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Comparison of the Response of a Structure Isolated from the Base with a Similar Structure in a Fixed Form

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ABSTRACT

The seismic response characteristics of a 5-story isolated structure on the foundation surface and a non-isolated foundation with an equal number of indeterminate degrees and three types of design earthquakes have been investigated. The isolators were modeled using a mathematical model and elastic and hysteretic rotors, and significant results were obtained. The effect of the shape of the isolator force-deformation ring on the response of the isolated structure is studied under the variation of important system parameters such as the isolator yield displacement, superstructure flexibility, separation period, and the number of stories of the structure separated from the foundation. The changes of the upper story absolute acceleration and bearing displacement are calculated for different two-line systems under different earthquakes to study the effects of the isolator residual ring shape. The maximum displacement in the isolated structure is at the ground floor and is zero in the same structure without the isolator at the same location. The forces generated, shear and moment, are also less in the isolated state than in the fixed state to the foundation. Low values of isolator yield displacement (i.e., sliding-type isolator systems) tend to increase the superstructure accelerations associated with high frequencies. In addition, superstructure acceleration also increases with increasing superstructure flexibility.

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1. Introduction

Seismic isolation is a method of controlling seismic vibrations by separating the structure from the ground in buildings and bridges. In contrast to conventional methods of seismic retrofitting and improvement, which increase the size of the structure, this method focuses on reducing the seismic response and the force and acceleration of the earthquake input to the structure isolation, which is now recognized as a mature and efficient technology, can be adopted to improve the seismic performance of strategically important buildings such as schools, hospitals, industrial structures, etc. in addition to the places where sensitive equipment are intended to protect from hazardous effects during earthquake [1-2]. Based on the extent of control to be achieved over the seismic response, the choice of the isolation system varies and thereupon its design is done to suit the requirements of use of the structure. In seismically base-isolated systems, the superstructure is decoupled from the earthquake ground motion by introducing a flexible interface between the foundation and the base of the structure. Thereby, the isolation system shifts the fundamental period of the structure to a large value and dissipates the energy in damping, limiting the

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amount of force that can be transferred to the superstructure such that inter-story drift and floor accelerations are reduced drastically. The matching of fundamental frequencies of base-isolated structures and the predominant frequency contents of earthquakes is also consequently avoided, leading to a flexible structural system more suitable from an earthquake resistance viewpoint. The two most common types of base isolation systems adopted in practice utilize either rubber bearings or sliding systems between the foundation and superstructure for isolation from ground motions in buildings as well as bridges.

It is very essential to understand the different parameters affecting the response of base-isolated structures when used for seismic protection of the structures. Especially in the case of the base-isolated structures, that house sensitive equipment, determination of acceleration imparted and associated peak displacement are the key issues for the design engineer [3].

Moreover, the pounding and structural impacts in the case of base-isolated structures made upon the adjacent structures, when separation gap distances are inadequate become a major concern because these phenomena may lead to catastrophic failures leading to immense isolator damage. Such failures and damages can be avoided by properly estimating the peak isolator displacement and recommending appropriate isolation gap distances. To predict peak displacement and determine the accurate separation gap distance required- meant for a base-isolated structure it is mandatory to know, in prior, the different parameters that affect the bearing displacement and its consequent effect on the superstructure acceleration. The failures due to such impacts can be avoided by reducing the peak bearing displacement by compromising with an increase in superstructure acceleration to an acceptable level i.e. tolerable reduction in the effectiveness of isolation. Selection of different parameters characterizing an isolation system is important given keeping control over response quantities, especially the excessive bearing displacement at the isolator level. The dynamic response of a base-isolated structure, therefore, is considerably reduced when compared to its counterpart, the fixed base structure as documented in the literature available on base isolation [4-5].

The behavior of isolation systems and the base-isolated structures is now well established and codes are developed for designing the base-isolated structures [6-7]. For non-linear isolation systems, the codes allow to use of the equivalent linear model to permit the use of the response spectrum method for designing the isolated structures. The equivalent linear models are based on the effective stiffness at the design displacement and the equivalent viscous damping is evaluated from the area of the hysteresis loop. The comparison of equivalent linear and actual non-linear models for the response of isolated bridge structures has been demonstrated in the past [8-9] and shown that the equivalent linear model can be used for predicting the actual non-linear response of the system.

The LRB isolators with hardening behavior were developed for low to mid-rise buildings located in the moderate seismicity area, and besides, the behavior of the base-isolated building was accurately predicted by nonlinear dynamic analyses performed with relatively long-period ground motions [10].

2. Structural model of base-isolated building

The figure shows the idealized mathematical model of the N-story base-isolated building considered for the present study. The base-isolated building is modeled as a shear-type structure mounted on isolation systems with one lateral degree of freedom on each floor.

The following assumptions are made for the structural system under consideration:

1. The superstructure is considered to remain within the elastic limit during the earthquake excitation. This is a reasonable assumption as the isolation attempts to reduce the earthquake response in such a way that the structure remains within the elastic range.

2. The floors are assumed rigid in their plane and the mass is supposed to be lumped at each floor level.

3. The columns are inextensible and weightless providing the lateral stiffness

4. The system is subjected to a single horizontal component of the earthquake ground motion

5. The effects of soil structure interaction are not taken into consideration

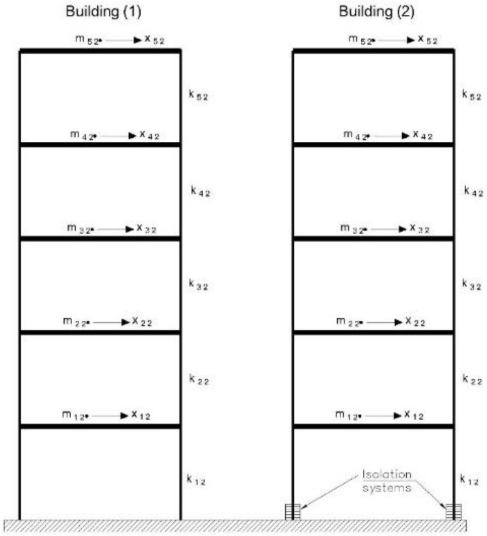
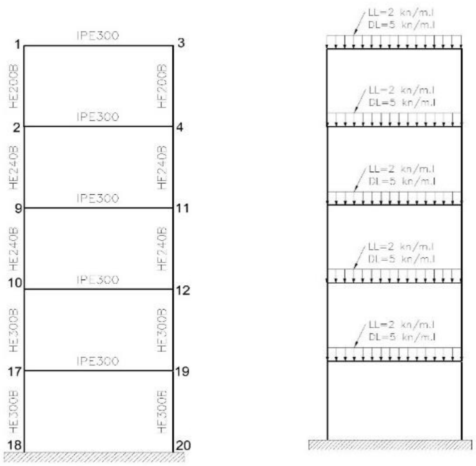


Figure 1. Mathematical model of N-story base-isolated structure



(a) Living and dead forces entering the frame (b) Node number - frame sections

Figure 2. Specifications of structural components, node number and amount of load applied at floor level

2.1. Damping force

Figure 1. Mat hem The force generated in the viscoelastic damper comprises two components: elastic force and damping force. The elastic force is proportional to the relative displacement between the connected floors, whereas the damping force is essentially proportional to the relative velocity of the piston head concerning the damper casing. Hence, the damper force can be expressed ascetical model of the N-story base-isolated structure.

$$F_d = [K_d]\{Ub.U1.U2.\ldots.Ul\}^T + [C_d]\{\dot{U}b.\dot{U}1.\dot{U}2.\ldots.\dot{U}l\}^T \quad (1)$$

The vectors of relative displacement and velocity between the damper-connected floors of the adjacent buildings and the over-dot denote the derivative concerning time. Here, the stiffness elements of dampers placed along the height of the adjacent structures is

2.2. Bilinear model and parameters of the lead core isolator model

The bilinear model, used to express the relation between the shear force and the lateral displacement, can be defined by three parameters: elastic stiffness, key, post yield stiffness, kip, and characteristic strength, Q The characteristic strength, Q, is usually utilized to estimate the stability of hysteretic behavior when the bearing experiences many loading cycles. Fig 3 shows an idealized bilinear model based on test data [11].

3. Unconnected building systems

In general, three different types of isolation systems are used in the structure in question: High Damping Rubber Bearings (HDRB), Lead Rubber Bearings (LRB), and Friction Pendulum Systems (FPS) which are placed under the base isolation buildings. For a fixed base building, the corresponding isolation in the above governing equations of motion with appropriate modifications in the mass, stiffness and damping matrices

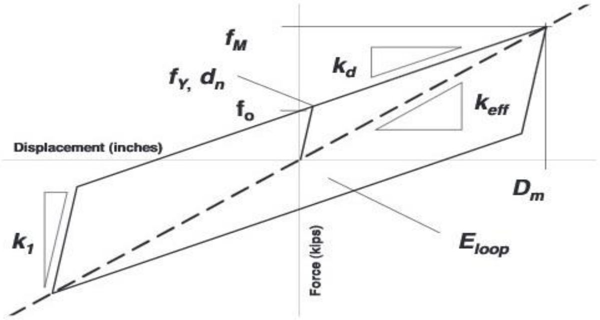


Figure 3. SBFEM applied to semi-infinite layer

3.1. High-damping rubber bearing

The bi-linear behavior is selected because this model can be used for all isolation systems used in practice. The characteristic strength Q is related to the yield strength of the lead core in the elastomeric bearings and friction coefficient of the sliding type isolation systems. The stiffness and damping of the HDRB are selected to provide the specific values of the two parameters characterizing the system namely the isolation time period (Tbi) and damping ratio (ξ_{bi}) defined as.

$$T_{bi} = 2\pi\sqrt{\frac{M_i}{K_{bi}}} \quad (2)$$

$$\xi_{bi} = \frac{C_{bi}}{2M_i\ \omega_{bi}} \quad (3)$$

where $\omega_{bi} = \frac{2\pi}{T_{bi}}$ is the isolation frequency.

3.2. Equivalent linear elastic viscous damping model of isolators

As per the Uniform Building Code [13] and International Building Code [7], the non-linear force deformation characteristic of the isolator can be replaced by an equivalent linear model through effective elastic stiffness and effective viscous damping. The linear force developed in the isolation system can be expressed as

$$F_b = K_{eff}\, x_b + c_{eff}\dot{x}_b \quad (4)$$

The equivalent linear elastic stiffness for each cycle of loading is calculated from experimentally obtained force deformation curve of the isolator and expressed mathematically as

$$= K_{eff}\frac{F^{+}-F^{-}}{\Delta^{+}-\Delta^{-}} \tag{5}$$

The effective viscous damping of the isolator unit calculated for each cycle of loading is specified as

$$\beta = {}_{eff}\frac{2}{\pi}\left[\frac{E_{loop}}{K_{eff}\,(|\Delta^{+}|+|\Delta^{-}|)^{2}}\right] \tag{6}$$

Where E loop is the energy dissipation per cycle of loading.

At a specified design isolation displacement, D, the effective stiffness and damping ratio for a bi-linear system are expressed as

$$K_{eff} = K_{b} + \frac{Q}{D} \tag{7}$$

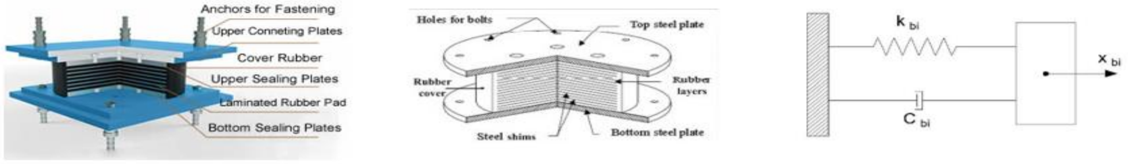
$$\beta = eff\frac{4\,Q\,(D-q)}{2\,\pi\,K_{eff}\,D^{2}} \tag{8}$$

4. Solution of equations of motion

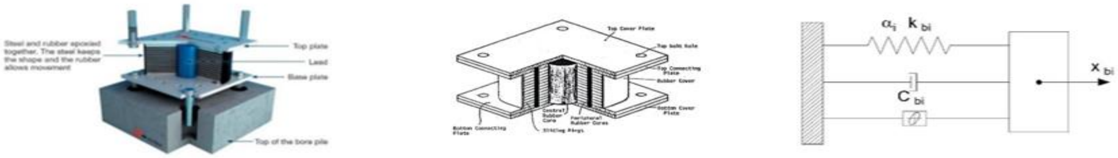
The classical modal superposition technique cannot be employed in the solution of equations because the system is not classically damped due to the difference in damping in the isolation system as compared to the damping in the superstructure of a base-isolated building as well as the damper links. Therefore, for different earthquakes, the equations of motion are solved numerically using Newmark's method of step-by-step integration; adopting a linear variation of acceleration over a small time interval of Ar. The time interval for solving the equations of motion is taken as 0.02/20 sec (ie □t 0.001 sec). At each time instant, the responses, namely the accelerations and displacements are obtained at each floor level of the two adjacent buildings.

5. Numerical study

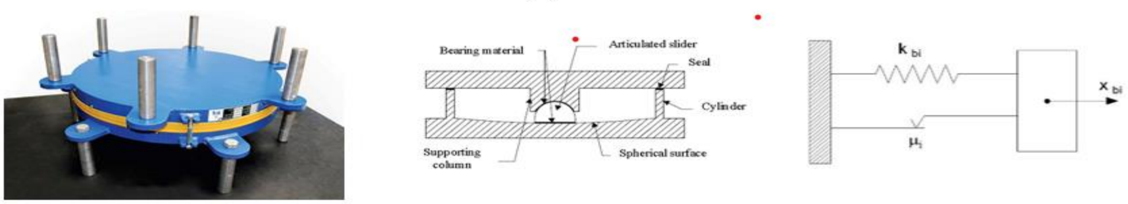
The seismic response of two adjacent multi-storied buildings, connected using viscoelastic dampers, either both or one of them supported on isolation devices is investigated here. The multi-degree-of-freedom shear models of the adjacent buildings are used, with linear viscoelastic damping devices at different floor levels in Fig 1. The earthquake selected for this study (1) The Bam earthquake was a magnitude 6.6 earthquake that shook the city of Bam and its surrounding areas in eastern Kerman Province at 5:26 a.m. on Friday, January 25, 2003, for 12 seconds (2) The Tabas earthquake was a 7.8 magnitude earthquake that occurred at 7:36 PM on Saturday, September 15, 1978, at a depth of 10 kilometers, destroying the city of Tabas and its surrounding villages (3) The Rudbar-Manjil earthquake of 31 June 1980, with a magnitude of 7.4, occurred at 30:00 AM Iranian time, i.e. in the early hours of Thursday, 31 June 1980 (equivalent to 20 June 1990 at 21:00 GMT), approximately 16 km from Rudbar, centered in the village of Pakdeh and its affiliated villages in Gilan province



(a) HDRB



(b) LRB



(c) FPS

Figure 4. Schematic models of isolation systems (a) HDRB (b) LRB and (c) FPS

5.1. The shape coefficient of the spectrum of the ground plan

According to Standard 2800 of Iran, the shape coefficient of the spectrum of the plan used in this study, type II land and the acceleration of the plan for the area with a very high-risk area is considered 0.35. In the figure3, the shape factor of the design spectrum for all types of soils in the zone of high risk and high void can be seen.

5.2. Technical and mechanical specifications used in dampers and separators

A seismic isolation head and a viscoelastic damper were used to analyze 5-story structures and observe the displacement in the structure based on 3 design earthquakes. The mechanical specifications and initial analytical results for use in the SAP2000 program are specified in the tables below. Considering the initial results and placing each of them in 5-story structures, they were analyzed according to Figure 1

The following tables show the results of structural analysis in cases where a viscoelastic damper is used to connect two structures on the floor or as a metal member. Also, a seismic isolator is also used in the structures at the same time, as shown in Figure 1. The amount of dead and live loads used in structural analysis is also specified in Figure 1.

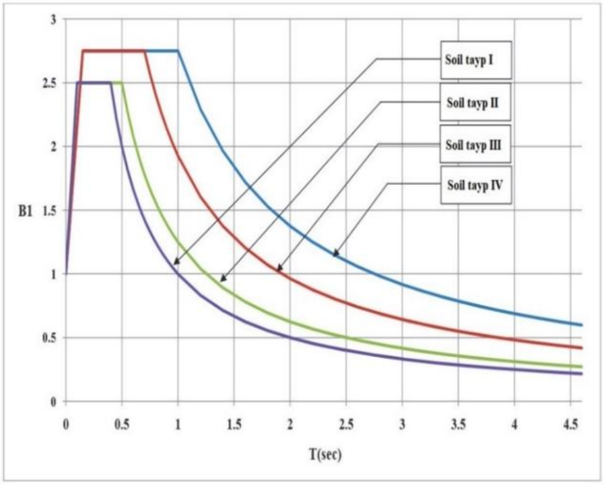


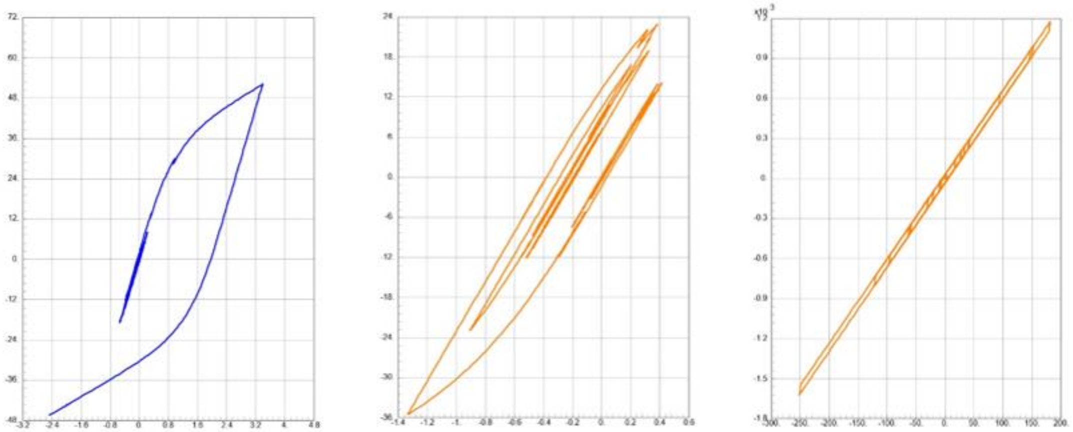
Figure 5. Shape coefficient of the design spectrum for all types of soils

Table 1.

Characteristics of Earthquakes

position	Load applied to the column W (ton)	Lead core yield strength Q (ton)	Yield strength Fy (kn)	stiffness k0 (kn/m)	Effective stiffness Keff (kn/m)	Effective periodicity Teff (sec)	Effective damping ratio ζeff	Effective damping Ceff (kn.s/m)
5-storey structure	63.00	3.15	37.12	3711.94	849.03	1.71	0.16	73.02

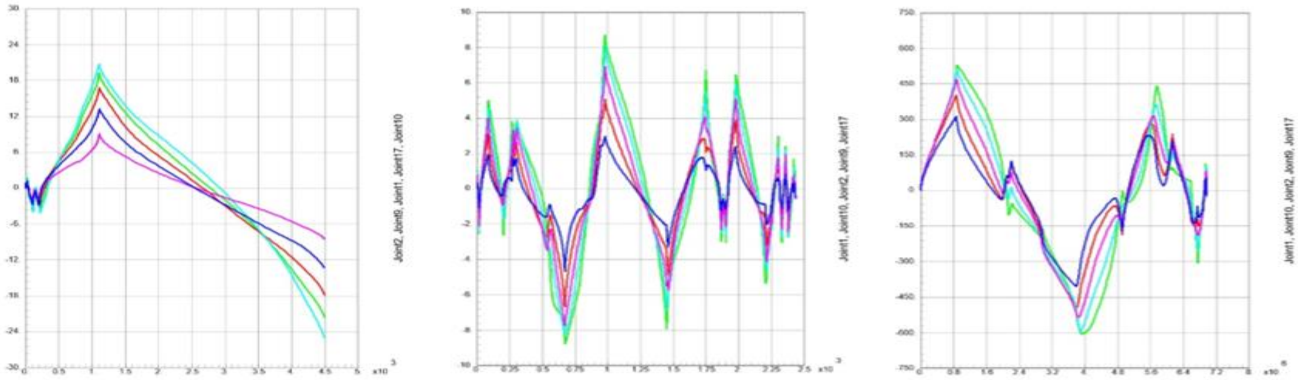
5.3. Hysteresis diagram of the separator at the column foot position



(a) The Bam earthquake (b) The Tabas earthquake (c) The Rudbar-Manjil earthquake

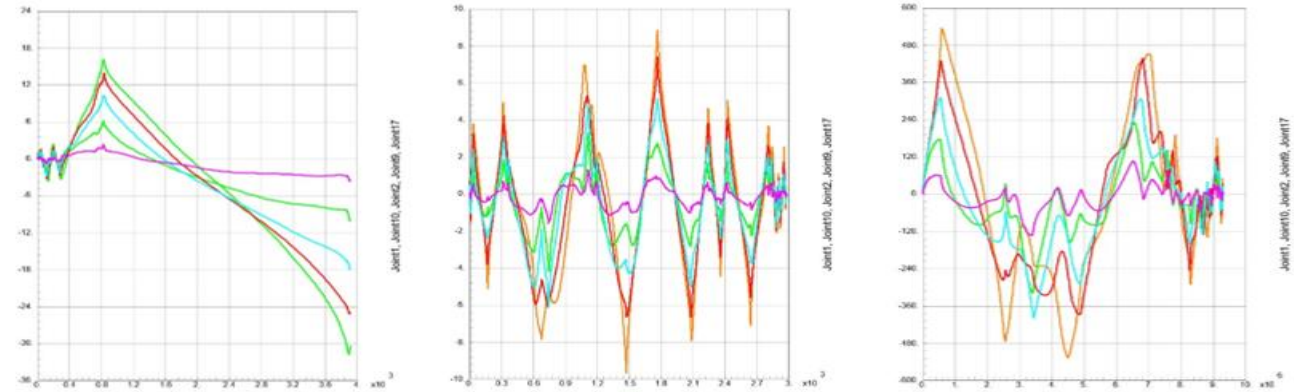
Chart 1. Isolator hysteresis diagram according to design earthquake

5.4. Damping energy at node positions



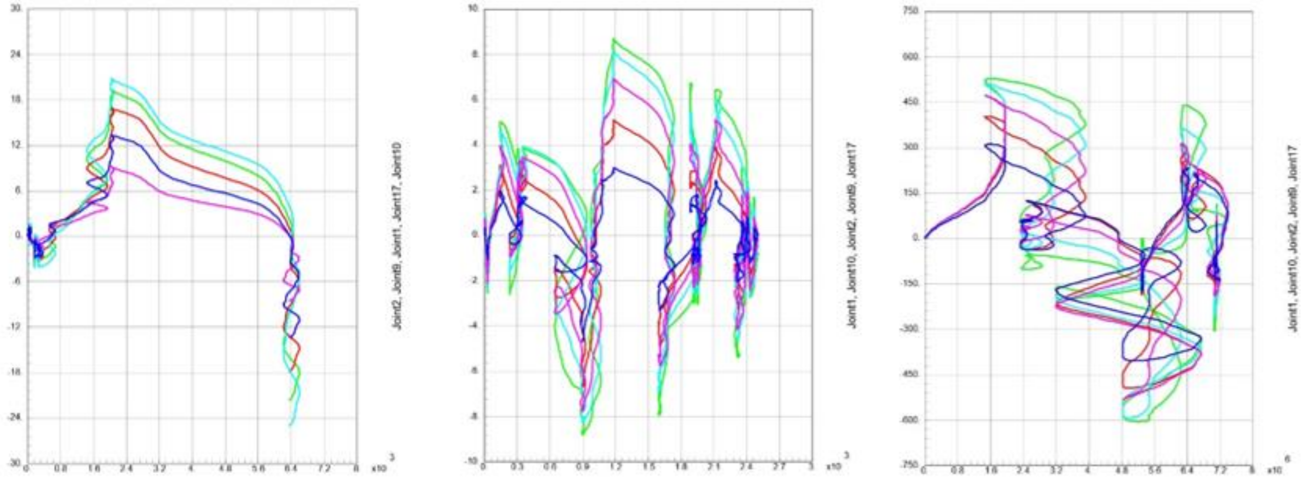
(a) The Bam earthquake (b) The Tabas earthquake (c) The Rudbar-Manjil earthquake

Chart 2. Damping energy at node positions when using an isolator



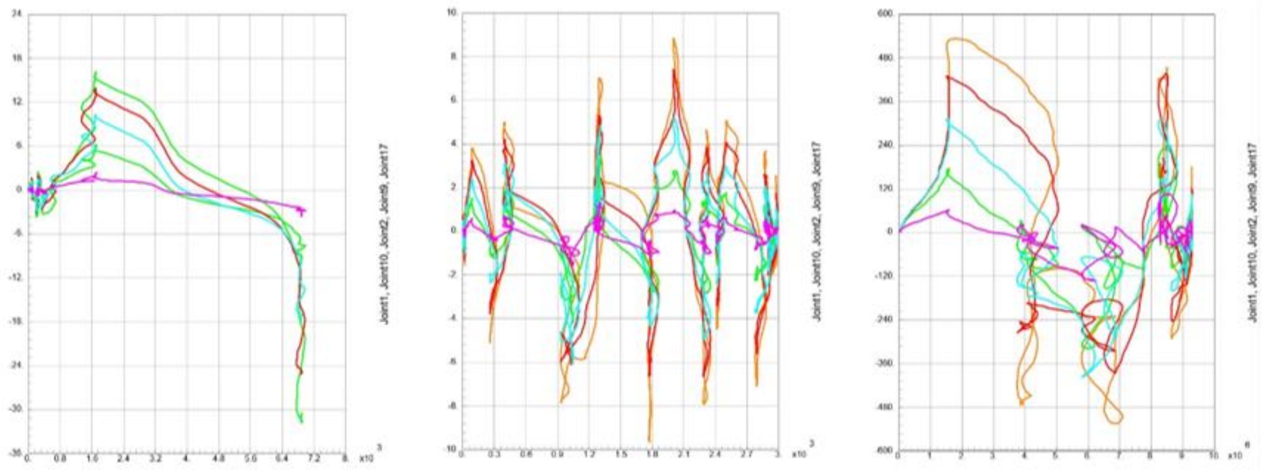
(a) The Bam earthquake (b) The Tabas earthquake (c) The Rudbar-Manjil earthquake

Chart 3. Damping energy at node positions in the fixed connection mode in the foundation



(a) The Bam earthquake (b) The Tabas earthquake (c) The Rudbar-Manjil earthquake

Chart 4. Diagram of energy input at node positions when using the isolator



(a) The Bam earthquake (b) The Tabas earthquake (c) The Rudbar-Manjil earthquake

Chart 5. Diagram of energy input at the node positions in the beam-foundation connection mode

6. Conclusions

The displacement and seismic response of buildings in two cases (1) placed on a foundation in a fixed connection mode and (2) placed on a seismic isolator were investigated in this study, and the following results were obtained.

1. The hysteresis behavior of the isolator placed under the columns in the isolated state (Building 2) has different performance due to the loading cycles caused by the earthquake, depending on the type of uniform structure, so that in Figure (C) related to the Rudbar-Manjil earthquake, it tends to be linear.

2. As can be seen in Chart 2 and 3, with respect to the design earthquake, the damping value at node positions at different levels of the structure in the isolated state is less than in the case where the structure is directly fixed on the foundation.

3. Chart 4 and 5 show the amount of energy entering the structure. Considering the design earthquake, the damping value at node positions at different levels of the structure in the isolated state is much lower than in the case where the structure is located directly on the foundation.

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