SEISMIC BASE ISOLATION OF HIGH-RISE RC SHEAR WALLS BUILDING USING LEAD CORE RUBBER BEARINGS

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Abstract

The use of base isolation technique is an effective way to control the seismic demands in buildings. In Japan, most of base isolated tall buildings have either moment resisting frame or braced frame as their primary lateral load resisting system. The RC shear wall buildings represent the typical high-rise construction in several parts of the world. The seismic story shears and overturning moments of these buildings are generally dominated by the contributions from higher modes of vibration. In this study, using a case study building (40-story high-rise RC building), it is shown that the base isolation mechanism results in the reduction of higher-mode effects, thereby reducing the overall seismic demands of otherwise higher-mode dominating buildings. The base isolated structure is analysed for vertical and horizontal components of strong real ground motions. The results show that the vertical component of ground motions has negligible effect on lateral seismic demands such as inter-story drift, floor acceleration, story shear and story moment, whereas it causes high fluctuation of axial stresses in bearings due to induced vertical inertial force. In some bearings under the shear walls and corner columns, it can cause tensile stresses larger than allowable limits prescribed by various codes and guidelines. In this study, the tensile stresses in bearings are kept within the allowable limits by structural modification of foundation system and proper arrangement of bearings. The performance of bearings is also evaluated for combined axial stresses and lateral shear strains. Lastly, the effectiveness of base isolation system is evaluated by comparing the inelastic seismic responses of base-isolated structure with those of fixed-base structure. It is shown that the base isolation resulted in the suppression of higher modes which resulted in a significant reduction in overall inter-story drifts, floor accelerations, story shears and overturning moments.

Keywords: base isolation; lead core rubber bearing (LRB); tensile loading in bearing; vertical ground motion effect, high-rise RC shear walls

1. Introduction

The use of base isolation system is an effective way to reduce the seismic demands of structures subjected to strong ground motions. This mechanism decouples the seismic forces at the ground level prior to transmission in superstructure [1] and therefore results in reduction in story shear and overturning moment. This technique is generally considered more effective for low-rise buildings which generally have short natural periods. Since the low-rise buildings primarily deflect in lateral shear mode under strong ground motions, the isolation bearings primarily deform in shear mode without much change in their axial compressive stiffness. On the other hand, the high-rise buildings with RC shear walls may deflect in flexure-dominating mode under the ground motions [2] and may undergo high overturning moments. This may result in development of tensile stress in some isolation bearings under shear walls and columns. Tensile stress in bearing is highly undesirable because it degrades the performance of bearings [12], [13]. Several solutions comprising of tension restraining mechanisms have been proposed to address this issue [5], [6], [7]. Similarly, another important issue related to the application and design of base isolation mechanism for high-rise buildings is the consideration of vertical component of ground motions. Several studies have indicated that the consideration of vertical component of ground motion (along with horizontal components) may result in high fluctuation of axial stress in bearing and it may develop tension as well in bearing under shear walls and columns [8], [9]. This high fluctuating axial stress is mainly developed due to the vertical inertia forces caused by vertical ground acceleration.

In this study, the effectiveness of base isolation is investigated for high-rise building with RC shear walls. For this purpose, a case study building is selected for the detailed analysis. The lead core rubber bearings are used in this building for an effective base isolation. First, the axial stresses (compression and tension) in bearings under columns and shear walls are studied under service loads and the maximum considered earthquake (MCE) loads. Under service loads, these axial stresses should remain in compressive state in order to ensure a safe function of isolation bearings. During the MCE loads, the allowable axial tensile stresses in bearings is limited to 2 MPa for satisfactory performance [10]. After confirming that all bearings are performing satisfactorily, the detailed non-linear response history analysis (NLRHA) is used to study the horizontal and vertical responses of base-isolated building. The corresponding responses of the same building modelled without isolation mechanism were also determined. This evaluation is performed for two ground motion cases: a) the ground motions applied along horizontal X and Y directions, and (b) the ground motions applied along X, Y and Z (vertical) direction. The results have provided a useful insight into the effectiveness of base isolation system for high-rise RC shear wall buildings subjected to different real ground motions.

2. Description of the Case Study Building

The selected case study high-rise building is a 40-story building with dual reinforced concrete core wall and frame system. It represents the typical high-rise buildings in urban areas of several countries. The primary gravity load carrying system is RC column-slab frame system while the lateral load resisting system is RC walls and RC core wall system. The structural plan layout and 3D view are presented in Fig.1. The linear and nonlinear structural models of both the fixed-based and base-isolated buildings are constructed for the detailed analysis. For the modal analysis and linear elastic analysis, the 3D elastic models of the case study building are constructed using ETABS 2016 [13]. All the columns and beams are modelled using the elastic frame elements, while the RC shear walls and slabs were modelled using the thin shell elements. For the detailed NLRHA procedure, the inelastic finite element models are constructed using Perform 3D [17]. All elements of RC shear walls were divided into many vertical nonlinear concrete and steel fibres to simulate the combined axial-flexural behaviour. The concrete fibres were modelled using the Mander's unconfined stress strain model [17] approximated by tri-linear envelope. The steel fibres were modelled with a non-degrading type bilinear hysteretic model including the strain hardening. The lumped fibre modelling was used for RC columns with steel and concrete fibres at both ends (having a length equal to effective depth of column cross-section) with elastic frame element in between. The RC slabs were modelled using elastic thin shell element. The modelling of base isolation system in linear and nonlinear models of the case study building is explained in the subsequent section.

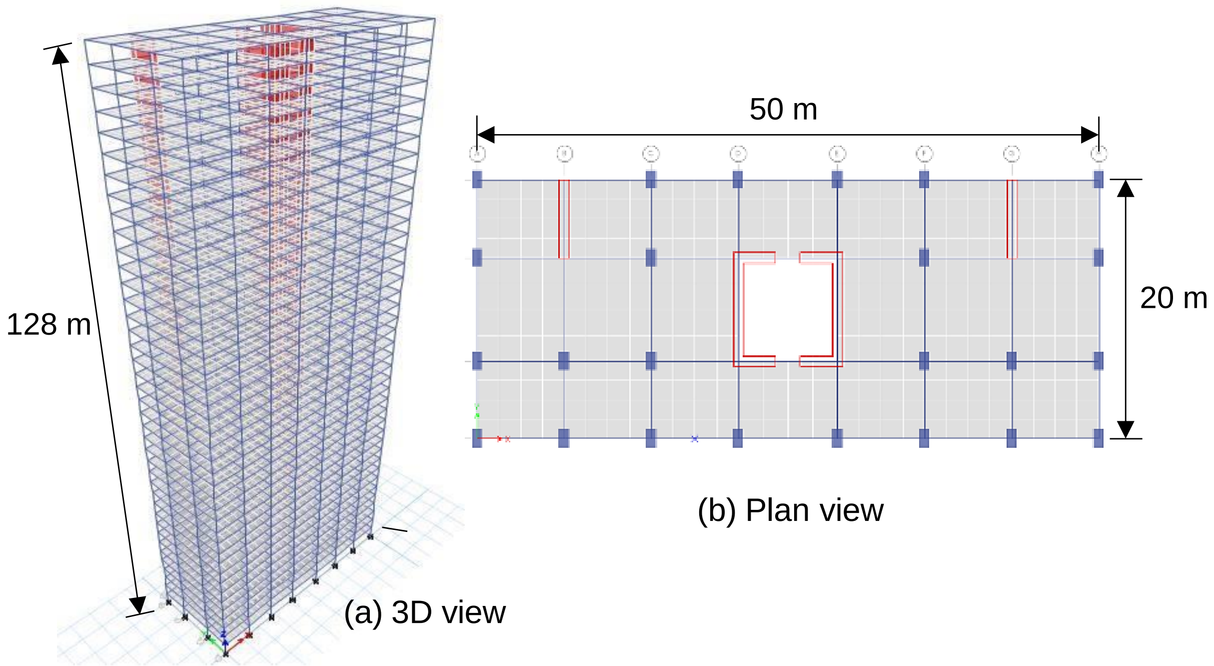


Fig. 1 – The plan and 3D views of the selected case study building

3. Modelling of the Base Isolation System

In the case study building, the plane of the isolation system is kept below the ground floor and above the existing foundation. The lead core rubber bearings (LRBs) have high axial compressive load capacity to support the weight of superstructure. However, several studies have evaluated the tensile capacity of lead core rubber bearings and concluded that their tensile capacity can be as low as one-tenth of their compressive capacity [14]. Therefore, for the vertical behaviour of bearings, an unequal linear axial stiffness (soft in tension) is used as shown in Fig. 2(a). In lateral direction, the behaviour of lead core rubber bearings can be idealized by a bilinear horizontal force-deformation relationship as shown in Fig. 2(b). The post-yield lateral stiffness of these bearings is around one-tenth of the initial lateral stiffness [14]. This low lateral stiffness effectively isolates the superstructure from its substructure during the strong earthquake shaking. For the nonlinear model of base-isolated building, the lateral behaviour of isolation system is modelled using the bilinear shear hysteretic element as shown in Fig. 2(b). However, for the linear elastic model of base-isolated building, the concept of equivalent linear system is used. The bearings with bilinear force-deformation behaviour are converted into equivalent linear systems with equivalent stiffness defined by the secant point at the maximum deformation under a ground motion. In this study, the additional hysteretic damping is not considered during this conversion and the bearings were assumed to remain linear with effective (secant) stiffness (K_{eff}) shown in Fig. 2(b).

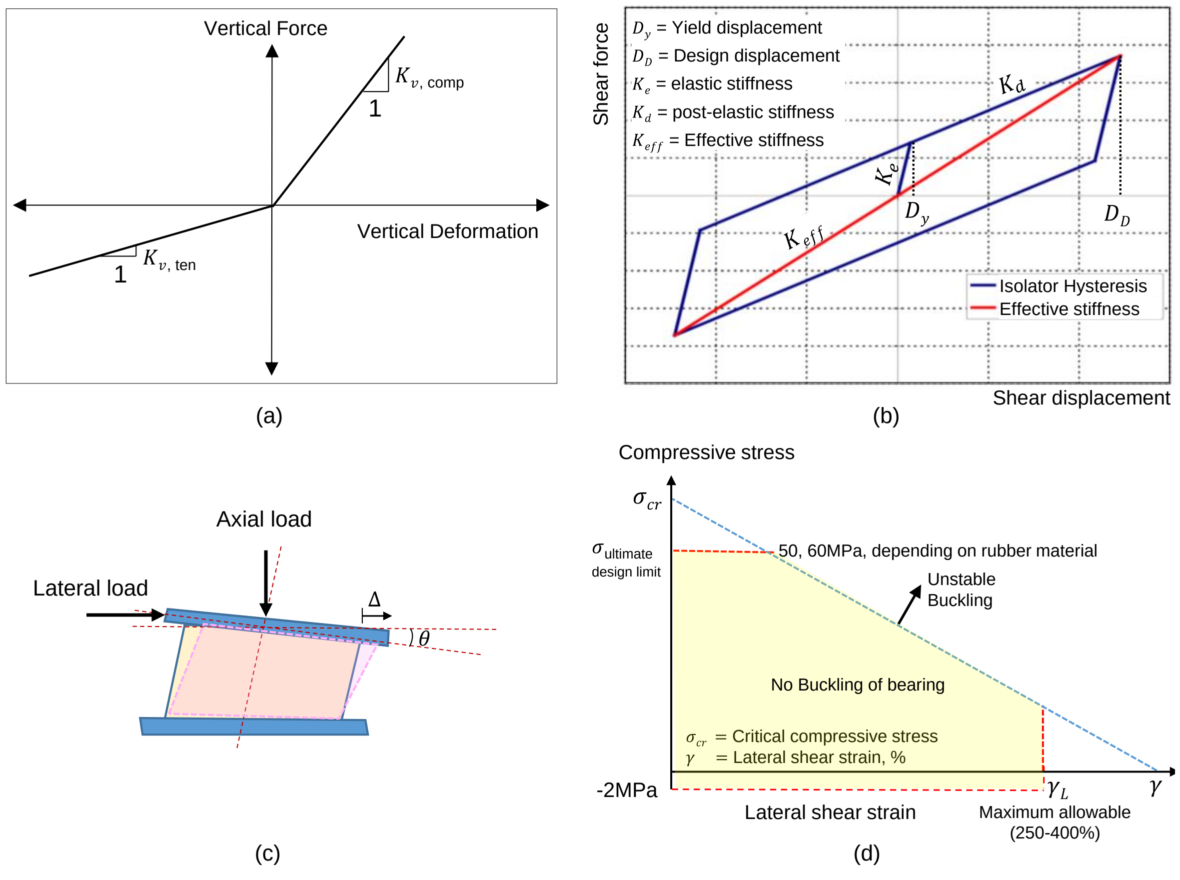
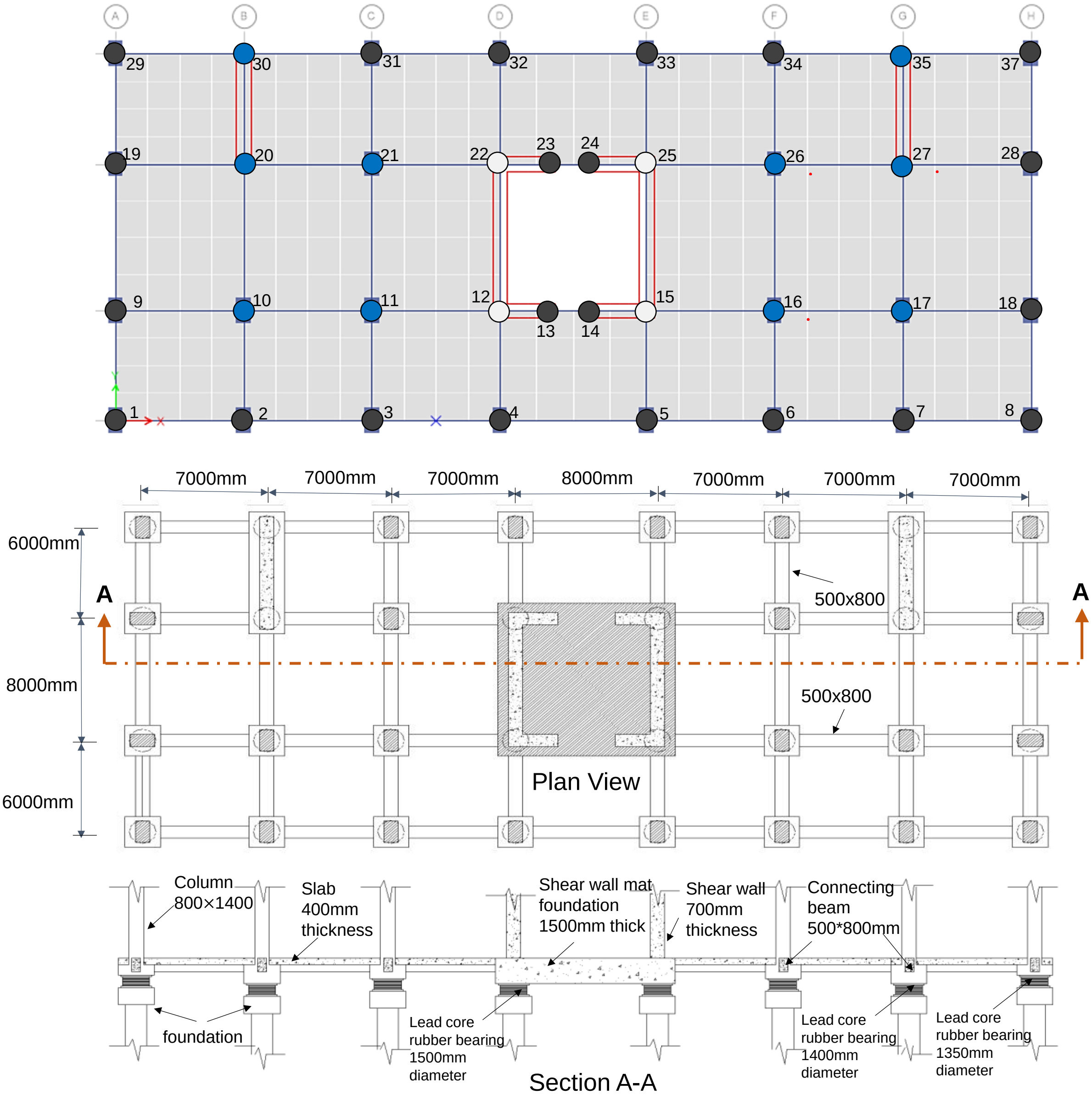


Fig. 2 – (a) The vertical properties, and (b) horizontal properties of the lead core rubber bearings. (c) the induced shear deformation due to rotation, (d) the ultimate property diagram for lead core rubber bearings

During the development of high axial loading in bearings, a component of vertical load may act along the flexible layers of bearing which may result in inducing an additional shear deformation and tensile deformation (Fig. 2(c)). When this induced shear deformation is large enough under combined axial and lateral loading, it may cause shear buckling of lead core rubber bearing. Many studies have suggested to avoid the tensile state in bearing as it degrades the performance of bearing. However, in high-rise structures, the tensile state in bearing is likely to occur and therefore, several studies have suggested an allowable axial tensile stress limit of 2 MPa

[10]. The ultimate property diagram (Fig. 2(d)) is used to evaluate the combined effect of axial stress and its corresponding lateral shear strain [14]. Any set of values lying beyond the shaded region in Fig. 2(d) is considered to cause shear buckling failure. In this study, the bearings are designed for 100% shear strain while the critical axial load capacity of bearing is three times of the design axial load. Three types of lead core rubber bearings are designed based on the relationships proposed by Kelly [9]. The designed properties are then compared with commercially available products. The bearings with suitable properties, aspect ratio and shear deformation capacity are adopted from the commercial catalogues. The isolation system consists of 36 lead core rubber bearings (LRBs) with three different sizes; LRB-1 (22 units with the diameter of 1350mm), LRB-2 (4 units with the diameter of 1400mm), and LRB-3 (4 units with diameter of 1500mm). Fig. 3 shows the structural plan, cross section view at isolation level of the structure while Table 1 presents the mechanical properties of lead core rubber bearings used in the case study building.



Bearing	Design Axial Load	Diameter
1. ●	13000 KN	1350 mm
2. ●	19000 KN	1400 mm
3. ○	28000 KN	1500 mm

Fig. 3 – The layout of bearings with numbers in structural plan view and the section view at isolation level

Table 1 – Lateral and vertical properties of lead core rubber bearings used in the case study building

Parameter	LRB-1 D1260mm	LRB-2 D1350mm	LRB-2 D1550mm
F_y (kN)	263.1	325.3	331
D_y (m)	0.022	0.022	0.022
D_D (m)	0.85	0.91	0.91
K_d (kN/m)	1228	1517.8	2853
K_{eff} (kN/m)	1606	1986	3365
$K_{v,comp}$ (kN/m)	3.43×10^6	4.79×10^6	6.17×10^6
$K_{v,tens}$ (kN/m)	3.43×10^5	4.79×10^5	6.17×10^5
β_{eff}	20%	20%	20%

4. Selection of Service Loads and Earthquake Ground Motions

During the vertical service loads (i.e. combined gravity and live loads, DL+0.5LL), the LRBs should have enough pre-compressive load. The Japanese Road Association [18] suggests that the pre-compressive load in bearings should be in the range of 2 MPa to 12 MPa. The pre-compressive load should not be too low in order to prevent the development of tensile stresses in bearings. Fig. 4 shows that all bearings have enough pre-compressive loads (i.e. greater than 2 MPa and lesser than 12 MPa) during the service load condition.

Fig. 4 – The pre-compressive load in bearings under the service load condition

The isolated system is expected not to get activated under the lateral service loads (such as the service-level wind). In order to make sure that the isolation system will not get activated during these conditions, the yielding force of the overall isolation system is compared with service level lateral demands. The service-level wind load corresponding to an hourly mean wind speed (10 years return period) of 25 m/s is considered. The wind pressure for X and Y- directions are applied to the exposure area of structure on all stories. The total yielding strength capacity of isolation system is 9900 KN. During the service level wind load, the shear demand at isolation level is 3067 KN in X-direction and 9500 KN in Y-direction which are lesser than the total lateral capacity of the isolation system. This implies that the isolation system will remain within the elastic limit and will not get activated during the service-level wind loads.

For the detailed non-linear time history analysis, a set of five real ground motions representing the shallow crustal far field ground motions (both horizontal and vertical components) in NEHRP site class D are considered. The Table 2 presents the characteristics of real ground motions. The response spectrum for horizontal and vertical components of these ground motions are presented in Fig. 5. Since the earthquake is an unpredictable event which can occur in any place, those ground motions are not considered for site specific spectral matching in this study.

Table 2 – The ground motions used in the detailed nonlinear response history analysis of case study building

Event	Station	Magnitude (M_w)	NEHRP Site Class	PGA in Horizontal direction	PGA in Vertical direction
Imperial Valley	Elcentro Array # 11	6.53	D	0.36g	0.12g
Superstition Hills	Poe Road (temp)	6.5	D	0.48g	0.13g
Loma Prieta	Gilroy Array # 3	6.93	D	0.54g	0.29g
Landers	Coolwater	7.28	D	0.32g	0.18g
Northridge -1994	Beverely Hills	6.69	D	0.443g	0.33g

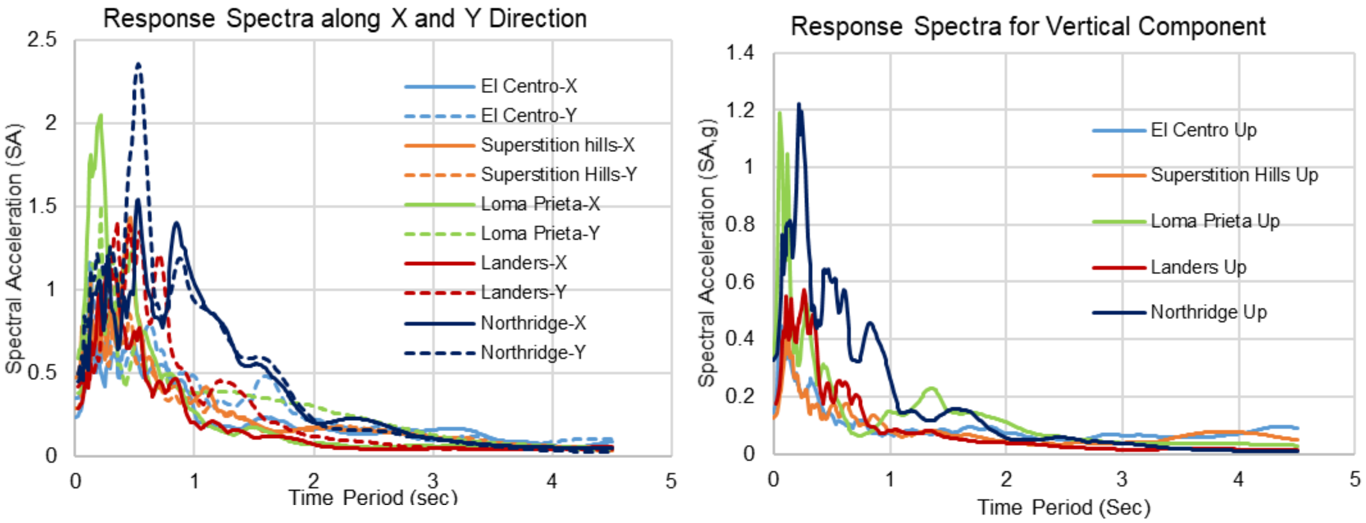


Fig. 5 – The response spectra (5% damped) of horizontal and vertical components of shallow crustal far field ground motions

5. Results and Discussion

5.1 Modal Properties of Fixed-base and Base-isolated Structures

The modal properties of both fixed-base (FB) and base-isolated (BI) structure are obtained using the eigenvalue analysis of their linear elastic models. These results characterize the basic dynamic behaviour of the structure and are an indication of how a structure responds to the dynamic loading [15]. It should be noted that the modelling of bearings in the linear elastic model of base-isolated structure is based on the concept of equivalent linearization. The bilinear hysteretic behaviour of bearings is approximated by an equivalent soft spring with effective (secant) stiffness [K_{eff} as shown in Fig. 2(b)]. The properties of equivalent soft springs depend on the level of bearing deformation, which depends on the level of ground shaking. A comparison of the modal properties in terms of structural period and modal participation factor (MPF) in X-direction and Y-direction of the case study building are shown in Table 3. In base-isolated structure, the isolated mode "Mode-0", and first structural mode "Mode-1" of base isolated structure has a combined mass participation of approximately 90% indicating that these modes will have significant contribution towards the dynamic response. The higher vibration modes have negligible mass participation ratios indicating that the higher-mode contributions will not be dominant in the total response. However, in the case of fixed base structure, the higher modes may be expected to significantly contribute towards the dynamic response of the structure (in cases where their spectral acceleration is much higher than that of the first mode). For a further evaluation of this idea, a typical code-based response spectrum which represents the response characteristics of typical design ground motions is selected (UBC-97, site class D, with C_a=0.44 and C_v=0.98). Using this spectrum, the Fig. 6 explains the influence of shifting the structural period in X-direction and Y-direction to the spectral acceleration induced to the superstructure. This shows that the base isolation is effective in tall buildings because it can eliminate the effects of higher modes.

Table 3 – The modal properties of case study building for FB and BI cases

	X-direction				Y-direction			
	FB structure		BI structure		FB structure		BI structure	
Mode	Period (sec)	MPF (%)	Period (sec)	MPF (%)	Period (sec)	MPF (%)	Period (sec)	MPF (%)
0	-	-	4.51	84.21	-	-	4.66	80.66
1	3.5	71.31	1.28	12.81	3.38	67.2	1.37	17.24
2	1.01	13.05	0.72	2.3	0.83	16.33	0.63	1.8
3	0.52	4.38	0.45	0.4	0.37	6.01	0.35	0.17

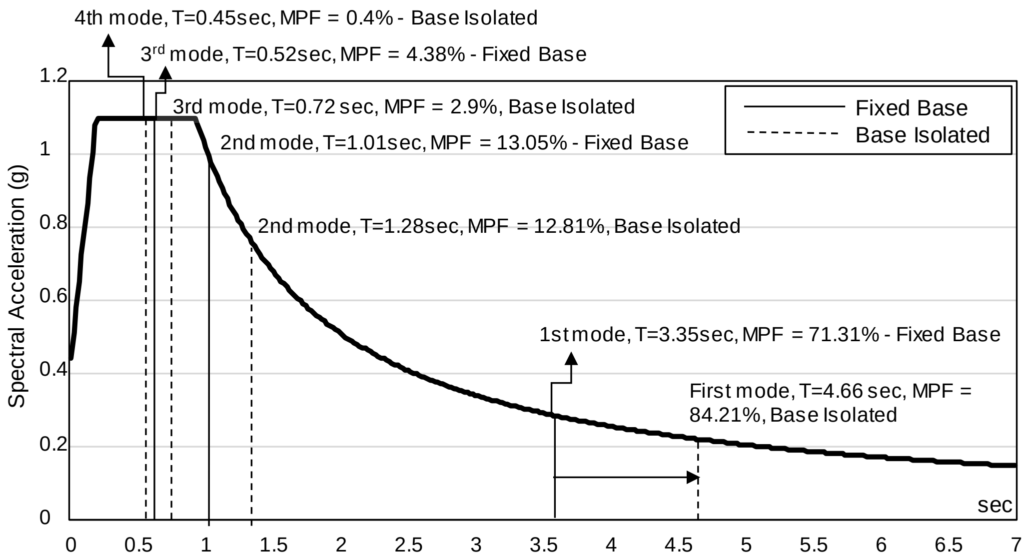
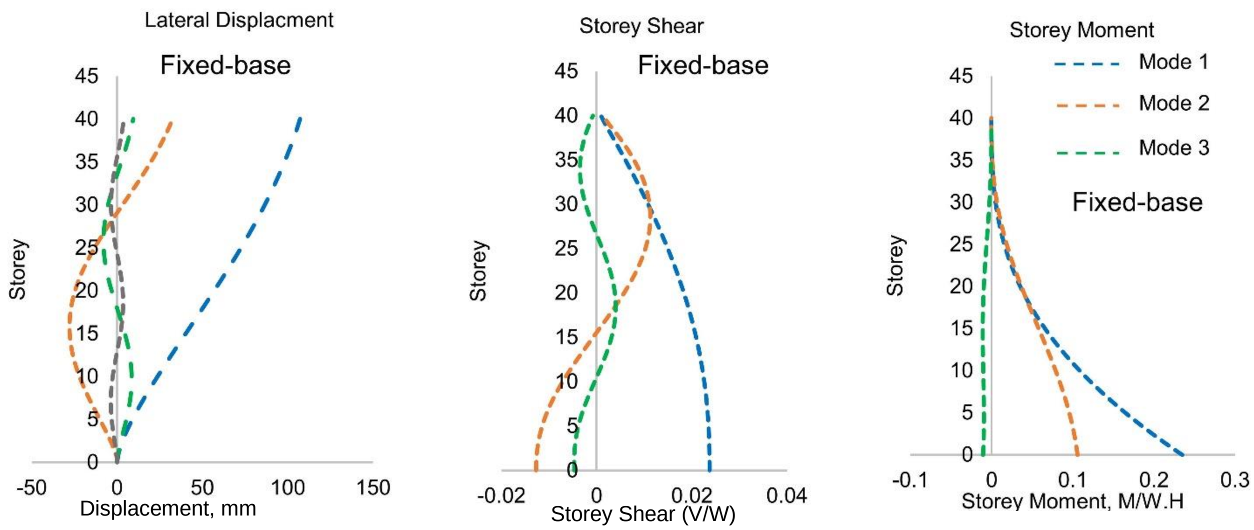


Fig. 6 – The natural time periods of fixed-base structure and base-isolated structure

To clearly understand how the base isolation can diminish the higher modes effect, the response spectrum analysis is conducted using the spectrum shown in Fig. 6 for both the base-isolated and fixed-base structures. The results for first three vibration modes of the structure are shown in Fig. 7.



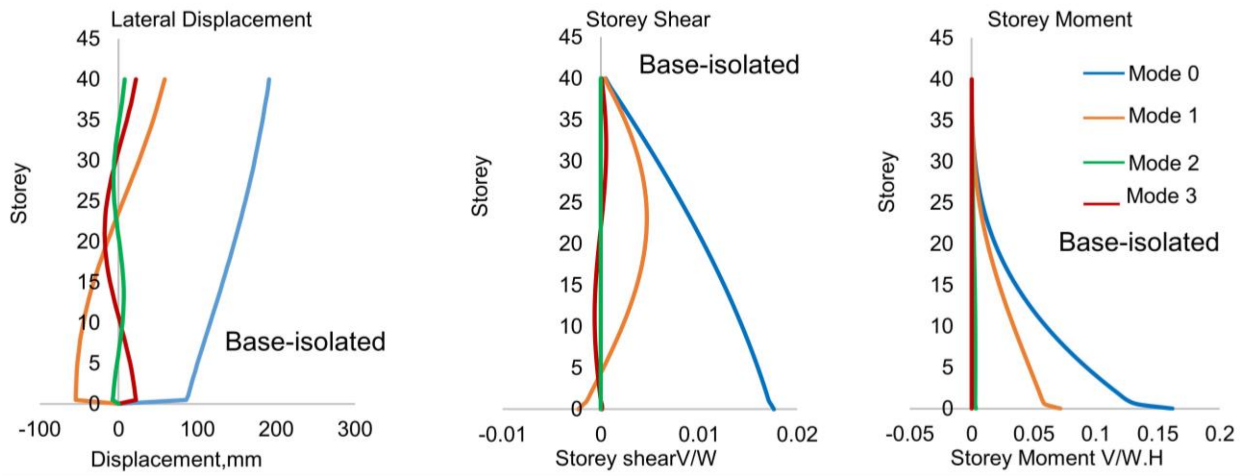


Fig. 7 – The comparison of modal demands for fixed-base and base-isolated systems

5.2 Effect of vertical component of ground motions

After this preliminary investigation, the detailed non-linear time history analysis is performed for different cases of real ground motions. Firstly, only the horizontal ground motions are considered, while only vertical ground motion is considered at second stage. Lastly, both the horizontal and vertical components of ground motions are considered. The structural responses of fixed base and base isolated structure for these three cases are presented in Fig. 8. In this figure, the red line represents the response of horizontal components of ground motions, blue line represents the response of vertical component of ground motions, and black line represents the response of structure for both horizontal as well as vertical ground components of ground motions. It can be seen that the vertical component of ground motions has insignificant effect on lateral responses of the structure. When all three components (one vertical and two horizontal) are considered, the storey shear is increased by 14% and base moment is increased by 20% compared to the case of horizontal ground motions. Although the case of only vertical component has shown a lower storey shear and base moment compared to the case of horizontal components, it has caused a much higher fluctuation in axial stresses in the bearing as shown by the blue line in Fig. 9. Furthermore, when all three components are considered, the fluctuation in axial stress is highly varied from compression to tension. This high fluctuation of axial stress not only demands a higher capacity but may also result in the development of tensile stresses in the bearings.

5.3. Performance of Lead Core Rubber Bearings

The axial reaction is evaluated for each bearing for a set of different real ground motions including vertical and horizontal components. The ultimate design compressive stress capacity of bearing is 48 MPa and the allowable tensile stress in bearing is 2 MPa. Fig. 10(a) shows that for two example ground motions, two bearings have compressive stresses of 54 MPa and 50 MPa respectively, exceeding the ultimate compressive stress. Similarly, some bearings under shear walls and corner columns have experienced the tensile stresses larger than the allowable limit of 2 MPa. To keep the axial stress in bearing within acceptable limits, the concept of increasing moment arm of foundation under the shear wall is applied which helps in reducing the coupling force in bearing. Based on this concept, the foundation structure under the shear wall is modified as shown in Fig. 10(b). The area of mat foundation under the shear wall is increased from 10m x 10m to 14m x 14m. The base-beam at the edge is extended by 3m outside and rearranged the bearing position as shown in Fig. 10(b). By using this approach, the maximum compressive stress in all bearings is kept smaller than ultimate compressive stress of 48 MPa and tensile stresses in bearings are also kept within the limit of 2 MPa as shown in Fig. 10(c). The ultimate property diagrams of combined axial stress and lateral shear strain of bearings are shown in Fig. 10(d). For all ground motions, none of the bearings have the plot of axial stress and its corresponding lateral shear strain beyond the ultimate property diagram which is indicated by the blue line. This indicates that the bearings are safe from shear buckling [12] and their satisfactory performance is ensured under all ground motions.

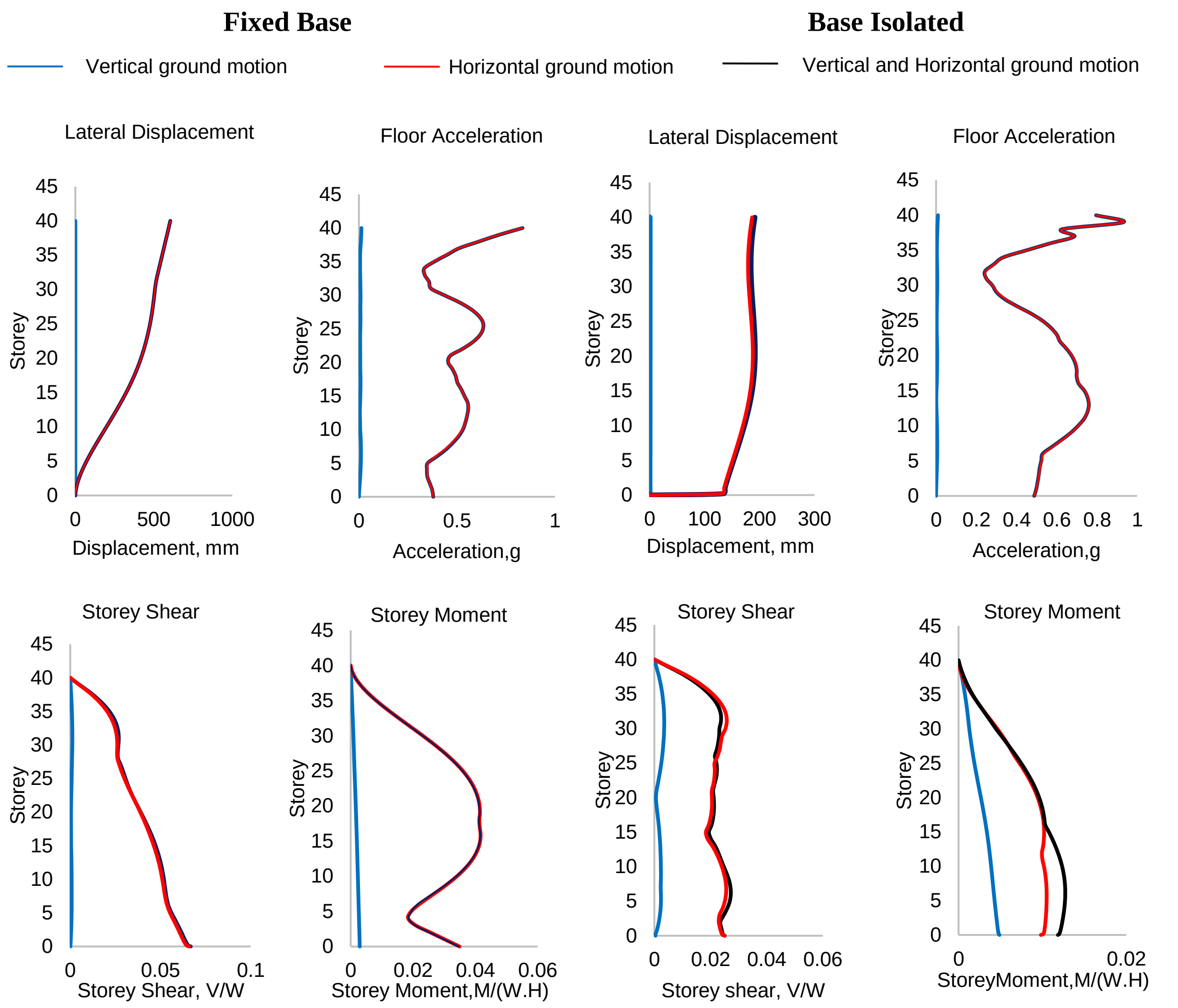


Fig. 8 – The comparison of lateral displacement, floor acceleration, storey shear and storey moment for fixed base and base isolated cases for effect of vertical and horizontal components of ground motions

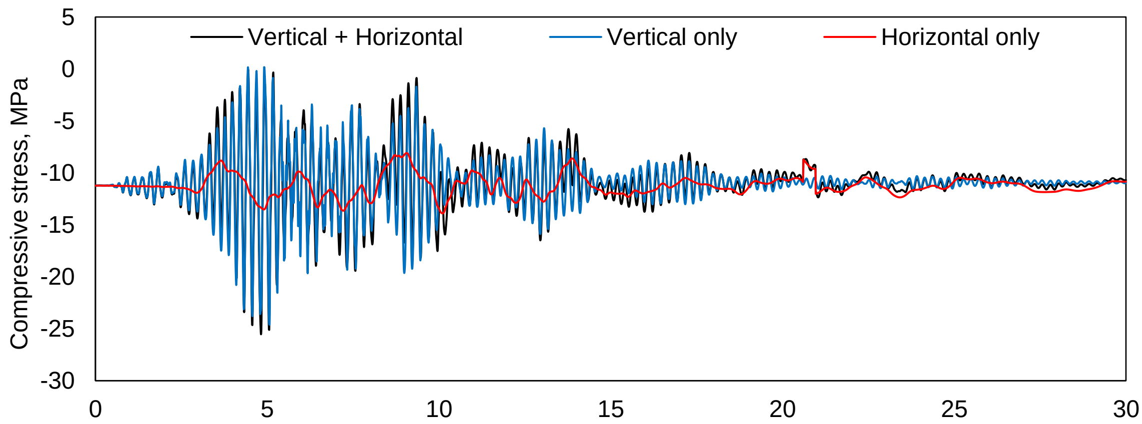


Fig. 9 – The axial stress in Beaing #12 under different cases of ground motion components

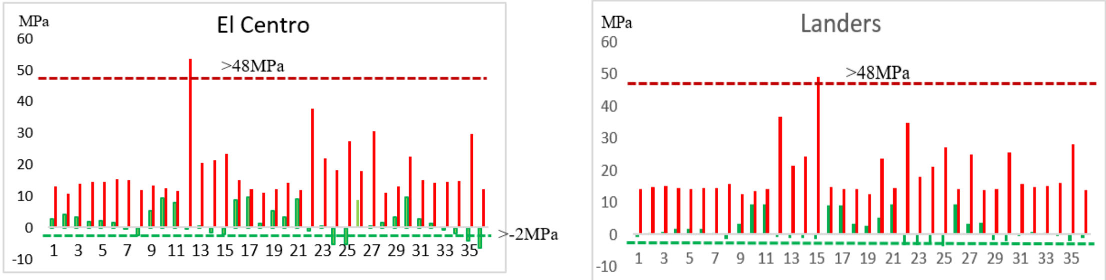


Fig. 10(a) – Axial reaction in bearings (bearing numbers are shown in Fig. 3)

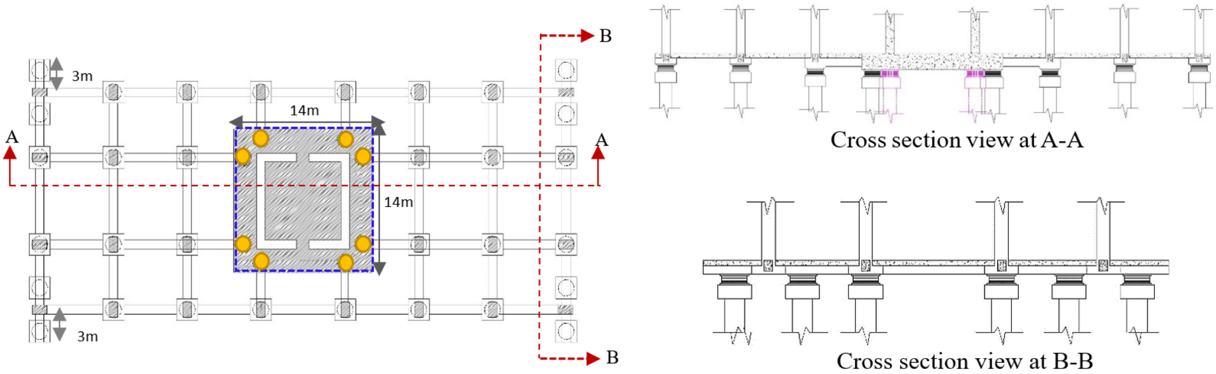


Fig. 10(b) – The plan layout and cross-section view at isolation level

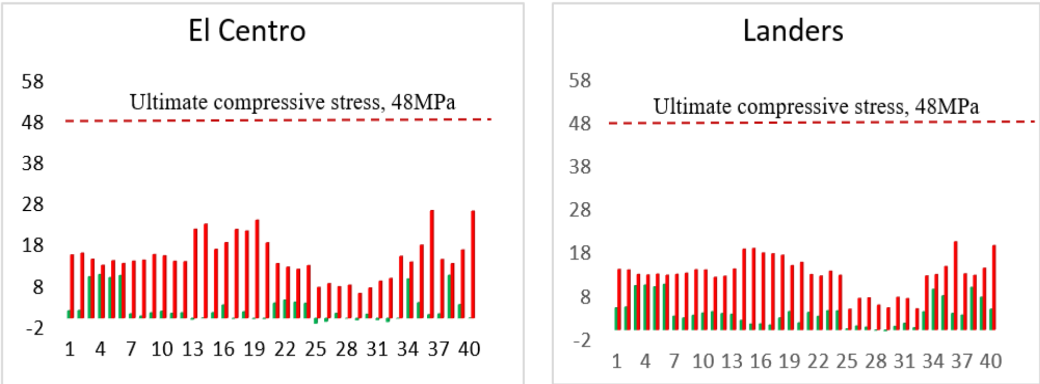


Fig. 10(c) – The axial compressive stress in bearings after applying the mitigation technique

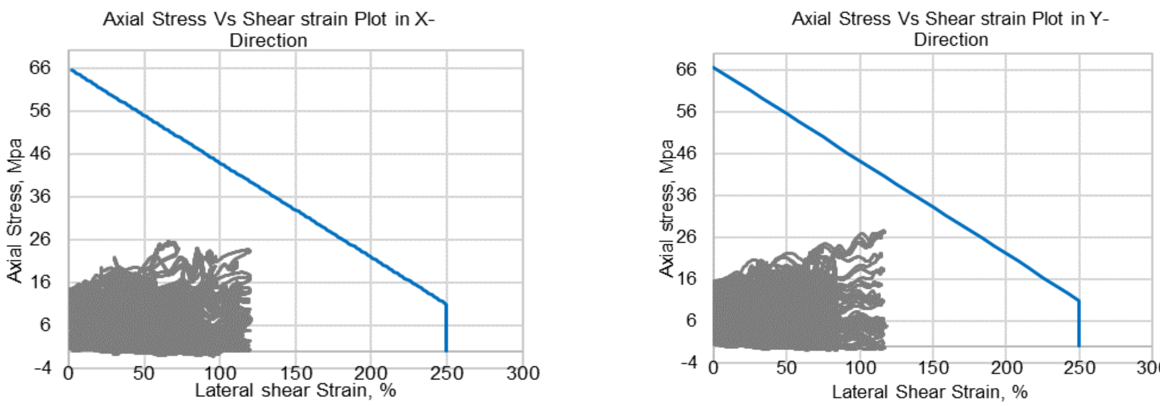


Fig. 10(d) - The ultimate property diagram of combined axial stress and lateral shear displacement

5.4. Comparison of Nonlinear Responses of the Fixed-base and Base-isolated Structures

After confirming that all bearing responses are within the acceptable limits, the effectiveness of base isolation in reducing the overall inelastic seismic demands is investigated in detail. The comparison of lateral inelastic responses of fixed-base and base-isolated structures are shown in Fig. 11. The reduction in storey drift, storey acceleration, storey shear and storey moment of base-isolated structure are in a range of 40-85%, 48-77%, 20-80% and 20-80% of the corresponding fixed-based structure, respectively. The lateral top displacement of the base-isolated structure is not much reduced but the profile of lateral displacement changes greatly which is dominated by the isolation mode ‘Mode-0’. There is a significant reduction in storey drift. The drift response of isolated structure is dominated by Mode 1 compared to Mode ‘0’ which is a rigid mode. The base isolation system is highly effective in reducing the floor accelerations because the effect of higher modes is diminished. On the other hand, in fixed-based structure, the higher modes (2, 3, 4, and higher) are significantly contributing to the total floor acceleration. This large reduction in story drifts and floor accelerations can significantly reduce damage to drift- and acceleration-sensitive components (e.g. building contents and other non-structural components). Furthermore, a significant reduction in storey shear and storey moment is observed on base-isolated structure as these demands are mainly dominated by mode ‘0’ and ‘1’. This significant reduction in storey shear and storey moment allows a reduction in the required design strengths of RC shear walls and other structural members.

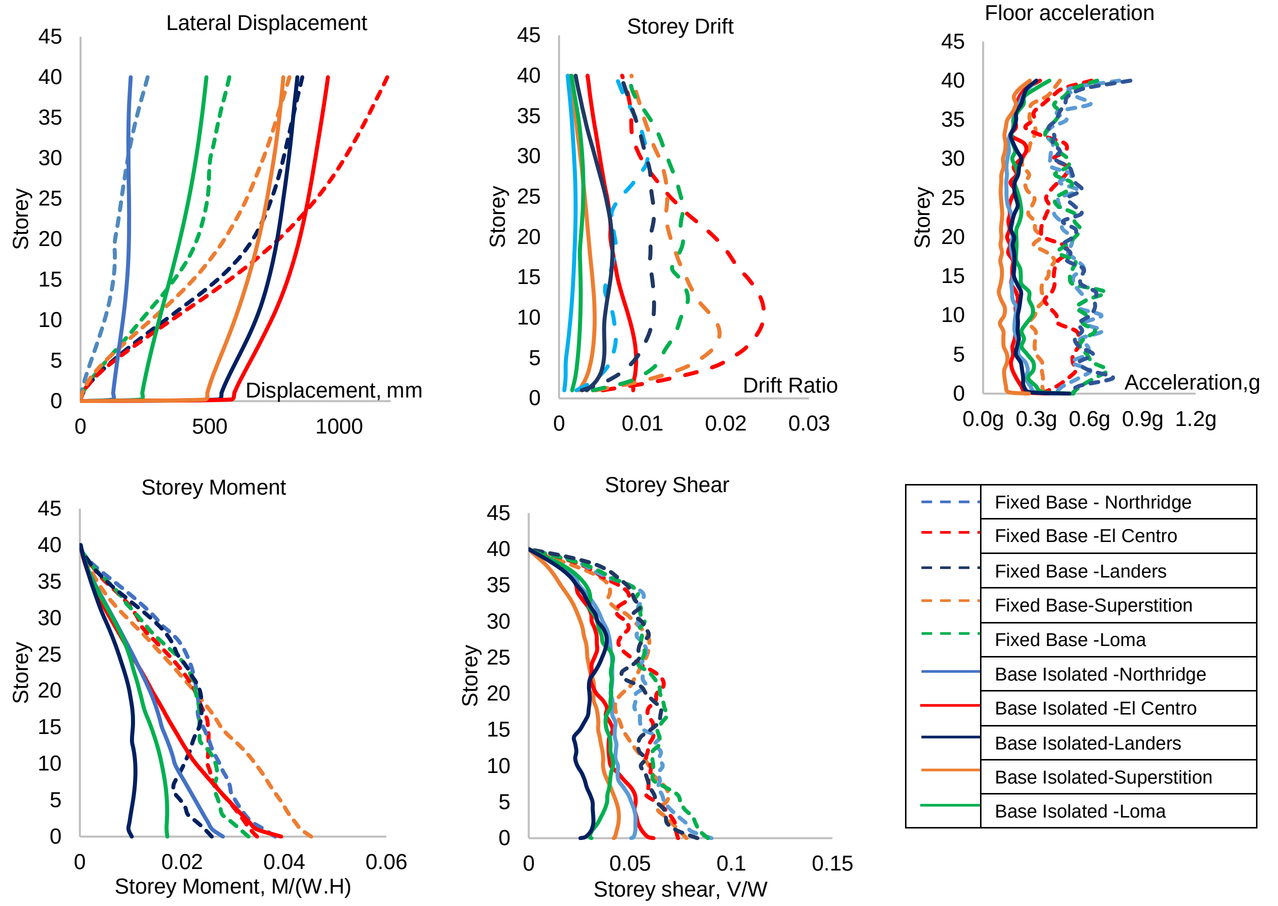


Fig. 11 – The comparison of total inelastic seismic demands of fixed-based (broken line) and base-isolated (solid line) buildings subjected to 5 input ground motions

6. Conclusion

This study evaluates the effectiveness of base isolation for high-rise buildings with RC shear walls. The results of an example building (40-story high-rise building with RC shear walls) show that the base isolation mechanism can results in the suppression of higher-mode effects in these buildings, thereby reducing the overall seismic demands. This idea (later confirmed by the results of the detailed NLRHA procedure) is first evaluated using the results of modal analysis and the individual modal contributions determined using the response spectrum analysis procedure. The nonlinear models of both the fixed-based and base-isolated structures are subjected to the detailed NLRHA procedure. Under MCE level of seismic shaking, including the vertical component of ground motions in the analysis, the performance of lead core rubber bearings is also evaluated. The results show that the vertical component of the ground motions can cause a high fluctuation in axial stresses (with a possibility of causing tensile stresses) in the bearings. It is shown that this issue can be mitigated by proper structural modification under shear walls and the rearrangement of bearing positions. After ensuring that the bearings are performing satisfactorily, the effectiveness of base isolation system for the example building is studied using the detailed NLRHA procedure. The overall results show that the use of lead core rubber bearings can result in significant reductions in inter-story drift, floor acceleration, story shear and story moment of high-rise building with shear walls. This reduction is due to significantly reduced contributions of higher vibration modes in the dynamic response of base-isolated buildings, in contrast to the fixed-based buildings.

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