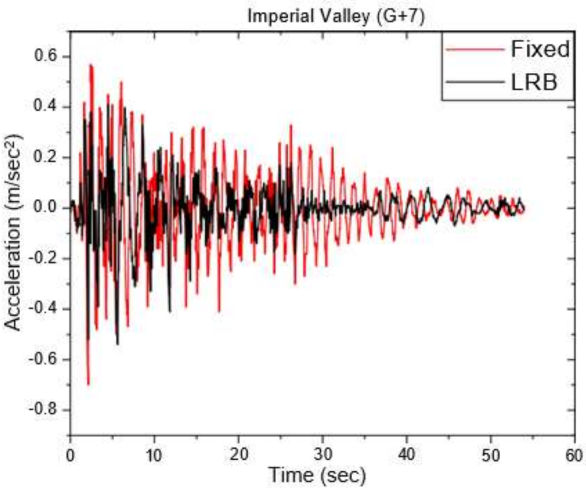


(a) Imperial Valley Earthquake

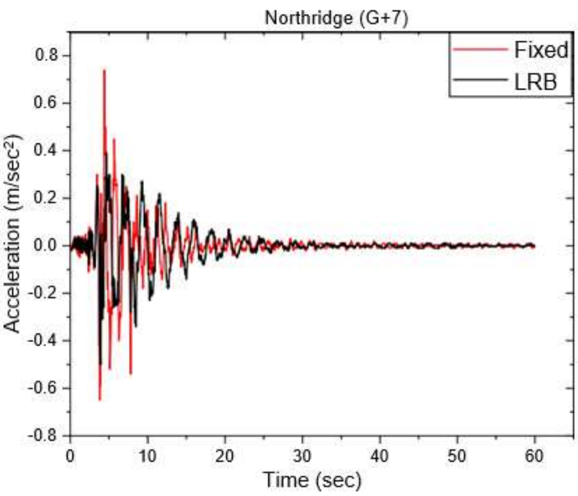


(b) Northridge Earthquake

Fig. 10 Base Acceleration of 4-Storey Building with LRB and the Fixed Base Structure



(a) Imperial Valley Earthquake



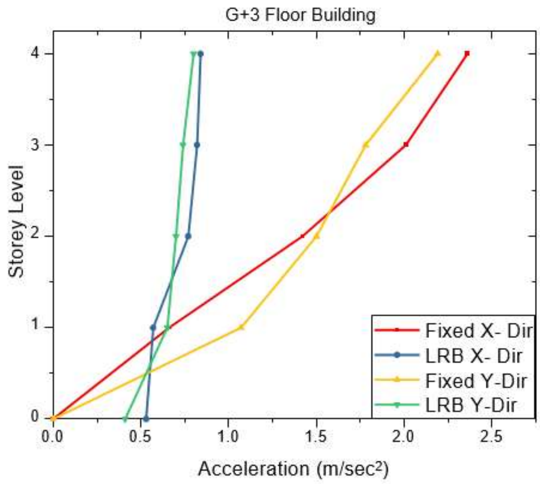
(b) Northridge Earthquake

Fig. 11 Base Acceleration of 8-Storey Building with LRB and the Fixed Base Structure

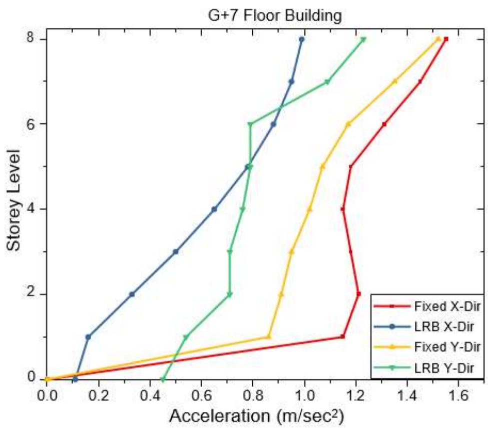
both the building G+3 and G+7 floors for both the seismic ground motions taken regarding the fixed-base building. Thus, LRB reduces the dynamic loading response demand of the structure to a particular level by absorbing and dissipating the energy imparted on the structure due to dynamic loading in comparison to the fixed base structure.

Also in Fig. 12, it can be observed that the response of the highest acceleration in both 4- and 8- storey building has been significantly reduced in LRB mounted buildings in comparison to the fixed-base buildings. It can be noted that for G+3 base-isolated structure, the reduction in acceleration both in X and Y direction is around 63% to 64% compared to fixed-base. Whereas for G+7 it reduces to 42% in X-direction and 25% for Y-direction. By viewing this reduction in acceleration coincided to fixed-base, it can be indicated that elevating number of levels reduces the effect of seismic isolation on buildings.

The maximum displacement and Inter-storey drift of 4- and 8- storey building were compared, as shown in Fig. 13 and Fig.14. Fig.13 revels that displacements in an isolated building are much higher than fixed-base buildings. It can also be noted that displacements in lower floors of base-isolated buildings are relatively elevated than fixed base due to the flexibility offered by insulators at the base of the buildings [6]. Moreover, the Lead Rubber system provides a greater dissipation capacity than there counterpart fixed-base structure.

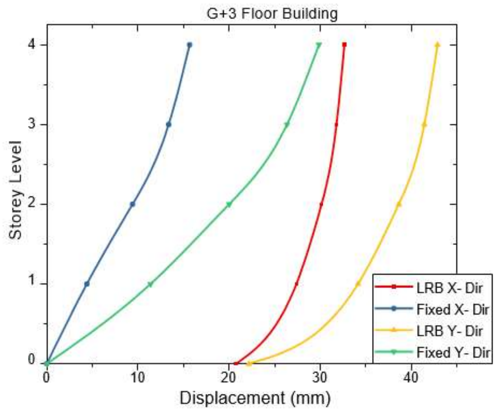


(a) G+3 Steel-frame Building

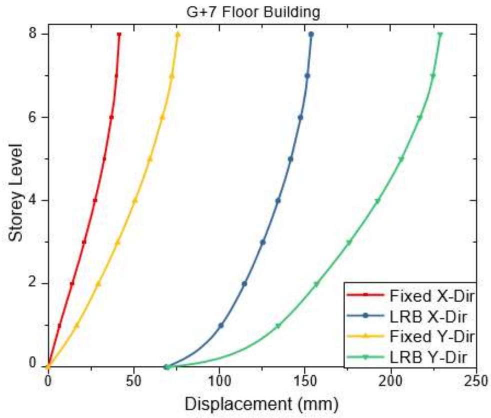


(b) G+7 Steel-frame Building

Fig. 12 Maximum Acceleration on each floor in LRB and Fixed Base Structure

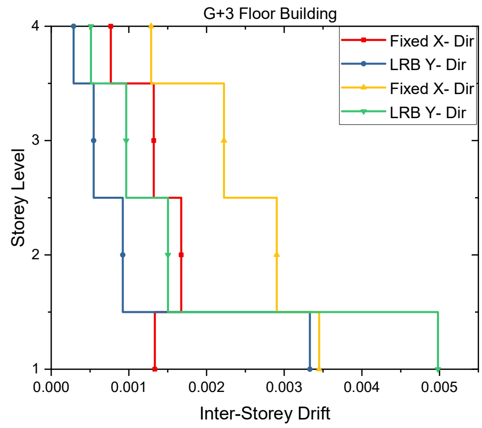


(a) G+3 Steel-frame Building

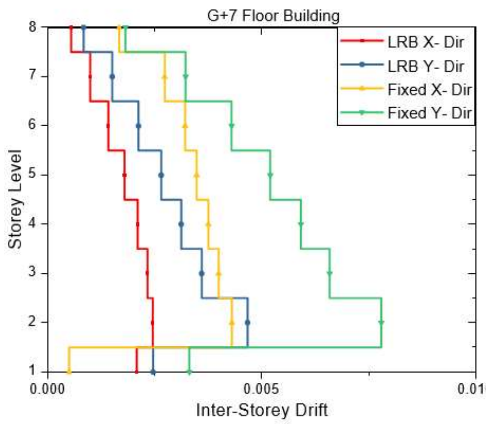


(b) G+7 Steel-frame Building

Fig. 13 Maximum Displacement on each floor in LRB and Fixed Base Structure



(a) G+3 Steel-frame Building



(b) G+7 Steel-frame Building

Fig. 14 Inter-storey drift in LRB and Fixed Base Structure

Fig .14 provides the knowledge of inter-storey drift of G+3 and G+7 floors building, where inter-storey drift can be indicated as the relative distance between the floors. From Fig. 14, it's observed that inter-storey drift of the steel buildings is around 71% to 87% more in the lower storey as compared to the upper-storey for both fixed and LRB mounted buildings. Also, inter-storey drifts are found well within the permissible limit of (0.004*h), where h represents storey height according to IS: 1893(2016).

5. Conclusions

Steel-frame buildings were investigated when mounted with the Lead Rubber Bearing (LRB) isolation system with the traditional fixed-base design for low-rise and mid-rise buildings respectively. The procedure for designing LRB isolator was adopted from various International codes along with the reference of Indian Code IS: 1893(2016). Some of the major conclusions have been summarized below-

Results shows, the percentage reduction in base shear of base-isolated compared fixed-based condition for Imperial valley earthquake vary between 45% to 49% for four and eight-storey steel buildings. In contrast, for Northridge earthquake reduction in the base shear differs from 43% to 49% for low- and mid-rise buildings. Reduction of maximum acceleration for both X- and Y-directions varies in the range of 60% to 64%, whereas acceleration widely varies in both directions in the range of 25% to 42% for eight-storey buildings. Results signify that base-isolation limits the structural response under seismic events and also imparts flexibility to the structure, thereby reducing the forces induced in the members. There is an increase in the maximum displacement for both low- and mid-rise base-isolated buildings of around 44% to 64% in four-storey steel buildings, whereas the increase of displacement is as high as 73% to 79% in eight-storey buildings. The results signify the reduction in the seismic response and greater resilience at the base level of the building as correlated to fixed-base buildings. It is also concluded that the relative inter- storey drifts is significantly reduced in base-isolated buildings indicating that the superstructure exhibits behaviour close to rigid body behaviour in base insulation. This reduced the risk of non-structural and structural components substantially.

Finally, all these results confirm that the LRB can adequately seclude the influence of the seismic events on the buildings, and decrease the seismic hazards caused by an earthquake to the building structure.

Disclosures

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