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Dynamic response characteristics of seismic isolation systems for building structures †

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Abstract

Isolation is an effective method of reducing effects of seismic events on building structures. Steel-reinforced elastomeric isolator (SREI) is one kind of isolation system which is used extensively, but there are some problems associated with its use, such as cost and weight. Fiber-reinforced elastomeric isolator (FREI) has been developed in an attempt to solve the problems of high cost and heavy weight for SREI. In this study, mechanical properties for the SREI and the FREI are investigated. Systematic dynamic response analyses are performed for three different models such as a fixed based, an SREI based and an FREI based low-story building structures. Two-dimensional and three-dimensional dynamic response analysis results for each model are compared in terms of displacement, drift, acceleration and shear force in this study. In the two-dimensional dynamic response analysis, the SREI and the FREI based structures are proven to be the more effective isolation systems against seismic events by comparing with the fixed based one. As a result, the FREI has shown better isolation performances than that of the SREI. Furthermore, to extract the characteristics of the FREI on building structure resisting the seismic effects, two models of three-dimensional framed structure with fixed bases and FREI isolated bases are built, respectively. After the dynamic response analysis of these two structures subjected to bi-directional ground motions, the analyzed results are compared with each other. It is shown that the FREI could effectively absorb the seismic energy, and decreases the destructive effects acting on a building structure due to ground horizontal motions that could occur in an earthquake.

Keywords: Dynamic response analysis; Base isolation system; Steel reinforced elastomeric isolator; Fiber reinforced elastomeric isolator; Building structure; Seismic events

1. Introduction

Base isolation of building structures is a passive control technique used to protect the building from seismic effects. The seismic isolator is installed in the building structure's foundation to absorb the seismic energy, and prevent the building structure from damage due to the seismic motions, which are transmitted the horizontal earthquake wave to the low-story building structure in Fig. 1. Therefore, the isolator needs sufficient vertical rigidity to sustain a gravitational loading, and enough horizontal flexibility to shift the foundational frequency of the isolated building away from dominant frequency range of most earthquakes. As a general rule, the isolator has excellent flexibility in the horizontal direction, which could extend the natural period of the building structure's mode of vibration to be far away from the dominant range of the earthquake's vibration bandwidth.

The commonly used in-structure isolator against the seismic effects is the rubber isolator, which has bidir ectional hysteretic properties. The profile of the laminated rubber bearing was studied [1], and the mechanical properties of the isolation bearings were

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identified by using a visco-elastic model [2]. A macroscopic model for predicting the large-deformation behaviors of the laminated rubber bearing had been researched [3], and a study on the response during large deformation under seismic isolation was conducted [4], as well as the seismic performance of base-isolated structures using a shaking table and a pseudo-dynamic test was evaluated [5].

Steel-reinforced elastomeric isolator (SREI), as one of the base isolation systems used for building structure could supply sufficient vertical rigidity to endure the gravitational loading by using the steel reinforced plates, and provide good horizontal flexibility to change the fundamental frequency of the isolated structure. However, this isolator is large, expensive and extremely heavy. To solve these disadvantages of the SREI isolation system, the fiber-reinforced elastomeric isolator (FREI) has been introduced and examined analytically for its compression stiffness. Additionally, a comparative study on the effects of the mechanical properties for the FREI with a hole and lead plug effects was also carried out [6-9].

The main objective of this study is to investigate the dynamic response characteristics of low-story isolated building structures with the SREI and the FREI base isolation systems, respectively. To confirm the availabilities of the SREI and the FREI base isolation systems, the mechanical properties of these two systems were studied. In 2-dimensional dynamic response analysis, the response characteristics of the fixed base, the base isolation using the SREI and the FREI were simulated and compared with each other. From the results, the SREI and the FREI were proven to be more effective isolation systems against the seismic events by comparing with the fixed base. Furthermore, to extract the characteristics of the FREI base isolator on building structure in resisting the seismic effects, two models of 3-dimensional frame structure with the fixed base and the FREI isolated base were built, respectively. After the dynamic response analysis of these two structures subjected to bi-directional ground motions, the analyzed results were compared to show that the FREI base isolator could effectively absorb the seismic energy, and also decrease the destructive effects acting on the building structure due to the ground's horizontal motion caused by the earthquake. More importantly, it was confirmed that the FREI base isolator could give the better isolation performance than that of the SREI.

Fig. 1. Seismic damage on low-story building by big earthquake of Han-Shin area in Japan, January 17, 1995.

2. Mechanical properties of SREI and FREI

2.1 Design of SREI and FREI

To estimate the efficiency of the SREI and the FREI in cases of seismic excitation, the elastomeric isolators were reinforced with steel plates for the SREI, and carbon fiber layers for the FREI were designed as shown in Fig. 2. Fig. 3 shows the manufacturing process of the FREI. The SREI consists of two end steel flanges on the top and the bottom, and multi-layers of rubber and steel. On the other hand, the FREI is composed of two steel flanges on the top and the bottom, and multi-layers with rubber and fiber layers, which form the reinforced pad of the elastomeric isolator. The thickness differences between fiber and steel plates were adjusted by using multi-layers of fiber and rubber in the FREI.

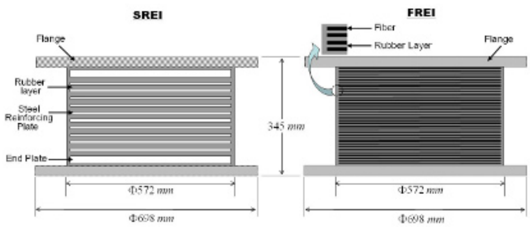


Fig. 2. Configurations and specifications of SREI and FREI.

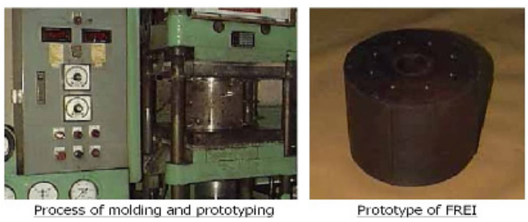


Fig. 3. Manufacturing process of FREI.

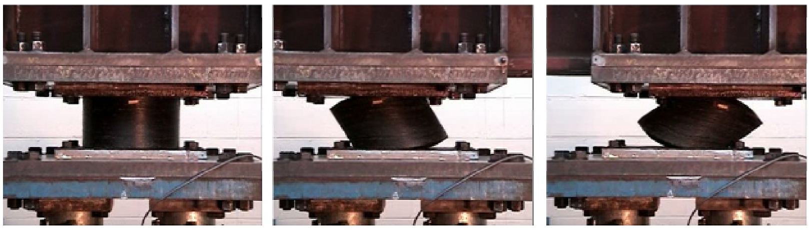


Fig. 4. Experimental views for FREI isolator to obtain mechnaical properties.

In this study, the SREI was only used to confirm the mechanical properties of the FREI as a seismic isolator, by comparing them with each other. To obtain the FREI isolator with high elongation and high tensional stiffness, raw rubber was mixed with a few chemical materials. Several tests such as crevice endurance, extensional stiffness and its ratio, hardness, properties after aging, and resistance against O_3 were carried out according to Korean Standard Test Classification, KSM6518. Also, dipping and molding processes were performed to improve the bonding strength between the rubber and the fiber, and optimize the elastic characteristics against seismic excitation.

2.2 Evaluation of mechanical properties

To obtain the vertical and the horizontal stiffness of the SREI and the FREI, a series of tests were performed as shown in Fig. 4. The vertical stiffness ($\boldsymbol{K}_v$) of the isolator is extracted from Eq. (1).

$$K_v = [E_C A]/t_r \tag{1}$$

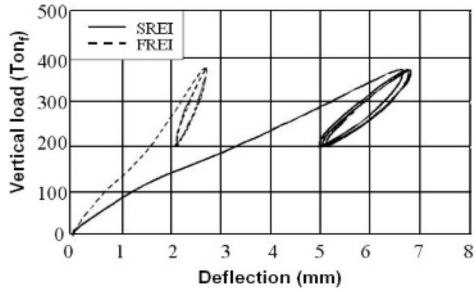
where $\boldsymbol{A}$ is the cross-sectional area of the isolator, $\boldsymbol{t}_r$ of the total thickness of the isolator, and $\boldsymbol{E}_C$ of the instantaneous compression modulus of the rubber-steel, or the rubber-fiber composite under a given axial stress.

The average effective horizontal stiffness and equivalent damping coefficient of the SREI and the FREI could be obtained from the horizontal tests. Then the effective horizontal stiffness ($\boldsymbol{K}_{eff}$) is examined from the peak-to-peak value in each hysteresis loop by Eq. (2).

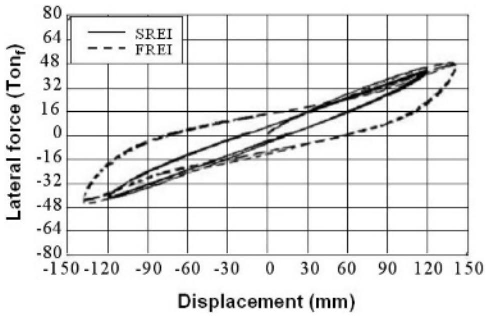
$$K_{eff} = [F_{\max} - F_{\min}]/[\Delta_{\max} - \Delta_{\min}] \tag{2}$$

$$\beta_{eq} = [EDC]/[2\pi K_{eff}(\Delta_{\max})^2] \tag{3}$$

where $\boldsymbol{F}_{\max}$ and $\boldsymbol{F}_{\min}$ are the maximal positive and negative shear forces, $\Delta_{\max}$ of the maximal positive shear displacement and $\Delta_{\min}$ of the minimum negative shear displacement, respectively.



(a) Results of vertical tests



(b) Results of horizontal tests

Fig. 5. Experimental results for mechanical properties.

The equivalent viscous damping coefficient (β_{eq}) is also calculated by measuring the energy dissipated in each cycle (*EDC*), which is the area enclosed by the hysteresis loop. The coefficient is defined as shown in Eq. (3). It is linear viscous model which assumes that the energy dissipates linearly in each cycle.

2.3 Mechanical properties of SREI and FREI

In this study, vertical and horizontal tests were performed on the test apparatus as shown in Fig. 4, which has a capacity of subjecting a set of an isolator to vertical and horizontal loadings, simultaneously. A vertical actuator of the apparatus is able to apply the

Table 1. Mechanical properties of SREI and FREI.

Type	Vertical Stiffness (kN/m)	Horizontal test		
		tan (γ)	Effective Stiffness (kN/m)	Equivalent Damping (β, %)
SREI	1,073,220	0.5	3,500	6.20
FREI	3,208,570	0.5	3,300	15.85

maximal axial loads of 30,000kN on the seismic isolator.

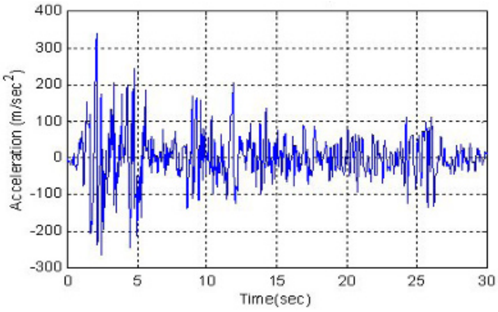
The vertical loading distributions of the SREI and the FREI are shown in Fig. 5(a), when three load cycles ranging between 1,900kN and 3,700kN were applied. The average vertical stiffness of the SREI and the FREI were investigated as 1,073,220kN/m and 3,208,570kN/mm, respectively. The hysteresis loops of the horizontal test for the SREI and the FREI are shown in Fig. 5(b). The test results, which showed the effective stiffness and the equivalent damping, were 3,500kN/m and 6.20% for the SREI, 3,300kN/m and 15.85% for the FREI, respectively. It is noticed that they have different mechanical properties, even when the same geometrically sized SREI and FREI were used in the tests. The mechanical properties of the SREI and the FREI are summarized in Table 1.

3. Modeling for dynamic response analysis

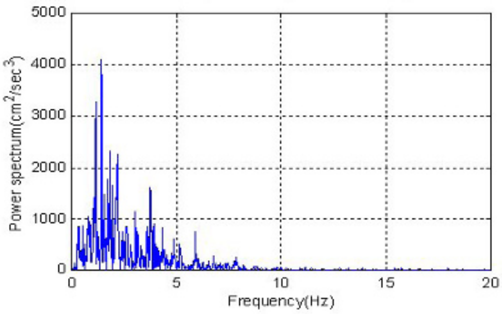
3.1 Conditions

The frames of both the beams and the columns are assumed as steel, and the thicknesses of each roof and floor are 0.15m and 0.25m in two building structural models comprising concrete slabs. In each model, a diaphragm constraint at each story is provided for rigidity. A point load of 4.5kN is loaded at each second, third and roof joint of each frame. In the numerical simulation, dead loadings on the roof and each floor are applied 3.75kN/m^2 and 6.25kN/m^2, and the living loadings on the roof and each floor are assumed to be 1kN/m^2 and 5kN/m^2, respectively.

In this study, the time history analyses of the 2- and 3-dimensional building structures were carried out for uni-directional and bi-directional ground motions by using the commercial finite element analysis software, SAP2000. As shown in Fig. 6, the ground motion used was the 1940 Imperial Valley El Centro records, and this seismic event was just recorded on the uni-directional ground motion. To carry out the time history analyses of the 3-dimensional building structure,



(a) Recorded data



(b) Power spectrum

Fig. 6. 1940 Imperial Valley El Centro ground motion record at California, USA.

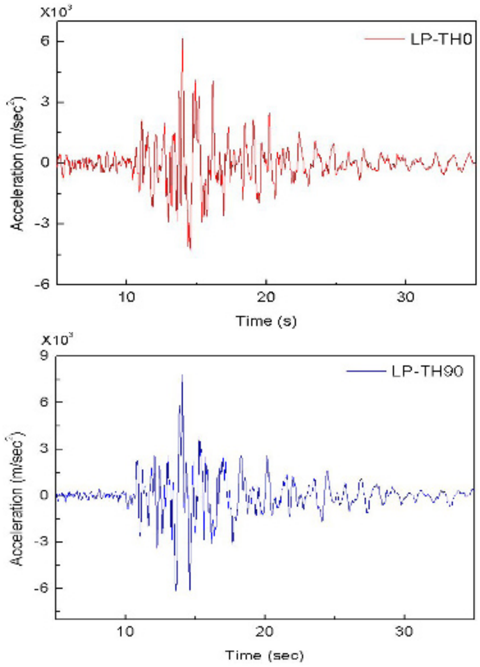


Fig. 7. 1989 Loma Prieta acceleration records at San Francisco bay area of California, USA.

the bi-directional ground motion records were needed, but because the 1940 Imperial Valley El Centro records had not included the bi-axial ground motion, the 3-dimensional building structure was assumed to be subjected to earthquake motion in two perpendicular directions such as the 1989 Loma Prieta acceleration records at San Francisco bay area of California using the representative symbols of LP-TH0 and LP-TH90 as shown in Fig. 7.

3.2 Modeling for 2-dimensional analysis

Three different structural models with three-story frames were built to investigate the effects of each isolation system such as the fixed base of Fig. 8(a), the SREI base of Fig. 8(b) and the FREI base of Fig. 8(c), respectively. In all models, the bay length of each model was 7.2m, and the height of the each story was 3.6m. The fixed base model consisted of three beams and six columns as shown in Fig. 8(a), and it was combined with four beams and six columns for the SREI and the FREI base models as shown in Fig. 8(b) and Fig. 8(c), respectively. The general mechanical properties of the SREI and the FREI were applied to the simulation models with the same geometry dimensions as shown in Table 2.

3.3 Modeling for 3-dimensional analysis

The 3-D frame structural models with the fixed base and the FREI base are shown in Fig. 9. The bay length of each model was 9m, and the height of each story was 3.6m, respectively. The base joint constrains were set to be fixed for the fixed base, and the base joints were set to have non-linear properties of the FREI characteristics for the FREI base. The time history analyses of the structures were carried out with using the bi-directional horizontal ground motions, LP-TH0 in the *x*-direction and LP-TH90 in the *y*-direction, applied simultaneously.

4. 2-Dimensional dynamic response analysis

4.1 Mode shape

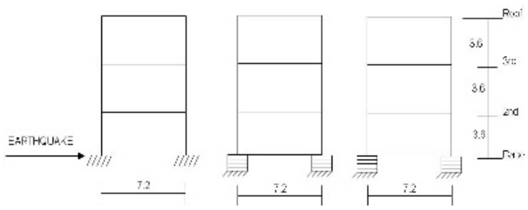
Fig. 10 shows the different mode shapes for each model such as the fixed base, the SREI and the FREI bases, respectively. The periods of the mode shape were compared with each other in Table 3, and it could be observed the isolated building's period increases noticeably, and the periods of each mode are very similar between the SREI and the FREI models.

4.2 Displacement

The relationship between the displacement and time is one of the important results in the seismic dynamic response analysis. From the analyzed results, Fig. 11 notices the distribution trends of the horizontal absolute displacement with the three models such as the fixed base, the SREI base and the FREI base, and it is found that all of the structural displacements of the fixed base model are more acute than those of other isolated models. As shown in Figs. 11 and 12, for the maximal displacements in each structural model were investigated the horizontal displacements on the roof, but the maximal displacements in the two

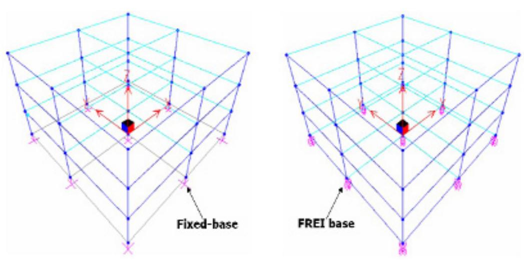
Table 2. Additional mechanical properties of SREI and FREI.

Type	Initial Shear Stiffness (kN/m)	Shear Yield Strength (kN)	Post Yield Shear Strength (kN)
SREI	15,000	150	2.1
FREI	19,000	200	1.1



(a) Fixed base (b) SREI (c) FREI

Fig. 8. 2-dimensional frame structural models with fixed, SREI and FREI base isolators.

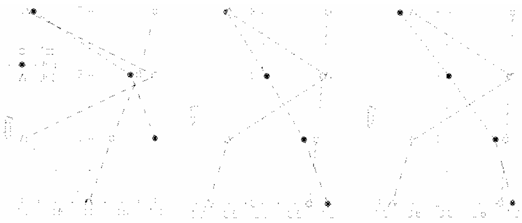


(a) Fixed base (b) FREI base

Fig. 9. 3-dimensional frame structure models with fixed and FREI bases.

Table 3. Analyzed results for mode shape.

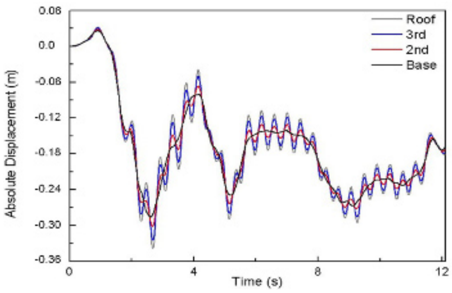
Mode	Fixed base (s)	SREI base (s)	FREI base (s)
1	0.415	1.392	1.365
2	0.133	0.302	0.226
3	0.081	0.089	0.089



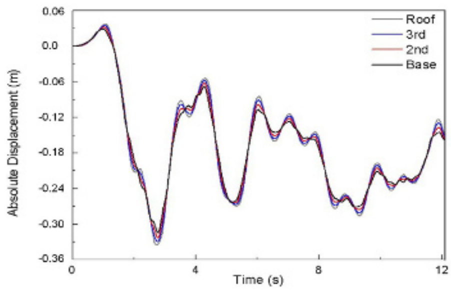
mode shape mode shape mode shape

(a) Fixed base (b) SREI base (c) FREI base

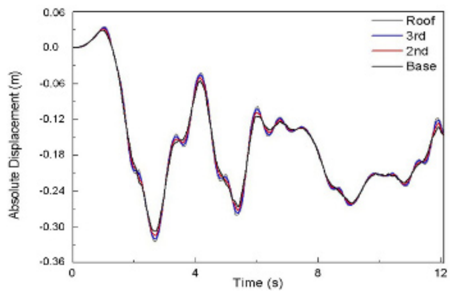
Fig. 10. Mode shapes of fixed, SREI and FREI base models.



(a) Fixed base

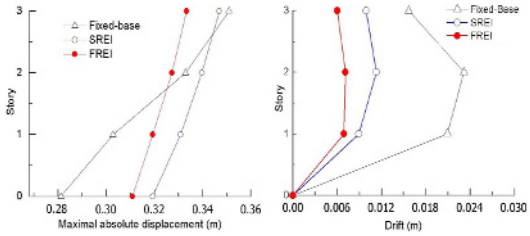


(b) SREI base



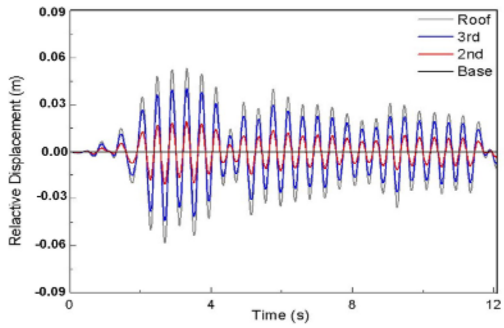
(c) FREI base

Fig. 11. Distribution of absolute displacement of each model.

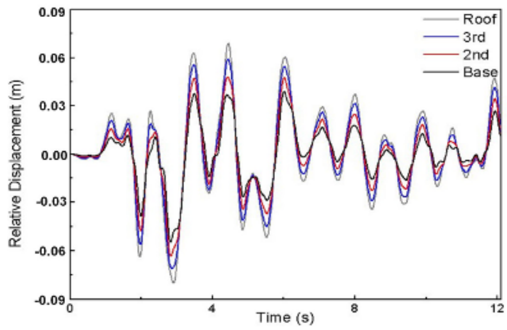


(a) absolute displacement (b) drift

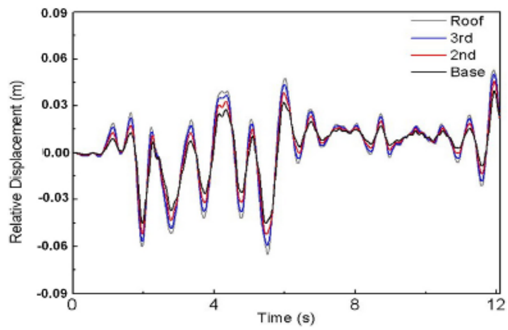
Fig. 12. Distribution of maximal absolute displacement and drift.



(a) Fixed base



(b) SREI base



(c) FREI base

Fig. 13. Distribution of relative displacement of each model.

isolated structures such as the SREI and the FREI models were measured much smaller than those of displacements in the different models compared with each story in Fig. 12(a), and it could be clearly the fixed base structure. The maximal absolute concerned that the maximal displacements of the FREI-isolated model were considerably smaller than those of the SREI model for each story. It means that the FREI is more effective than the SREI one during the ground motion in terms of reducing the displacement. Furthermore, it is observed that the drift of the FREI-isolated model was not only much smaller than that of the fixed base model, but also smaller than that of the SREI-isolated model. The inter-story drifts of each model were compared as shown in Fig. 12(b). Because the inter-story drift was calculated as the difference between each two adjacent stories, the small drift meant a small deformation of the structure. Moreover, it was ensured that the FREI could effectively decrease the building's deformation caused by the ground motion during seismic events. The relative displacements by the ground motion's time history trace of each structural model were evaluated as shown in Fig. 13. The relative displacement of the base was zero for the fixed base case, and the displacement of the building base was the same as that of the ground during the seismic excitation because the base was fixed to the ground. But, the relative displacements at the base in both SREI and the FREI isolated structural models were actually the displacements of each isolation system themselves; therefore the relative displacements were not zero. It means the relative displacements included the various distributions according to the time domain. In Fig. 14, the displacement of the isolation system in the base structure was investigated as quite large compared with the relative displacement of the other stories. It showed that most of the displacement in the structure occurred in the isolation system rather than in the stories of the isolated building. Although the displacements of the SREI and the FREI systems look similar as shown in Fig. 15, the displacement of the FREI base isolator was smaller than that for the SREI. Based on all of these results, it could be mentioned that the SREI and the FREI systems are able to effectively isolate the building structure against the seismic events. At the same time, the FREI isolator could provide better isolation performance in terms of the small displacements and deformations of the building structure than that of the SREI one.

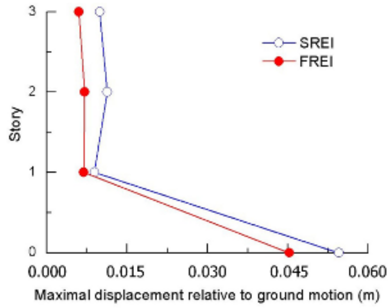


Fig. 14. Relative displacement distribution.

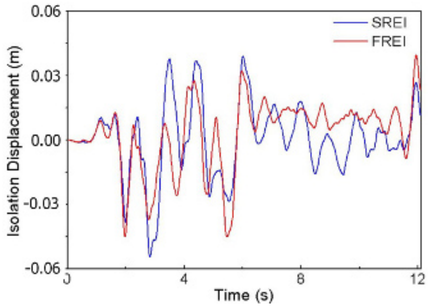
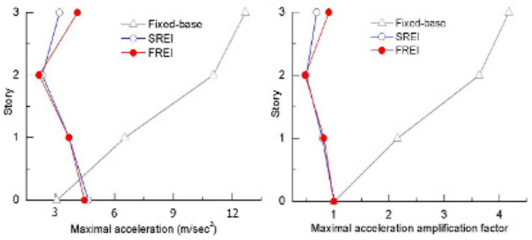


Fig. 15. Trends of distributions for displacement of isolateion systems.

4.3 Acceleration

The acceleration of each story is also one of the important parameters when the structure is influenced by seismic events. Fig. 16 shows the extracted results for the maximal accelerations in the isolated structure. But the maximal accelerations in the two isolated structures were noticed smaller than that in the fixed base structure except for the base structure itself as shown in Fig. 16(a). The acceleration amplification factors of each story in the different models are shown in Fig. 16(b). In Fig. 16(b), it could be found that all acceleration amplification factors of the stories including the roof exceeded unity in the fixed base structure, but not in the isolated structures. At the same time, it could be ensured that all other structure acceleration amplification factors of the FREI model were smaller than that of the SREI model excepting the roof. Additionally, the acceleration at the roof of the fixed base model was larger than that of the isolated models as shown in Fig. 17; this showed that the isolation systems are able to isolate the building from the seismic effects, more effectively. Fig. 18 shows the distribution of the acceleration of the different structure models where it could be clearly observed that the acceleration at each story in the fixed base



(a) maximal acceleration (b) amplification factore

Fig. 16. Distribution of maximal acceleration and amplification factor.

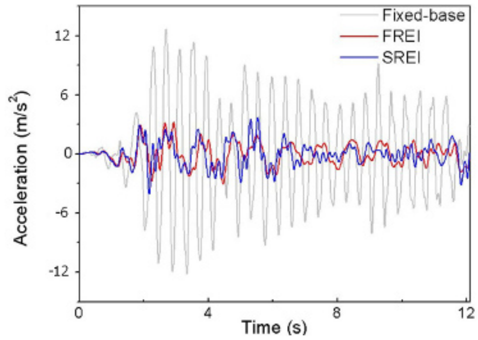
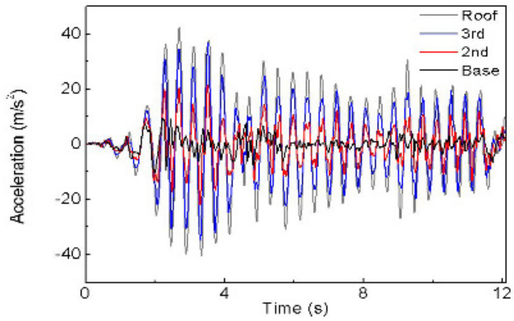
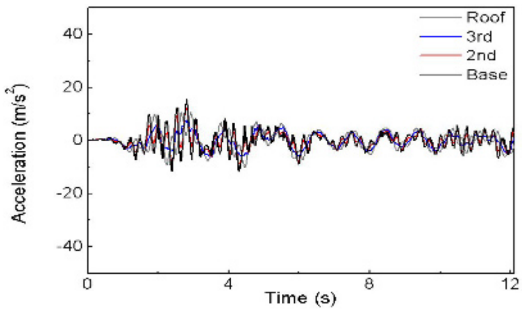


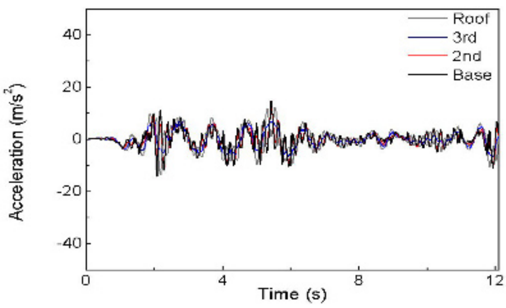
Fig. 17. Distributions of acceleration on roof of fixed, and FREI base models.



(a) Fixed base

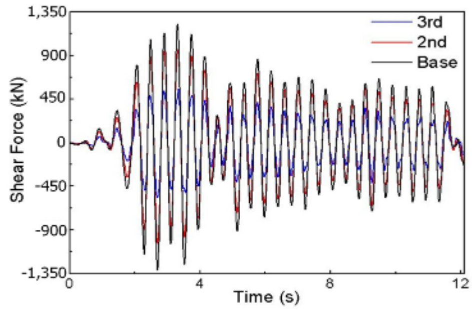


(b) SREI base

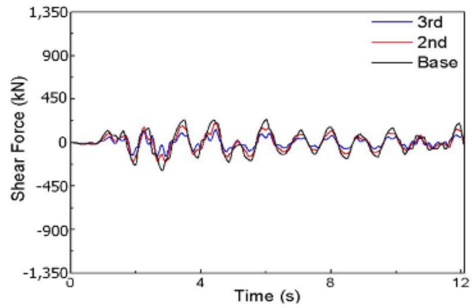


(c) FREI base

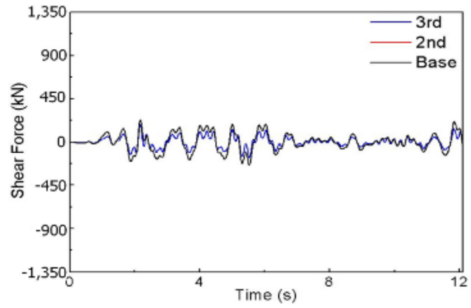
Fig. 18. Distribution of acceleration of fixed, SREI and FREI base models.



(a) Fixed base



(b) SREI base



(c) FREI base

Fig. 19. Distribution of shear force of fixed, SREI and FREI base models.

structure was amplified; in detail, the acceleration at the roof was observed to be maximized. According to the comparison with the acceleration results of the three different models, it was confirmed that the isolation systems could significantly decrease the destructive effect of an earthquake, and the isolation performance of the FREI was better than the SREI, especially at the base of the building structure.

4.4 Shear force

To obtain the shear force distribution in the structures, three inter-story columns in the building were considered. Fig. 19 shows the distributions and the trends of the shear force. These results show that the maximal shear forces in each different isolation model are extracted in the first columns above the base. As shown in Fig. 20 and Fig. 21, the maximal shear forces on each column in the isolated structures distributed far smaller than that in the fixed base structure. Although the maximal shear forces at the second and the third story in the FREI isolated model were greater than that in the SREI model, the shear force of the first column about the base in the FREI was smaller than that in the SREI model, as shown in Fig. 21. It means that the columns in the building with the FREI isolator would be experiencing smaller shear forces and destructive effects in an earthquake than the fixed base buildings. At the same time, the FREI isolator achieved better isolation performance for the building than the SREI. The results obtained from the simulation including the period, displacement, drift, acceleration and shear force, were compared among the three different isolation models with the different base restrictions. All the analyzed results showed that the isolation systems, both the SREI and the FREI, could effectively reduce the destructive effects induced in building structures by earthquakes, and the FREI showed better performance in view of the isolation behavior compared to the SREI. Because the FREI is also superior from other viewpoints such as cost and weight, and can ensure a better performance for a building, more detailed research is warranted for the FREI about general applications.

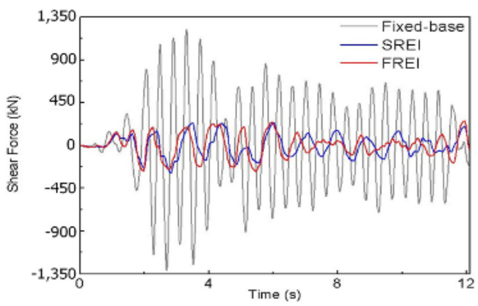


Fig. 20. Distribution of maximal shear force of each isolation model.

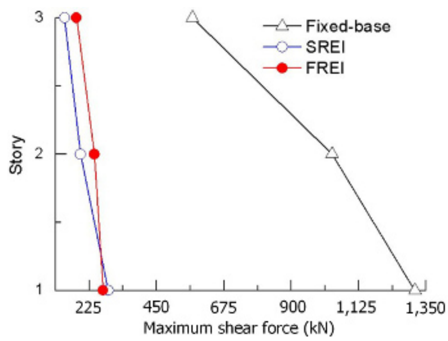


Fig. 21. Maximal shear force of each isolation model.

5. Bi-directional dynamic response analysis

In 2-dimensional dynamic response analysis, the performances of the SREI and the FREI were investigated by using the 1940 Imperial Valley El Centro seismic record at San Francisco area. This seismic event was recorded on the uni-directional ground motion. To confirm and verify the results of the dynamic response analyses of the 2-dimensional isolated building structure, 3-dimensional dynamic response analysis was adopted for the bi-directional ground motion such as the 1989 Loma Prieta acceleration seismic records at San Francisco bay area of California.

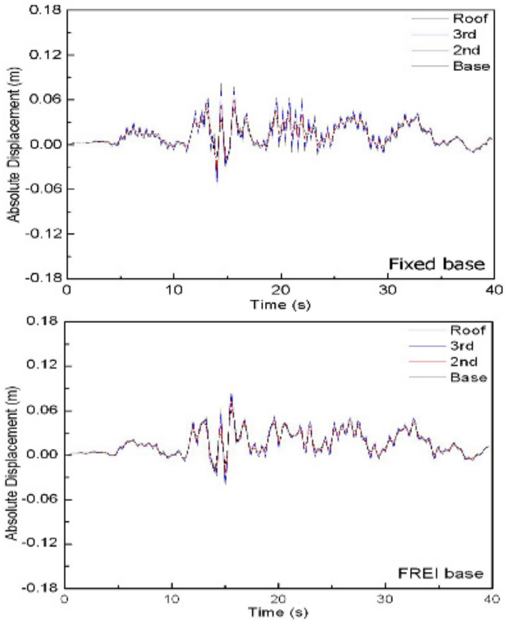
5.1 Mode shape

A dynamic response analysis was carried out to verify the validity of the FREI isolator for building structure under seismic excitation, and the typical results such as mode shape, displacement, drift, acceleration and shear force were obtained. Comparing between these results for the fixed based and the

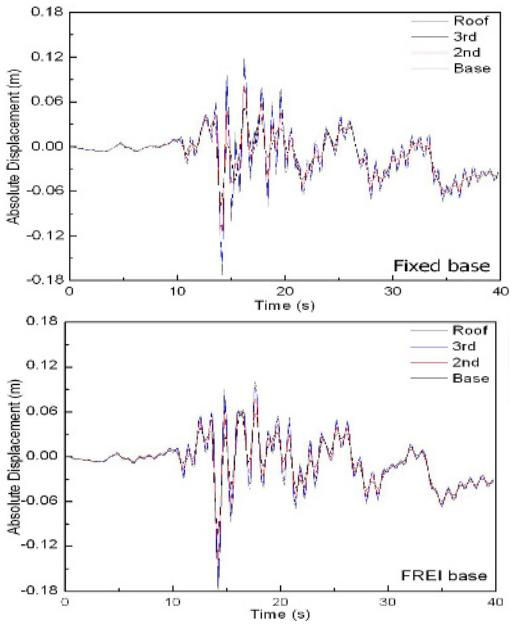
Table 4. Mode shape of 3-D structure model with fixed and FREI bases.

Mode	Fixed base (s)	FREI base (s)
1	0.415	1.365
2	0.133	0.226
3	0.081	0.089

FREI isolated structural models, it was shown the FREI isolator could reduce the influence of the seismic events on the structure, effectively. Table 4 shows the compared results for the periods of these two building structure models such as the fixed base and the FREI isolation, and it is observed the period of the FREI isolated structure increases noticeably. It means that the FREI isolation system could augment the vibration period of the building structure, and reduce the destructive effect produced by the seismic events.

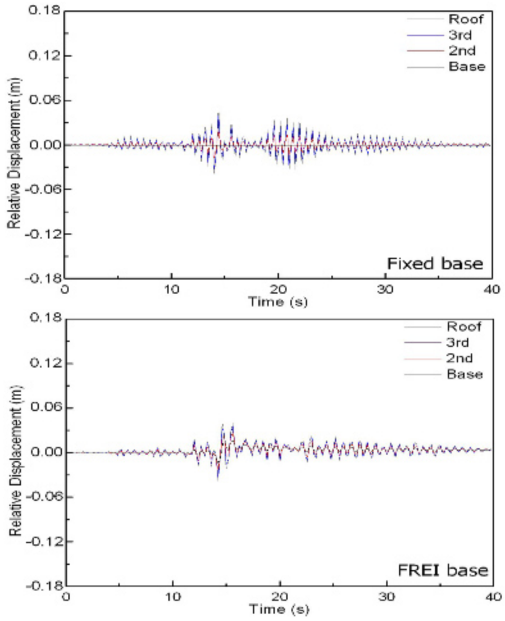


(a) x-direction (LP-TH0)

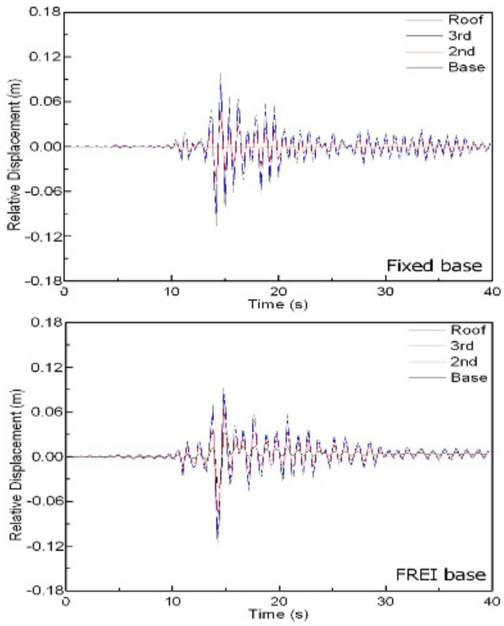


(b) y-direction (LP-TH90)

Fig. 22. Distribution of absolute displacement for fixed and FREI base models.



(a) x-direction (LP-TH0)



(b) y-direction (LP-TH90)

Fig. 23. Distribution of relative displacement for fixed and FREI base models.

5.2 Displacement

The trend of the displacement is one of the important results in the seismic dynamic response analyses. Fig. 22 shows the distribution of the absolute displacement of each story in the x and the y directions with the fixed-base and the FREI isolated models, respectively. It was found that all the superstructure displacements in the fixed base structural model fluctuate more acutely than those in the FREI isolated structural model in both x and y directions. That can be found clearly by comparing with the relative displacement of these different models in Fig. 23.

For the fixed base case, because the base was fixed to the ground, the displacement of the building base was the same as the displacement of the ground during the seismic excitation, and the relative displacement at the base was zero. However, the relative displacements at the base for the FREI isolated structural model were the actual displacements of the isolation system itself, which are not zero in the time domain. Also, as shown in Fig. 23, the maximal displacements in each structural model were those of the roof, but even the maximal displacements in the FREI isolated structures was much smaller than those for the fixed base structure as shown in Fig. 24.

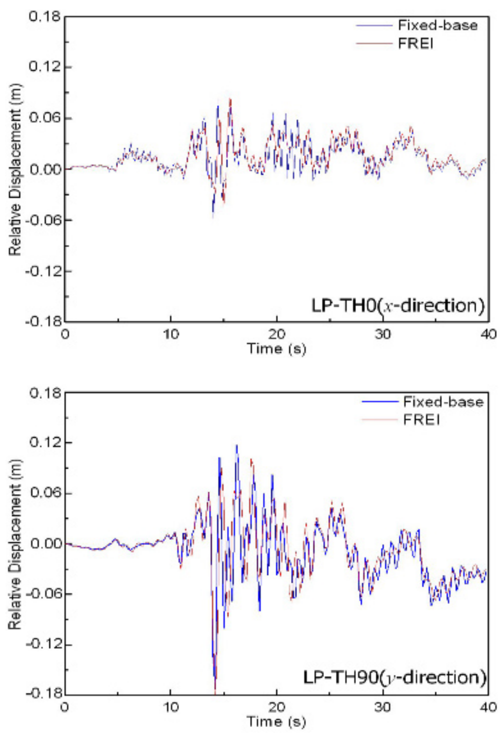
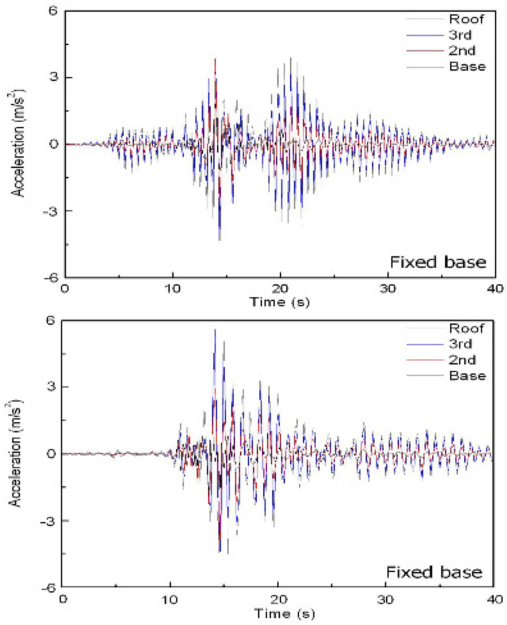


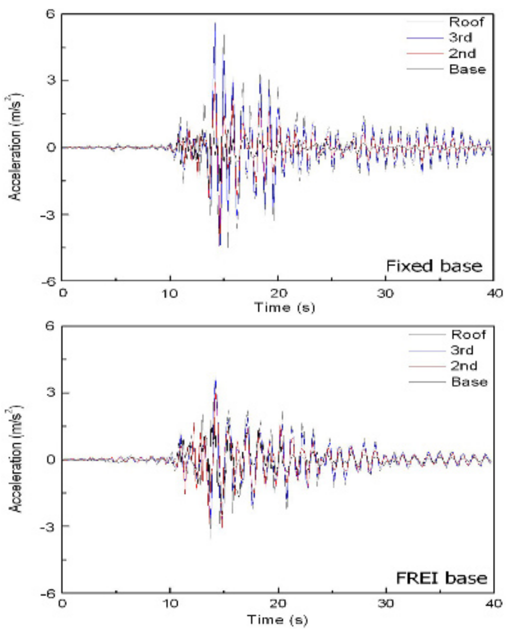
Fig. 24. Distribution of relative displacement on roof.

5.3 Acceleration

The prediction of the acceleration of each story on the structures is also one of the important issues in the structure influenced by seismic events. Fig. 25 shows the distribution of the acceleration of the different structure models in both x and y direction. It is clearly



(a) x-direction (LP-TH0)



(b) y-direction (LP-TH90)

Fig. 25. Distribution of acceleration for each model.

observed that the accelerations of the roof were the maximal accelerations in both models and directions. And the maximal accelerations in the FREI isolated structures were far smaller than in the fixed base structure. The maximal accelerations of each model are compared in Fig. 26.

5.4 Shear force

To investigate the shear force in the low-story building structure by seismic excitation, three ipsilateral inter-story columns of the 3-dimensional structure model were considered. As the simulated results, Fig. 27 shows the distribution of the shear force of these columns under the earthquake situation for each model. Furthermore, it shows that the maximal shear force was that of the first columns above the base. And the maximal shear forces in the FREI isolated structures were much smaller than those in the fixed base structure as shown in Fig. 27.

5.5 Other Results

The inter-story drifts, the maximal accelerations and the shear force of each model were compared as shown in Fig. 28. The drift of the FREI base isolation model in Fig. 28(a) was much smaller than that of the fixed one. Because the inter-story drift denotes the difference in displacement between each two adjacent stories, the small drift meant that there is a small deformation of the story structure. Also, Fig. 28(b) shows the maximal acceleration distributions of each story in the fixed base and the FREI base isolation models. Because the acceleration of the first story acceleration in the fixed base model was the same as the ground motion in an earthquake situation, whereas it was the acceleration of the isolator system of the FREI isolated model, so the latter was larger than the former. But the accelerations of other stories in the FREI isolated model were all far smaller than those in the fixed base model, as shown in Fig. 28(b). And Fig. 28(c) shows the maximal shear forces of each column during the seismic excitation in the models. The comparison with these shear forces shows that the columns in the FREI isolated model were subjected to a smaller shear force and destructive effect than the fixed one.

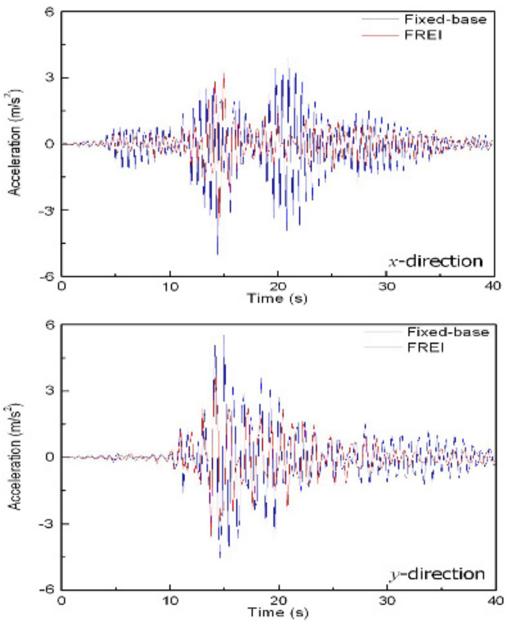


Fig. 26. Distribution of maximal acceleration for each model.

6. Results

6.1 2-dimensional dynamic response analysis

In 2-dimensional dynamic response analysis, three different framed structure models were built with the different base structures to study the characteristics of the SREI and the FREI base isolators, and a series of the simulations for the dynamic responses of these models against seismic excitations by using the 1940 Imperial Valley El Centro records. The analyzed results using numerical approach showed that the SREI and the FREI isolation systems could be active protection of the building structure against seismic excitations. It means the SREI and the FREI isolators could serve for the more good performance by a comparison with the fixed base structure. In detail, all of the analysis results reveal that the FREI isolation system could effectively reduce the destructive effects from an earthquake on the building structure. At the same time, the FREI isolator showed improved isolation behavior compared with the SREI. Therefore, the FREI isolator could be used to reduce the effects by seismic events on building structures. From the 2-dimensional dynamic response analysis, the following results were obtained.

(1) The displacements fluctuated in the fixed base structural model, acutely. However, those of the isolated structures occurred in the structure's base. Thus, the isolated building moved rigidly instead of fluctuating. In addition, all maximal displacements in the FREI isolated model were smaller than those in the

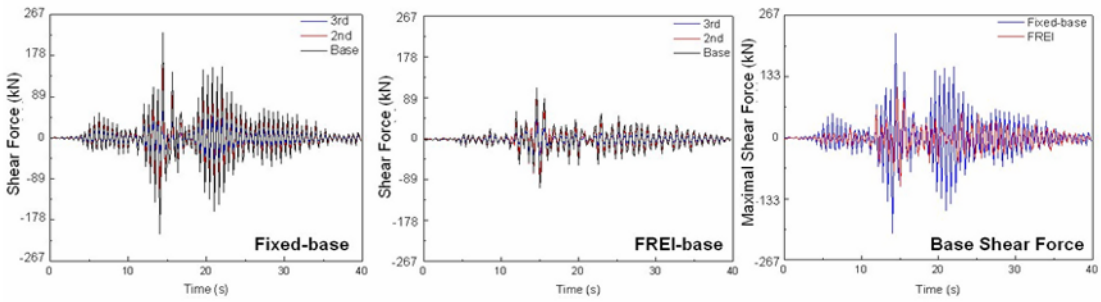


Fig. 27. Distribution of shear force for fixed base and FREI base isolators.

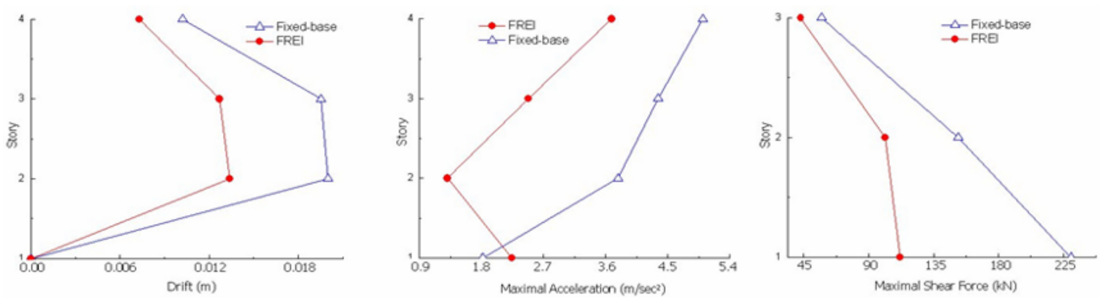


Fig. 28. Comparisons for inter-story drift, maximum acceleration and shear force of each model.

SREI model, for each story.

(2) The maximal accelerations were investigated at the base isolator acceleration. It meant the accelerations in all stories of the structure were not amplified in comparison with the fixed base structure case. In addition, the maximal accelerations of the FREI structure were smaller than that of the SREI structure.

(3) The maximal shear forces on each column were much smaller than in the fixed base structure, and the maximal shear forces in the FREI case were also smaller than those in the SREI model.

6.2 3-dimensional dynamic response analysis

From the mentioned results, it was determined that the FREI isolator has more good performance compared with the SREI. According to the results, to confirm and verify the performance of the FREI isolator in case of other seismic situation such as the 1989 Loma Prieta acceleration seismic records, a numerical comparative study was also performed. Analysis of the dynamic responses of these models under the influence of an earthquake event was carried out to extract the characteristics of the FREI model on the building with different base structures. From the analysis results, the following conclusions were obtained.

(1) The displacements in the fixed base structural model fluctuated acutely in 3-dimensional dynamic response analysis. But, the displacement of the FREI isolated structure mainly occurred in the isolation system rather than in each story. Thus, the isolated building moved rigidly instead of fluctuating. In addition, the maximal displacements in the FREI isolated model were smaller than in the fixed base model for each story. These results showed that the FREI could reduce the damage of the building structure due to the horizontal earthquake induced motions.

(2) The maximal acceleration in the FREI isolated structures was far smaller, about 45% on average than that of the fixed base structure. It means the isolator system installed in the structure's foundations could absorb the seismic energy and reduce the destructive effects of the seismic excitation to the structure.

(3) The maximal shear forces in the FREI isolated structures were much smaller about 35% than those of the fixed base one. The destructive force acting on the structure due to earthquake decreases because of the FREI isolating the superstructure from the ground motion.

7. Conclusions

The main goal of this study was to investigate the dynamic response characteristics of the isolated low-story building structures using the SREI and the FREI base isolators. In 2-D dynamic response analysis by using the seismic excitation record of the 1940 Imperial Valley El Centro records, the availability of the SREI and the FREI base isolators ensured that the SREI and the FREI were proven to give more effective isolation performances compared with the fixed base against the seismic events. Furthermore, to confirm and verify the results of the dynamic response analyses of the 2-D building structure, the 3-D dynamic response analysis was studied by using the bi-directional ground motion such as the 1989 Loma Prieta acceleration seismic records. It was shown that the FREI base isolator could absorb the seismic energy, and decrease the destructive effects acting on building structure due to ground horizontal motion caused by an earthquake, effectively. At the same time, one more important conclusion was that the FREI base isolator had obtained better isolation performance than that of the SREI.

All of these results confirmed that the FREI isolation system could effectively isolate the influence of seismic events to the building structure and reduce the destructive effect induced by an earthquake to the building structure.

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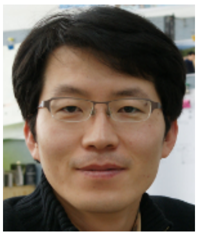

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