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Depiction of concrete structures with seismic separation under faraway fault earthquakes

Liang Luo[1,2], Hoang Nguyen*[3], Hisham Alabduljabbar[4], Abdulaziz Alaskar[5], Fahed Alrshoudi[5], Rayed Alyousef**[4], Viet-Duc Nguyen[6] and Hoang-Minh Dang**[7,8]

[1]Key Laboratory of High Performance Ship Technology (Wuhan University of Technology), Ministry of Education, Wuhan 430070, China
[2]School of transportation, Wuhan University of Technology, Wuhan 430070, China
[3]Institute of Research and Development, Duy Tan University, Da Nang 550000, Viet Nam
[4]Department of Civil Engineering, College of Engineering, Prince Sattam bin Abdulaziz University, Al-kharj 11942, Saudi Arabia
[5]Department of Civil Engineering, College of Engineering, King Saud University, Riyadh 11362, Saudi Arabia
[6]Thuyloi University, 175 Tay Son, Dong Da, Hanoi, Vietnam
[7]Division of Construction Computation, Institute for Computational Science, Ton Duc Thang University, Ho Chi Minh City, Vietnam
[8]Faculty of Civil Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam

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Abstract. One of the most suitable methods in structural design is seismic separator. Lead-Rubber Bearing (LRB) is one of the most well-known separation systems which can be used in different types of structures. This system mitigates the earthquake acceleration prior to transferring to the structure efficiently. However, the performance of this system in concrete structures with different heights have not been evaluated thoroughly yet. This paper aims to evaluate the performance of LRB separation system in concrete structures with different heights. For this purpose, three, 16, and 23 story concrete structures are equipped by LRB and exposed to a far-field earthquake. Next, a time history analysis is conducted on each of the structures. Finally, the performance of the concrete structures is compared with each other in the term of their response to the earthquakes and the formation of plastic hinges. The results of the paper show that the rate of change in acceleration response and the ratio of drift along the height of 8 and 23 stories concrete structures are more than those of the 16-stories, and the use of LRB reduces the formation of plastic joints.

Keywords: base isolation system; lead-rubber bearing; far-field earthquake; time history analysis; numerical analysis

1. Introduction

Base isolation system provides the required flexibility for deformation at the base level of structures. This system includes structural components with low horizontal stiffness that separates the structure from the ground. It generates the frequency which is highly lower than the constant frequency of a fixed base supporting system. The first dynamic deformation mode of a base-isolated structure is in the separator system at the base level and the upper parts of the structure almost remain rigid. The use of base isolation systems not only provides reliable supports for the structure but also reduces the inertial forces of the structure by absorbing and dissipating the earthquake energy. In the base isolation technique, the whole or a part of the structure is separated from the ground or the other parts of the structure and a seismic separator is utilized between the separated parts (Bazzaz *et al.* 2011, Andalib *et al.* 2014, Khorramian *et al.* 2015, Safa *et al.* 2020a). As a result, the ground acceleration is mitigated prior to transferring to the structure and structural members can thus be designed for fewer load demands. Therefore, base-isolated systems can efficiently reduce construction time and cost. The cyclic and monotonic tests have been introduced to investigate the flexural, and lateral response of the structures. The cyclic test could lead to calculate the hysteresis and dynamic response of the structural elements (Ciutina *et al.* 2011, Shariati *et al.* 2012b, Shariati *et al.* 2012c, Shariati *et al.* 2013, Andalib *et al.* 2014, Shariati *et al.* 2014, Shariati *et al.* 2016a, Shariati *et al.* 2017, Shao *et al.* 2018a, Shariati *et al.* 2018a, Shafaei *et al.* 2019, Shao *et al.* 2019a, Shi *et al.* 2019b, Taheri *et al.* 2019). There are different types of cyclic scenarios such as fully-cyclic, half-cyclic and reverse cyclic which are able to perform according to the study requisites (Ghiami Azad *et al.* 2018a, Ghiami Azad *et al.* 2018b, Mafipour *et al.* 2019a, Mafipour *et al.* 2019b, Shariati *et al.* 2013, Shariati *et al.* 2014, Bazzaz *et al.* 2015, Shariati *et al.* 2017, Shariati *et al.* 2018a, Ghiami Azad *et al.* 2019, Shariati *et al.* 2019b). Furthermore, several studies have been performed different types of numerical and analytical assessment to identify the seismic response of the structural elements (Shao *et al.* 2015, Ahmadi *et al.* 2016, Sharafi *et al.* 2018a, Sharafi *et al.* 2018b, Sharafi *et al.* 2018c, Kildashti *et al.* 2019, Shao *et al.* 2019b, Shi *et al.* 2019a, Usefi *et al.* 2019, Mortazavi *et al.* 2020).

*Corresponding author, Ph.D.
E-mail: nguyenhoang23@duytan.edu.vn
**Co-Corresponding author, Ph.D.
E-mail: r.alyousef@psau.edu.sa
***Co-Corresponding author, Ph.D.
E-mail: danghoangminh@tdtu.edu.vn

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Fig. 1 Lead-Rubber Bearing (LRB) base isolation system

Lead Rubber Bearing, or LRB seismic isolator, is currently the most common seismic isolator in the world. The LRB separator was invented in 1974 by Robinson and was used for the first time in William Clayton building in Wellington, New Zealand. This type of seismic separator has been known as the most practical seismic separator for many decades in countries such as New Zealand, Japan, the United States, South Korea, and Turkey. Base-isolated structures by LRB Separators have also shown a very reliable performance in the face of destructive earthquakes such as Loma Prieta, Northridge, Kobe, Darfieldand, Christchurch, and Tohoku. This support consists of natural rubber and steel layers that are interconnected (Safa *et al.* 2016, Heydari *et al.* 2018, Nasrollahi *et al.* 2018, Zandi *et al.* 2018, Mehrmashhadi *et al.* 2019, Trung *et al.* 2019a). There are one or more lead bars in the middle. In addition, there is a protective layer around this seismic separator to ensure stability and increase heat resistance. Fig. 1 shows the implemented LRB base isolation systems in construction projects (Ghassemieh *et al.* 2015, Bahadori *et al.* 2016, Zhao *et al.* 2018).

Construction of structures near or far from the faults is inevitable. The earthquakes which occur near the faults are called near-field earthquakes while the other ones which are far from the faults are known as far-field earthquakes (Shao *et al.* 2018b, Shao *et al.* 2019a, Shao *et al.* 2019b, Shi *et al.* 2019a). Researchers have recommended different definitions for the distances from the faults as the near field range. For instance, UBC-97 Code describes a distance equal to 15 Km around the fault as the near field range. The impact of these types of earthquakes on the structures is almost different. Near-field earthquakes have higher accelerations and restricted frequency content in higher frequencies than far-field ones (Shariati *et al.* 2016b, Toghroli *et al.* 2018b, Li *et al.* 2019, Xu *et al.* 2019). Moreover, the records of the near-field earthquakes possess pulses in the beginning of the recodes with higher period and domain. When the Forward directivity occurs, these pulses are even more significant. Therefore, the records change from Board-Band condition to Pulse-Like ones. These pulse-type ground motions often contain one or more distinct pulses in the acceleration-time, velocity-time, and displacement-time histories, and more frequency in the velocity. In recent years, several researchers have studied the impact of such systems on different structures exposed to far-field and near-field earthquakes (Wang *et al.* 2011, Shariati *et al.* 2012a, Shao *et al.* 2019b). Generally, analytical assessments have performed not only to investigate the authenticity of the empirical tests but also to evaluate the critical key parameters and identify the hidden side of a structural element. There are several available methods for analytical assessment such as Intelligence algorithms which contains broad techniques such as an artificial neural network (ANN), fuzzy systems, and machine learning (Sinaei *et al.* 2011, Mohammadhassani *et al.* 2013, Mohammadhassani *et al.* 2014, Toghroli *et al.* 2014, Safa *et al.* 2020b, Shariati *et al.* 2019e, Shariati *et al.* 2020a, Mohammadhassani *et al*. 2015, Safa *et al.* 2016, Shahabi *et al.* 2016, Khorramian *et al.* 2017, Mansouri *et al*. 2016, Sedghi *et al.* 2018a, Shariat *et al.* 2018, Toghroli *et al.* 2018b, Ziaei-Nia *et al.* 2018, Hamidian *et al*. 2012, Chuanhua Xu 2019, Katebi *et al.* 2019, Luo *et al.* 2019, Mansouri *et al.* 2019, Milovancevic *et al.* 2019, Shariati *et al.* 2019a, Shariati *et al.* 2019b, Shariati *et al.* 2019c, Shariati *et al.* 2019d, Trung *et al.* 2019b).

A research by (Barabadi *et al.* 2010) evaluated the performance of seismic separators in structures subjected to near-field and far-field earthquakes using inactive and active separator systems. The results of this study showed that the inactive separator system experiences large displacements in lower floors, while the active system can significantly mitigate such displacements. In another research by (Barazandeh Tagh *et al.* 2014) investigated the impact of seismic separators on the seismic behavior of irregular buildings in near-field earthquakes based on the relative displacement of stories. This study showed that irregular buildings with different heights show different types of rotational behaviors in near-field earthquakes. A research by (Ardakani *et al.* 2014) studied various types of seismic separators in seismic rehabilitation of existing structures and concluded that the use of seismic separators can efficiently decrease the rate of change in acceleration response of the structures. In another research by (Shakib *et al.* 1996) examined the behavior of structures with slipping supports against earthquakes and observed that such a separator system is capable of protecting and maintaining the serviceability of the structure during earthquakes. In another study, (Tehrani Zadeh *et al.* 2005) modeled two 5 and 13 story structures in order for investigating the nonlinear behavior of structures in near-field and far-field earthquakes. This study showed that the near-fault earthquakes have a lower ratio of peak ground velocity to peak ground displacement (PGV/PGD) than fault-induced earthquakes. Thus, more seismic requirements should be taken into account for the structures exposed to the near-field motions. In another research by (Nouri *et al.* 2014) reported the effects of near-field and far-field earthquakes on the base-isolated buildings by friction pendulum separators (FPS). It was shown that the rate of change in acceleration has a bilinear ratio in this system and the rate

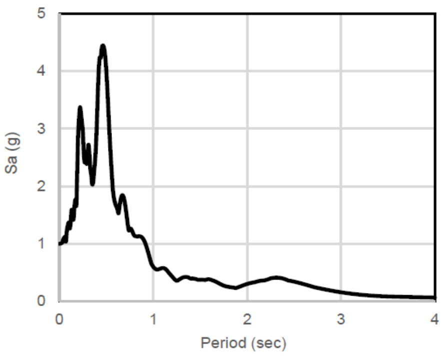
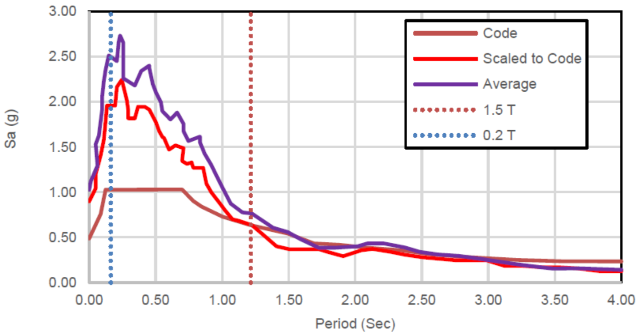
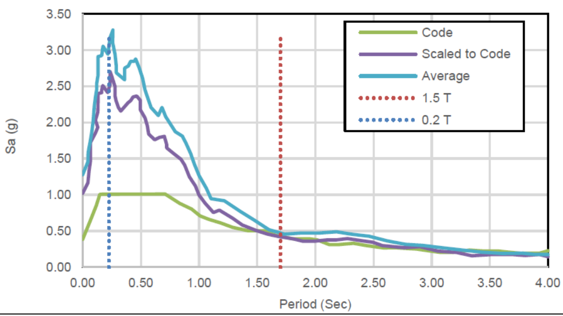


Fig. 2 Acceleration of the Kobe earthquake



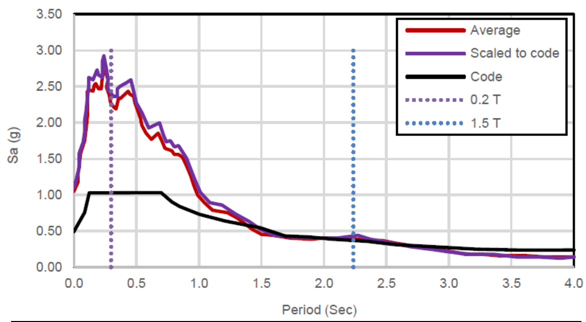
T	0.2T	1.5T	Scale factor
0.810	0.162	1.215	0.816

Fig. 3 Scaling for the 8-story concrete structure



T	0.2T	1.5T	Scale factor
1.130	0.226	1.695	1.210

Fig. 4 Scaling for the 16-story concrete structure



T	0.2T	1.5T	Scale factor
1.490	0.298	2.235	1.580

Fig. 5 Scaling for the 23-story concrete structure

of change in bilinear mode is greater than that of the triple mode. Also, it was observed that in far-field earthquakes, the acceleration of structure decreases by at least 20% due to utilizing FPS separators. In another research by (Nourizadeh *et al.* 2015) evaluated the seismic behavior of asymmetric base-isolated structures in various types of soils subjected to typical earthquake accelerations. They concluded that the relative displacement of middle stories and the frames which are far from the center is more. In a research by (Ozdemir *et al.* 2010) compared the efficiency of the equivalent lateral force (ELF) method with the response history analysis (RHA) method in estimating seismic isolator displacements. They concluded that the ELF method provides acceptably accurate predictions of shear isolator displacements and shear forces for a range of isolator properties. In another research by (Johnson *et al.* 1998) studied the efficacy of a passive base-isolated system, an active control device, and a semi-active magneto-rheological (MR) damper (Shariati *et al.* 2012a, Toghroli 2015, Sedghi *et al.* 2018b, Toghroli *et al.* 2018a). Simulations of the semi-active system demonstrated that the MR damper can decrease base displacements and peak acceleration typical of an active device (Andalib *et al.* 2014, Aghakhani *et al.* 2015, Abedini *et al.* 2017, Sadeghi Chahnasir *et al.* 2018a, Nosrati *et al.* 2018).

The main objective of this study is to evaluate the performance of concrete structures equipped by lead-rubber bearing (LRB) isolator devices in confronting with far-field earthquakes. For this purpose, the LRB isolator is initially modeled in ABAQUS (Sinaei *et al.* 2012, Mahdi Shariati 2019, Taheri *et al.* 2019). Then, this model is validated with the experimental results. Next, three types of 8, 16, and 23 story concrete structures are modeled in SAP2000 and ABAQUS. Two types of supporting systems including a fixed-base and an LRB are separately assigned to the models. Records of the far-field Kobe earthquake are applied to the modeled structures and non-linear time history analysis is conducted. Finally, the response of the concrete structures to the applied earthquake is recorded and presented.

2. Scaling the earthquake record

In this research, the far-field acceleration of Kobe earthquake was used in order for dynamic loading of the models. Therefore, this acceleration earthquake should be initially scaled. The acceleration of the earthquake is shown in Fig. 2.

Figs. 3-5 show the period of the structures and the manner of scaling. As could be expected, the structure with more height has the highest period and accordingly scaling factor.

3. Modeling in ABAQUS

Three types of 8, 16, and 23 story concrete frames have been modeled in ABAQUS. Two prototype of each model with fixed supports and LRB supports have been created. To validate the models of the concrete structures, the LRB seismic separator is modeled in modeled in ABAQUS (Shah

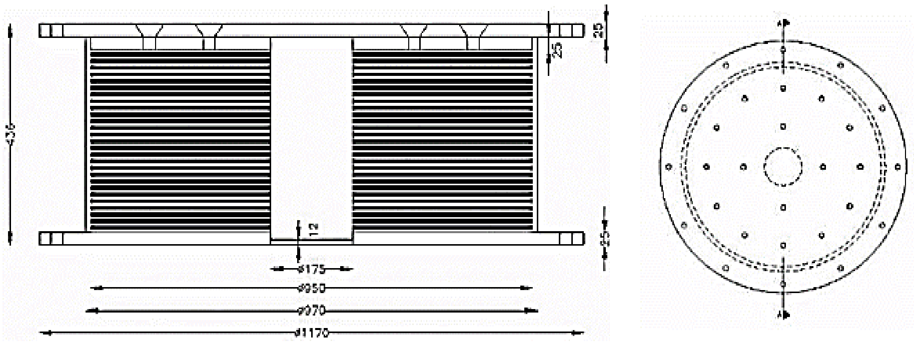


Fig. 6 Plan and cross-sectional view of the considered LRB

et al. 2016a, Shah *et al.* 2016b, Nguyen-Thoi *et al.* 2017, Shariati *et al.* 2018a, Shariati *et al.* 2020b, Chen *et al.* 2019). Then, the results of the model are compared with experimental results. In this section, the manner of modeling the LRB and concrete frames in ABAQUS are described.

3.1 LRB modeling

The considered LRB separator in this study is characterized with 27 steel plates with a thickness of 3 mm, 28 rubber plates with a thickness of 10 mm, a 25 mm thickness steel end-plate, two bearing plates with a thickness of 25 mm for connection, and a steel core with a diameter of 175 mm in center. Fig. 6 shows the plan and cross-section of the LRB model.

3.1.1 Rubber

Elastomeric materials have an almost linear behavior in small strains; however, a highly non-linear behavior in large strains. This behavior causes that the module of elasticity and module of shear changes in different strains. Rubber is an elastomeric material whose behavior is non-linear in large displacements. It is also known as a hyperelastic material as it is highly dependent on the load size, temperature, and strain. Hyperelastic materials are defined in the term of strain energy potential (U). Different types of strain energy potentials have been suggested in the literature and are available in ABAQUS. In this study, strain energy potential of the type Arruda-Boyce is used with the following equation

$$U = \mu \left\{ \frac{1}{2}(I_1 - 3) + \frac{1}{20\lambda_m^2}(I_1^2 - 9) + \frac{11}{1050\lambda_m^4}(I_1^3 - 27) + \frac{19}{700\lambda_m^6}(I_1^4 - 81) + \frac{519}{613750\lambda_m^8} I_1^5 - 243 \right\} + \frac{1}{D}\left(\frac{J^{el2} - 1}{2} - lnJ^{el}\right) \quad (1)$$

where μ, λ_m, and D are the temperature dependent materials; I_1, I_2, and I_3 are the deviatoric strain invariants; J^{el} is the elastic volume ratio.

To use Arruda-Boyce function in ABAQUS software, μ, λ_m, and D coefficients should be defined. These values have been considered according to Table 1.

Table 1 Parameters of the Arruda-Boyce strain energy function

μ	λ_m	D
0.4283	3.9142	0.001712

Table 2 Properties of steel

Modulus of elasticity	Poisson's ratio	Yield stress
210,000 MPa	0.3	240 MPa

Table 3 Properties of lead

Modulus of elasticity	Poisson's ratio	Yield stress
18,000 MPa	0.43	19.5 MPa

3.1.2 Steel

Steel is generally used in LRB separator to prevent high strains under vertical loads. This material can be described as elastoplastic. The characteristics of steel were defined as shown in Table 2.

3.1.3 Lead

The main role of lead in LRB separator system is to bear heavy loads and horizontal forces and absorb energy through plastic deformation. The lead core is compressed and yielded during the earthquake to dissipate the transferring energies. Lead shows a stable hysteresis behavior and fatigue does not occur in it. Lead can be also defined as an elastoplastic material as shown in Table 3.

3.2 Concrete frames modeling

Concrete frames were modeled in ABAQUS with Solid elements. For this purpose, a meshing with the size of 400 mm and of the type HEX with the structural meshing technique was used. In order to analyze the concrete frames, time history analysis was employed. The concrete frame that constitutes the structure under earthquake can be in Fig. 7. It has been modelled with beam elements, with a rectangular profile (0.5 m x 0.5 m). Typical concrete properties have been assigned. For the supports, two types of restrained supports (fixed) and LRB supports was assigned as described before.

4. Modeling in SAP2000

To model LRB in SAP2000, "rubber isolator" link

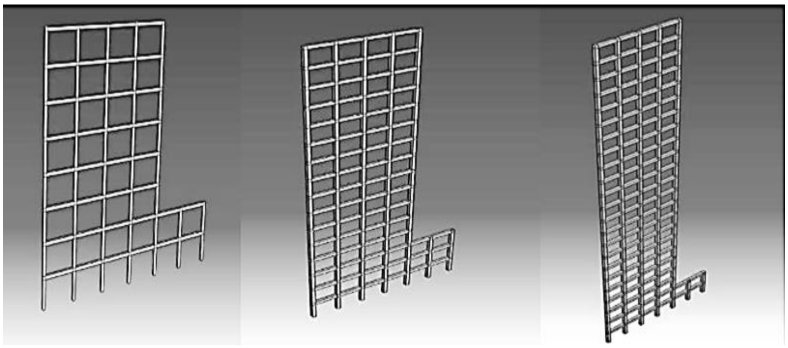
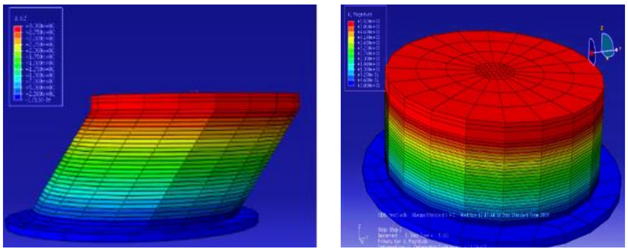


Fig. 7 ABAQUS models of the 8, 16, and 23-story concrete structures (from left to right)



(a) (b)

Fig. 8 Deformed shape of the LRB

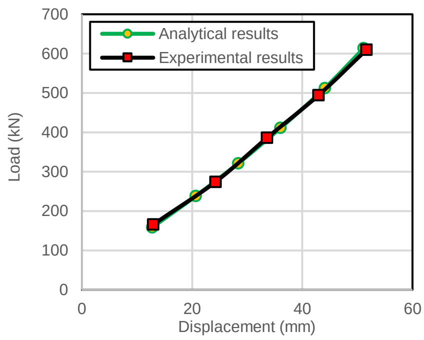


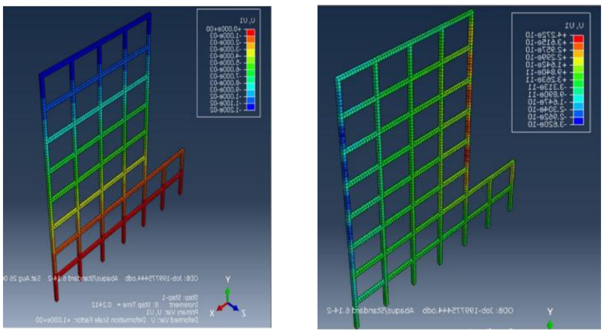
Fig. 9 Validation of LRB model by experimental results

element was assigned at the base level of the concrete structures. Then, the property of the LRB was defined in the SAP 2000 software.

5. Results

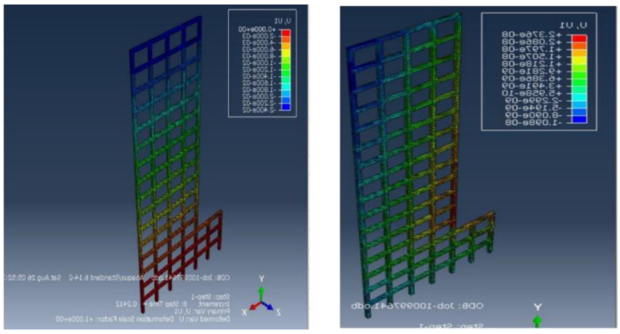
The experimental model mentioned in the ABAQUS software model designed and, analyzing the results, shows good match to the software model with the laboratory model. Fig. 8 shows the deformed shape of LRB after applying a horizontal load and Fig. 9 also represent the agreement between the experimental and analytical results.

After validation of the considered LRB, Two groups of three concrete frames with 8, 16, and 23 stories were modeled in ABAQUS. A fixed base support was assigned to the first group of structures while the second group was equipped by LRB seismic separator. Next, the record of Kobe earthquake was applied to the structures and a time history analysis was conducted. Figs. 10-12 show the deformed shapes of the structures. As can be seen, the structures with LRB have experienced a highly lower



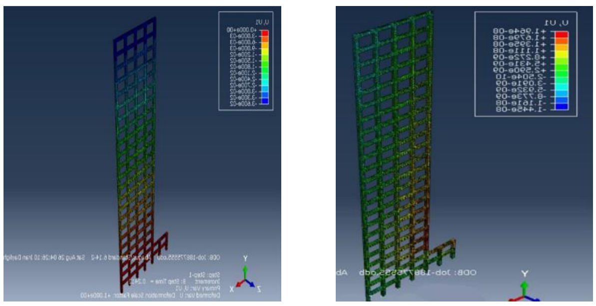
(a) (b)

Fig. 10 Deformed shape of the 8story concrete frame with: (a) fixed base support; (b) LRB support



(a) (b)

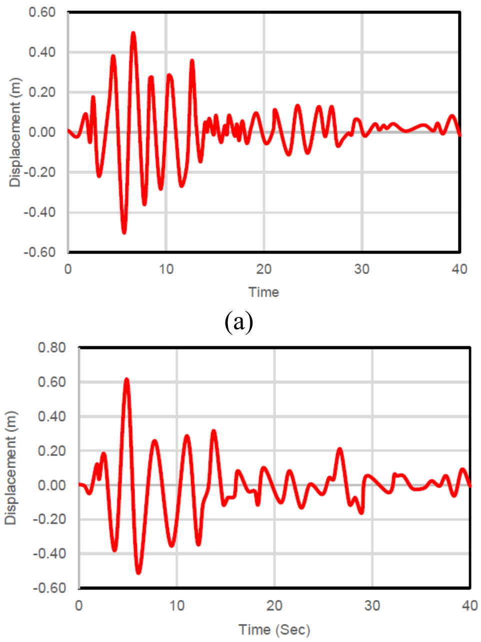
Fig. 11 Deformed shape of the 16story concrete frame with: (a) fixed base support; (b) LRB support



(a) (b)

Fig. 12 Deformed shape of the 23story concrete frame with: (a) fixed base support; (b) LRB support

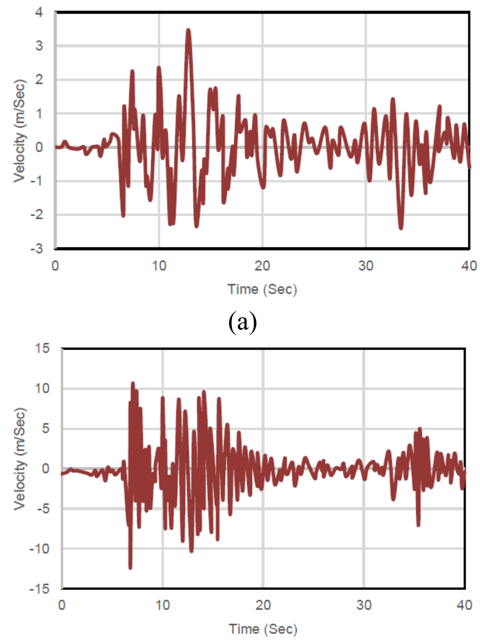
deformation comparing with the fixed base models. Also, it can be realized that in high-rise structures the impact of



(a)

(b)

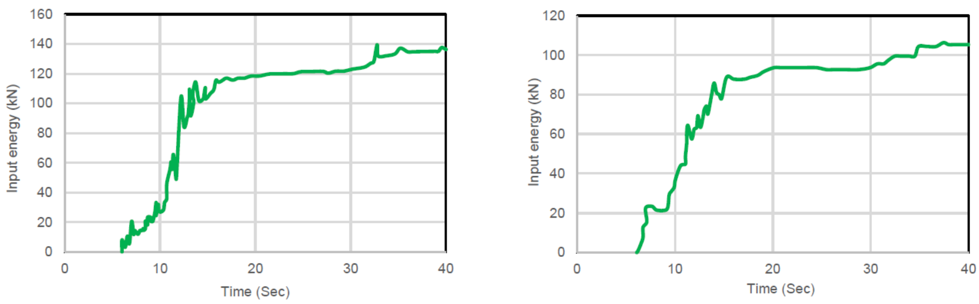
Fig. 14 Displacement-time diagram of the 8stoty concrete structure:(a) LRB support;(b) fixed support



(a)

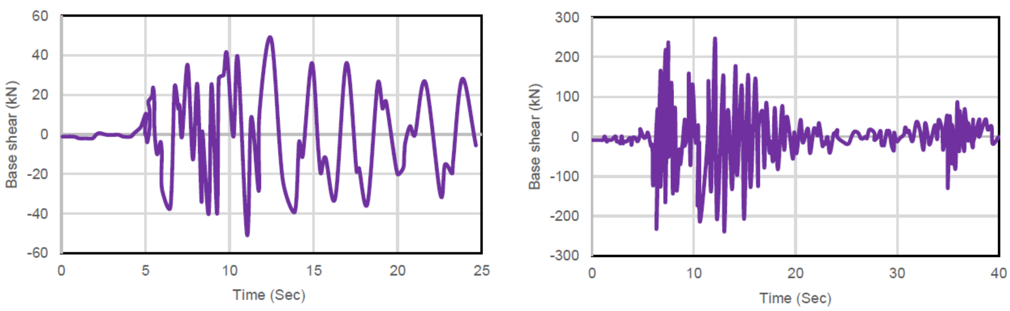
(b)

Fig. 15 Velocity-time diagram of the 8-stoty concrete structure: (a) LRB support; (b) fixed support



(a) (b)

Fig. 16 Energy-time diagram of the 8-stoty concrete structure: (a) LRB support; (b) fixed support



(a) (b)

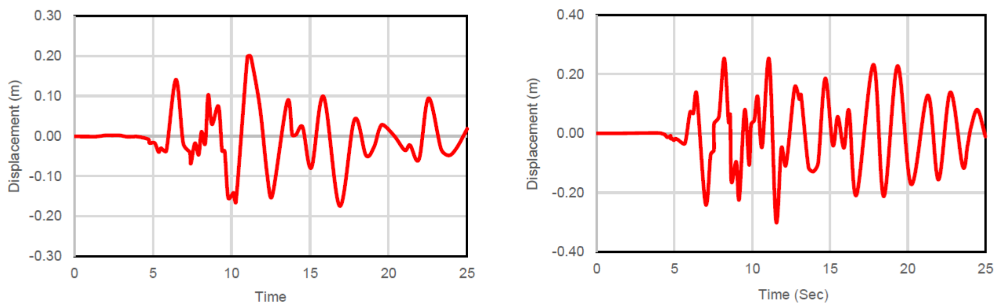
Fig. 17 Base shear-time diagram of the 8-stoty concrete structure: (a) LRB support; (b) fixed support

LRB on the behavior of the structures is more considerable. Fig. 13 shows and compares the base shear and the roof displacement of the structures. As can be seen, the implementation of LRB has caused that the domain of displacement and base shear decreases effectively.

Since ABAQUS has not been specifically developed to calculate the seismic behavior of high-rise structures, the concrete frames were also modeled in SAP2000. As described previously, two types of supports have been considered in this investigation:

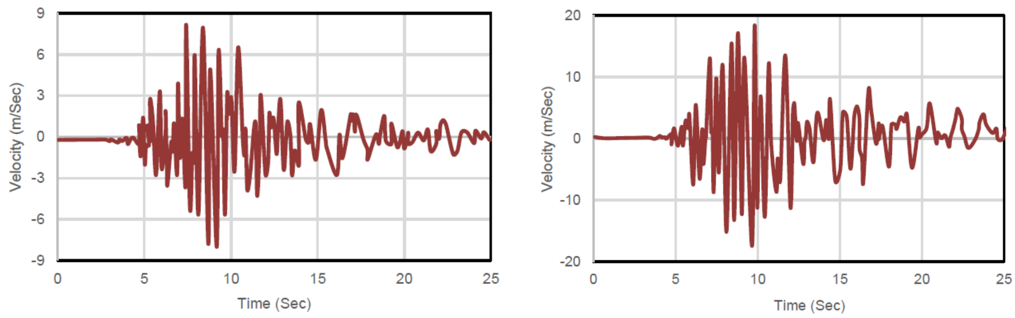
1. Fixed base support
2. Separated support by LRB

Totally 6 concrete frames were also modeled in SAP2000. Then, the acceleration of Kobe earthquake was applied to the structures and a time history analysis was carried out. Displacement, velocity, input energy, and base



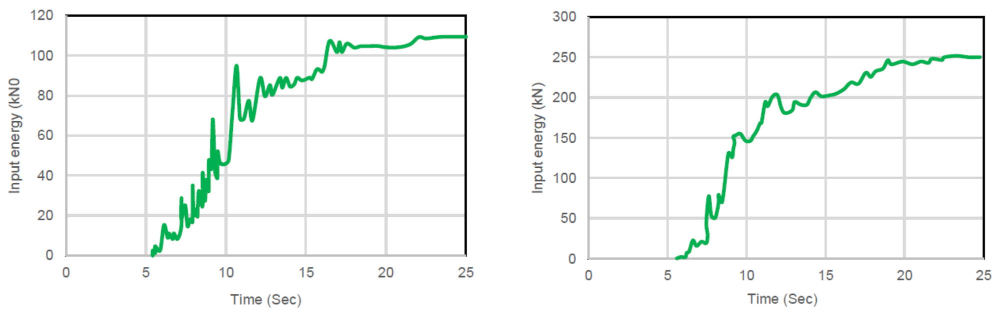
(a) (b)

Fig. 18 Displacement-time diagram of the16stoty concrete structure:(a) LRB support;(b) fixed support



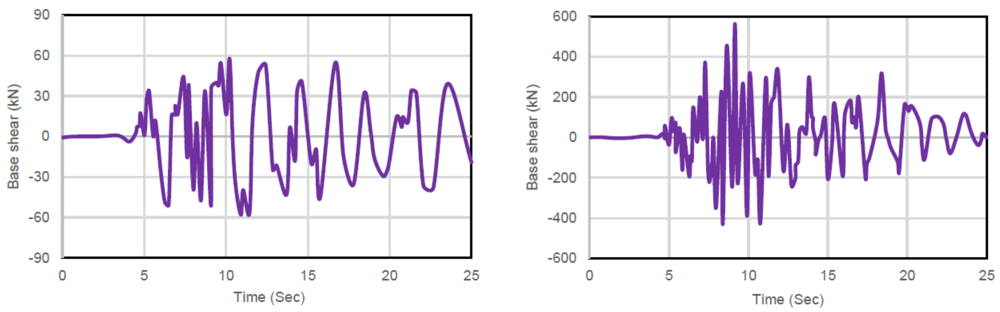
(a) (b)

Fig. 19 Velocity-time diagram of the 16 stoty concrete structure: (a) LRB support; (b) fixed support



(a) (b)

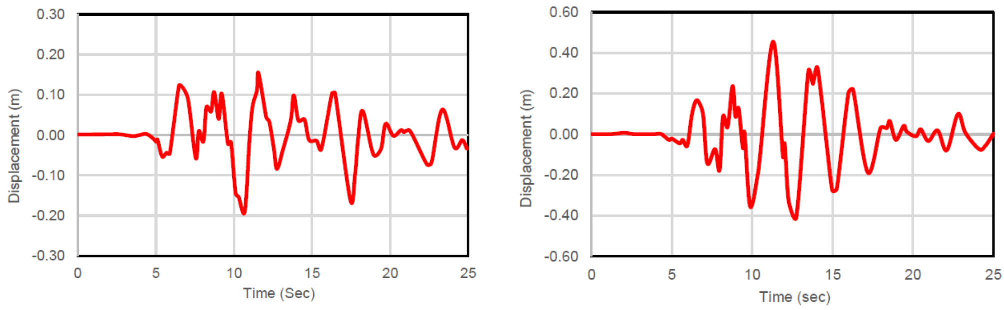
Fig. 20 Energy-time diagram of the 16-stoty concrete structure: (a) LRB support; (b) fixed support



(a) (b)

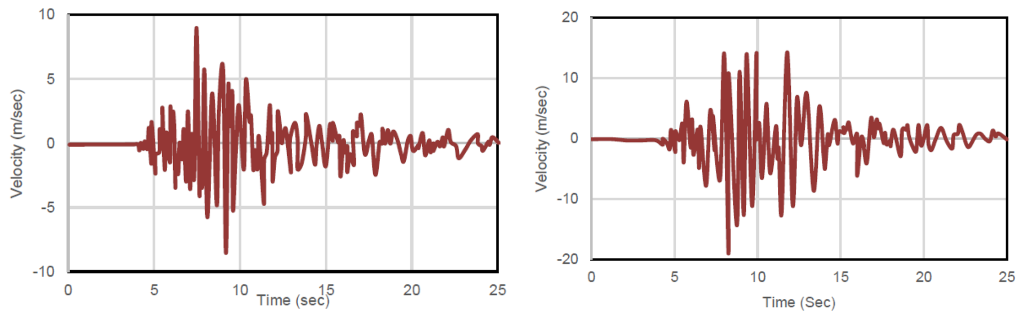
Fig. 21 Base shear-time diagram of the 16stoty concrete structure:(a) LRB support; (b) fixed support

shear of the structures were evaluated in both fixed based support structures and the equipped ones by LRB. Figs. 14-25 show the obtained diagrams from the SAP200 after the time history analysis. As can be seen in these diagrams, using LRB has mitigated the input energy of the structures. Accordingly, the base shear has been reduced effectively. In addition, the velocity and the displacement of the stories have also shown lower values comparing with those of the fixed base structures. The other point which should be mentioned is that the LRB system has exerted more impact on the 23-stoty concrete frame. This point can be realized if the displacement-time diagrams of the 23-story frame are



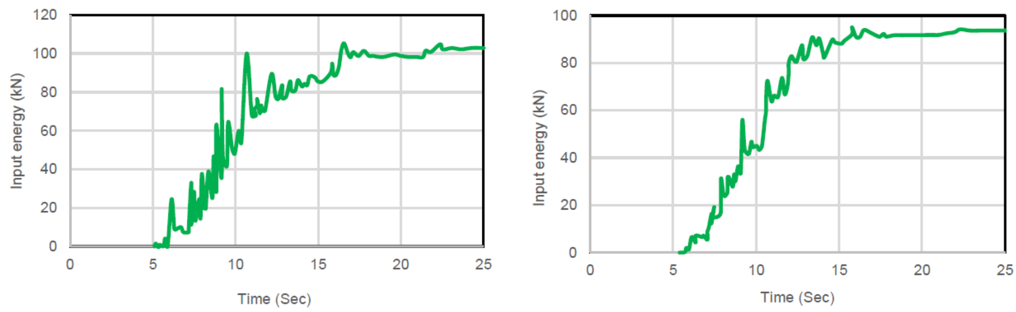
(a) (b)

Fig. 22 Displacement-time diagram of the23stoty concrete structure:(a) LRB support;(b) fixed support



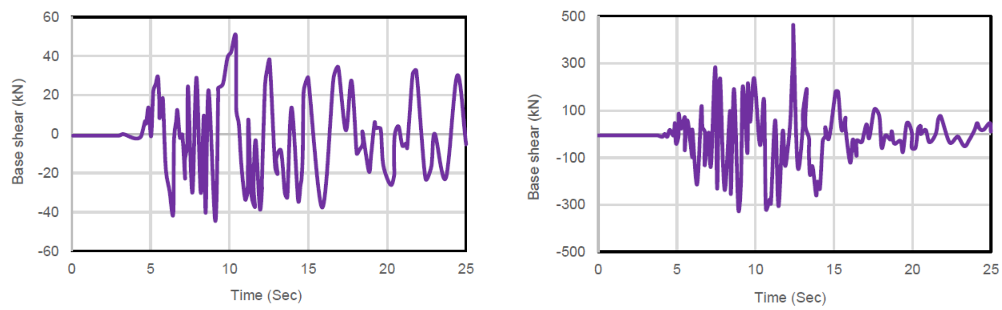
(a) (b)

Fig. 23 Velocity-time diagram of the 23-stoty concrete structure: (a) LRB support; (b) fixed support



(a) (b)

Fig. 24 Energy-time diagram of the 23-stoty concrete structure: (a) LRB support; (b) fixed support



(a) (b)

Fig. 25 Base shear-time diagram of the 23stoty concrete structure:(a) LRB support;(b) fixed support

compared with that of the 8-story structure. Therefore, it can be concluded that by increasing the height of structure the LRB would be a more efficient tool to reduce displacement of the stories. However, the base shear of all the structures with LRB has been in the same range and no specific change in the base shear can be observed.

5. Conclusions

In the current paper, to evaluate the performance of concrete structures with different heights, three concrete frames were modeled in SAP2000 and ABAQUS. Then, the finite element method was used to conduct a time history analysis of the structures. Considering the obtained diagrams such as Energy-time, Base shear-time, velocity-time, and Displacement-time, the following conclusions can be drawn:

1. Using lead core separator (LRB) reduces the cutting capacity of the classes.
2. Using lead core separator (LRB) reduces of formation of the plastic joint in the structure and increases the surface and yield and the useful life of the structure.
3. The use of lead core separator (LRB) increases in structural ductility is due to the concentrated deformation in the balance.
4. Using lead core separator (LRB) reduces relative displacement in the floors, which decreases with the height of the floors revenue.

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