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Improving the seismic resilience of RC bridge piers through the use of a low-cost friction sliding system

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Abstract

Bridges play crucial roles in the recovery process after an earthquake; however, the occurrence of several destructive earthquakes around the world have exhibited serious damages to reinforced concrete (RC) bridge piers. Primary, modern seismic design codes rely on the ductility of components to reduce the design lateral forces for a reasonable construction cost, allowing the large deformations to members (i.e. RC piers) in order to dissipate seismic energy. Therefore, the engineering community confronted the need to develop more resilient systems for sustainable infrastructures. Although isolation systems have been implemented in bridges to improve the seismic resilience, they often require expensive materials. A novel alternative to improve response of bridges is promoted through the use of steel and concrete materials as a low-cost design solution. The proposed system is a spherical flat-inclined surface, fabricated from an acrylic mold created by a three dimensional (3D) printer. The fundamental behavior of the proposed system is based on the energy dissipation by the friction generated during the sliding and the restoring force is attributed to the inclination of the sphere. Bi-directional shaking table tests are conducted to evaluate the seismic response in the longitudinal and transverse directions of a one-span bridge model. The experimental results demonstrated a reduction in shear forces transmitted to the bottom of RC piers with the small residual displacements. Compared to the non-linear response of traditional RC piers due to the formation of plastic hinges, proposed low-cost system can ensure the seismic resilience of bridges with a flat-inclined surface.

Keywords: friction sliding system; seismic resilience; shaking table test; low-cost design; 3D-printer.

1. Introduction

Over the last decades, serious damages caused by various destructive earthquakes have demanded revisions in the seismic design methodology to improve seismic resilience of RC structures. For instance, spherical concave shapes of commercial friction pendulum bearings (FPBs) have been applied to mitigate damages [1]. The curvature of the surface is fundamental to limiting residual displacement. Since the low friction coefficient allow systems to implement large radius of curvature, the natural period of the system is longer than the predominant period of seismic ground motions. The multiple surfaces [2] and variable surfaces [3, 4] of FPBs have been proposed to enhance the displacement response. Although extensive research and development on the applicability of FPBs have been made, they often require expensive materials. A novel pendulum system that introduced the use of conventional concrete and steel to isolate bridges was originally proposed in [5]. The uni-directional shaking table test demonstrated superior seismic performance compared to a traditional fixed-base design. However, it is necessary to confirm whether the higher friction coefficient found between steel and concrete can compromise the re-centering capability of the original system subjected to a bi-directional excitation. The higher friction coefficient requires enough restoring force that can be achieved with a short radius of curvature, but not effective in reducing response accelerations.

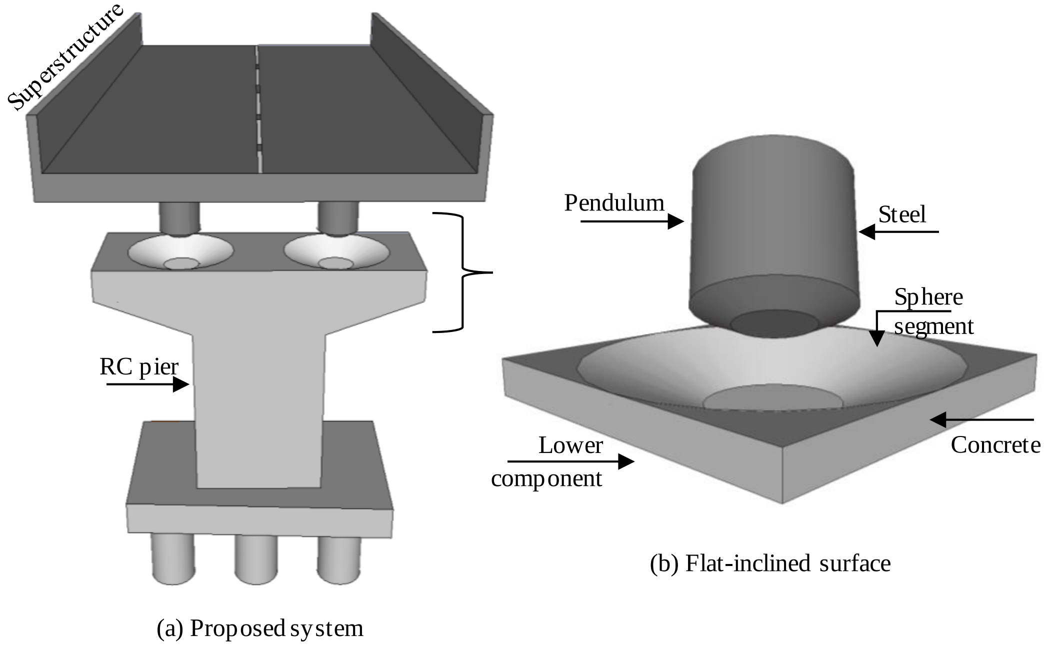


Fig. 1 – Proposed RC bridge pier with a spherical flat-inclined surface

A new shape as shown in Fig. 1 is developed taking into consideration the behavior subjected to bi-directional excitations. A combination between a flat surface with an inclined sphere segment, as shown in Fig. 1b, is proposed to improve the original system [5]. For instance, a flat friction sliding system has been recognized to dissipate large seismic energy due to the perfect plastic behavior that can introduce the stable hysteretic behavior, and the inclination of the sphere can provide a restoring force returning the system toward the initial location. Through the combination of a flat-inclined surface, the response acceleration and residual displacement can be reduced significantly, which are two main parameters to improve seismic resilience of bridges. In addition, the axial load during excitation is expected to remain more constant compared to the response using concave shapes.

Recently, some new systems have been proposed with flat-inclined shapes taking into conisderation uni-directional excitation [6]; however, there are no reports on their bi-directional behavior. The proposed spherical flat-inclined system shown in Fig. 1 is develop hereafter to improve seismic response subjected to bi-directional excitation. The hysteretic model as shown in Fig. 2a can be constructed based on a simplified uni-directional motion. The important parameters to construct the hysteresis response include the equivalent friction coefficient (μ), axial load (W), angle of inclination (θ) and total sliding (d) on the flat surface, as shown in Fig. 2b. The zero sliding displacement occurs at the instant when the external force is lower than the static shear force $F_s = \mu_s W$. Beyond this point, the superstructure initiate sliding and the system has a constant response of the frictional force $F_f = \mu(v)W$, where the friction coefficient under dynamic motions is a function of the sliding velocity [7]. The inclined surface provides a restoring force $F_r = N\sin\theta$ that contributes to restoring the system to the initial location, where N is the horizontal component of W. The total transmitted shear force is the sum of the frictional and restoring forces, F_f and F_r, respectively, as expressed by Eq. 1.

$$F = F_f + F_r \tag{1}$$

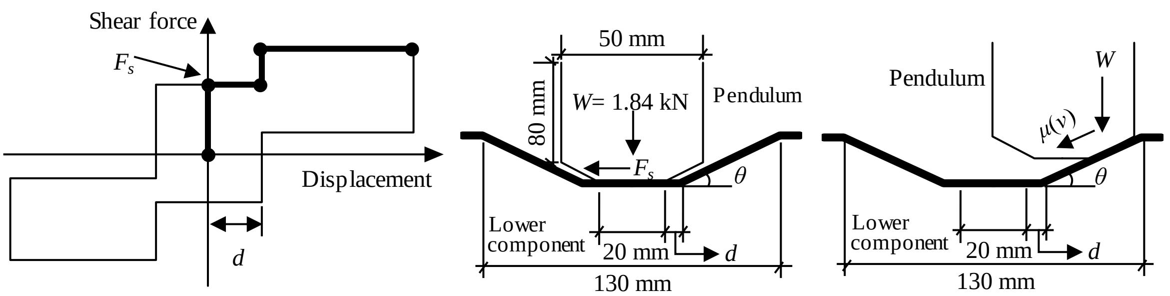
Subjected to a bi-directional excitation, commercial FPBs have been observed to exhibit certain increase of displacement with desintegration of the frictional force due to the two orthogonal components [7].

Therefore, the frictional force F_f of proposed system is decomposed into two shear forces as a function of the magnitude of the instantaneous velocity ($\bar{v}$) as provided by Eq. 2 [7].

$$F_f = \frac{\pm \mu W}{\bar{v}} \begin{bmatrix} v_x \\ v_y \end{bmatrix} \tag{2}$$

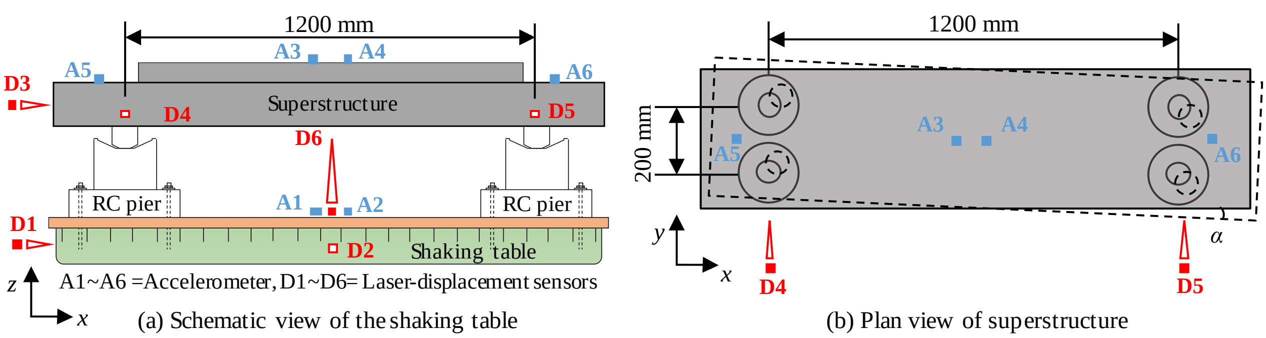
where v_x and v_y are the sliding velocities in the longitudinal (x) and transverse (y) directions, respectively.

With the use of a 3D printer, the proposed geometry can be easily fabricated using conventional concrete which is more cost-effective solution than the sophisticated materials used in commercial FPBs. However, considerations are needed in designing the RC pier due to the higher friction coefficient of concrete surfaces, which could cause the system to behave as a fixed-base structure during low intensity of earthquakes. Compared to a FPB that is activated even under very low intensity of earthquake, the proposed flat-inclined surface aims to improve response of bridges with sliding on the flat surface subjected to intermediate intensity of earthquakes. During earthquake excitation with a high intensity, the sliding movement reaches the inclined surface developing the restoring force F_r = $N\sin\theta$. The bi-directional excitation inflicts disintegration of F_f as expressed in Eq. 2. Additionally, the proposed system needs to have a larger inclination θ to produce a restoring force that is greater than the frictional force to return the upper component to the flat surface. The effect of θ on the seismic response is investigated experimentally to find the appropriate inclination for ensuring the seismic resilience of RC bridge piers.



(a) Hysteretic behavior (b) Specimens characteristics (c) Sliding movement

Fig. 2 – Hysteretic behavior and characteristics of specimen



(a) Schematic view of the shaking table (b) Plan view of superstructure

Fig. 3 – Characteristics of the bridge model

2. Experimental program

The pendulum was made of steel and the lower concrete component was fabricated with an acrylic mold created by a 3D printer. The size characteristics of the test described in Figs. 2b and 3, are based on the scale factors determined in [5]. Five values of θ were evaluated as θ = 25°, 18°, 11°, 7°, and 4°. The distance d for all specimens was set to 10 mm. One-span bride model composed of four RC piers with distances of 1200 mm and 200mm in the x- and y-directions, respectively, was set on the shaking table. The superstructure is a rigid steel plate of a total weight W = 7.36 kN. A schematic view of the test set-up is shown in Fig. 3a. The flat surface with a contact diameter of 20 mm, as shown in Fig. 2b, can transmit low axial pressure, which is vital to prevent local deformation on concrete surface that possess lower stiffness than advanced materials used in the commercial sliding systems. In addition, a thin layer of epoxy based on resin material was attached to the concrete surface to improve the abrasion resistant.

The dynamic experiments were conducted using five sets of four specimens named as F-25, F-18, F-11, F-7, and F-4. The bi-directional components of the Noto ground motion recorded in Japan during Noto-Hanto earthquake in 2007 was used. Accelerations and displacements were measured using accelerometers and laser-displacement sensors, respectively, as shown in Fig. 3a. The shear forces are calculated as the mass of the superstructure multiplied by the accelerations in x- and y-directions. The shear forces in the x- and y-directions are hereafter referred to as F_x and F_y, respectively. δ_x and δ_y are the sliding displacements in the x- and y-directions, respectively.

3. Experimental results

3.1 Hysteresis response

The shear force-displacement curves are plotted in Fig. 4. The flat surface is highlighted at the center of each curve. As shown in Figs. 4a and 4c, the x-direction shows more stable hysteresis curve compared to the y-direction mainly due to the size characteristics of the bridge model with a small aspect ratio of 0.17 (200/1200). Large shear forces are observed using specimens F-25 and F-18, as shown in Fig. 4a. The large shear forces are attributed to the large inclinations that increase the shear forces at the distance d = 10 mm, which is the distance where the pendulum reached the inclined surface. The shear forces at the distance d slightly exhibits a smoother decrease for specimen F-11 with lower shear forces than those exhibited by specimens F-25 and F-18.

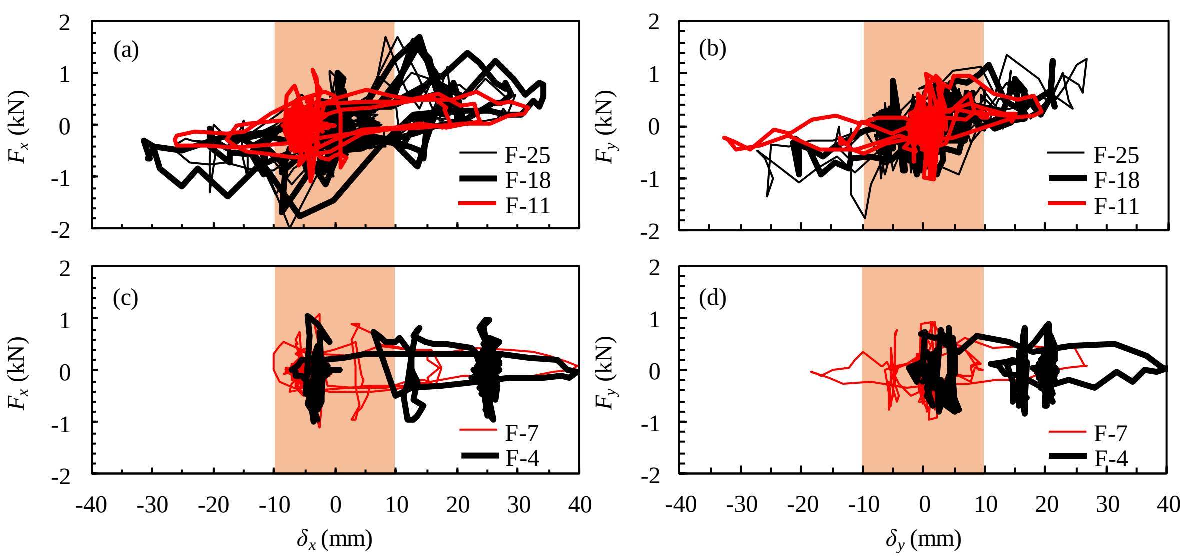


Fig. 4 – Hysteretic behavior

On the other hand, specimens F-7 and F-4 show smaller shear forces at large sliding displacements as shown in Figs. 4c and 4d through the *x*- and *y*-directions, respectively. However, the responses of specimens F-7 and F-4 show an asymmetric hysteresis curves with small displacements on the negative side. The experimental results confirm that a simplified uni-directional behavior as represented in Fig. 2a can overestimate shear forces since the hysteretic behavior shown in Fig. 4 exhibits a descending shear force with the increase of sliding displacements. This is consistent with previoud experimental results observed in FPBs subjected to a bi-directional excitation [7] that exhibits lower shear forces compared to a uni-directional excitation due to the disintegrations into two components of the frictional force along a circular sliding motion.

3.2 Displacement orbit

The bi-directional effect can be clarified with the sliding displacement orbits, as shown in Fig. 5. The displacements in *x*- and *y*- directions are plotted to follow the sliding paths developed during the excitation. The flat surface with the diameter of d = 10 mm is highlighted at the center of each orbit. As shown in Figs. 5a and 5b, after the sliding displacement is larger than d, the system moves on the inclined surface developing a circular path for specimens F-18 and F-11, respectively. Although the circular path is not completed for specimen F-7 as shown in Fig. 5c, the bi-directional excitation of proposed system tends to develop a circular motion which differ significantly from a simplified uni-directional motion as discussed in Section 3.1. In addition, it is important to consider that with a small inclination the sliding path considerably changes as observed for specimen F-4. As a result, due to the low restoring force, the sliding path of specimen F-4 develops only half circle as shown in Fig 5d, leading to a large residual displacement at the end of excitation.

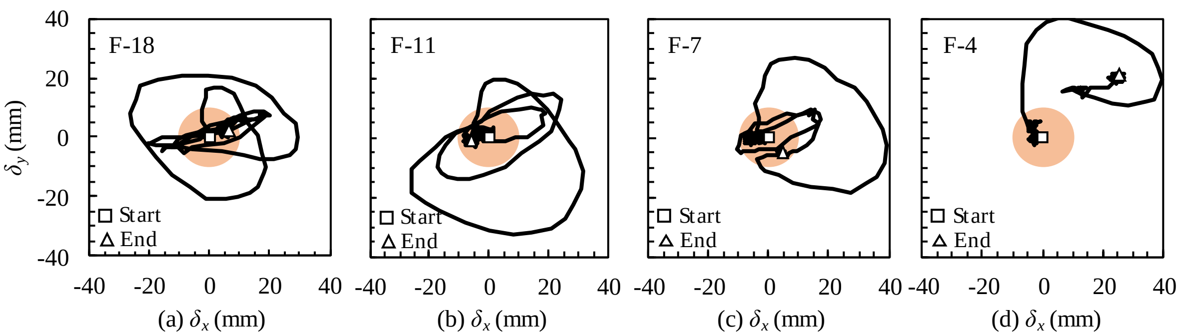


Fig. 5 – Sliding path

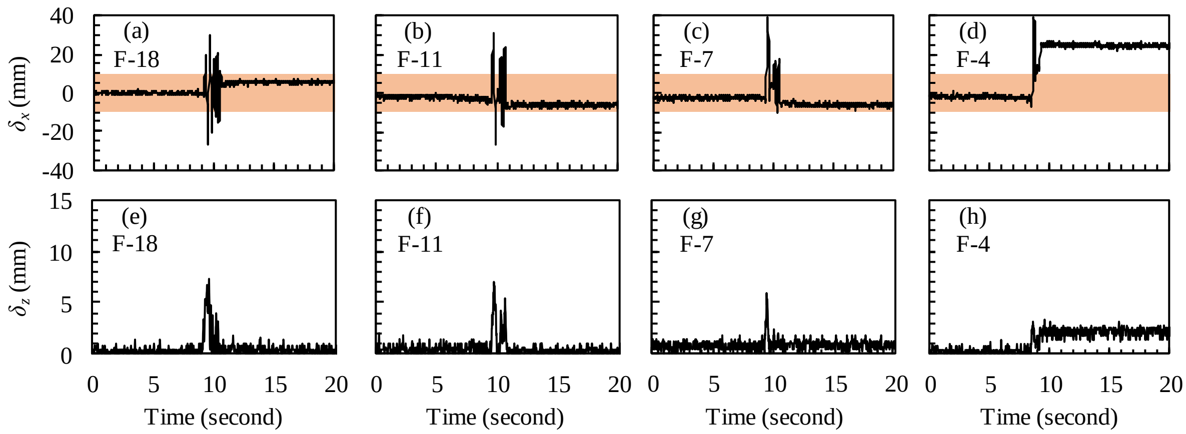


Fig. 6 – Time history displacements of δ_x and δ_z

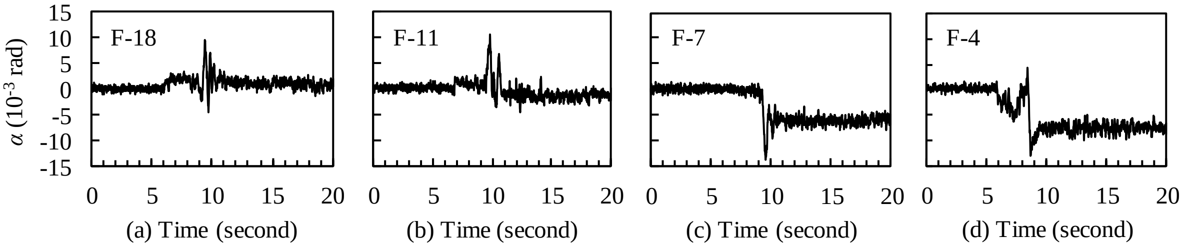


Fig. 7 – Time history response of α

3.3 Displacement responses of the horizontal and vertical directions

The time history displacements in the longitudinal x- and the vertical z-directions are shown in Fig. 6. For instance, specimen F-18 shown in Fig. 6a slides in the x-direction nearly to 30 mm, which further increases to 40 mm for specimens F-7 and F-4 as shown in Figs. 6c and 6d, respectively. For specimens with inclination equal or larger than 7° (i.e., F-18, F-11 and F-7), the system returns to the flat surface at the end of excitation. Large θ possesses sufficient restoring force F_r that contributes to returning the system to the flat surface at the end of excitations; however, specimen F-4 exhibits deviation from the baseline at 9 seconds as shown in Fig. 6d. Beyond this point, the time history shows that the offset remains until the end of excitation dealing with a residual displacement of 26 mm, which is located outside of the flat surface highlighted at the center. Hence, the contributions of the restoring force is effective with the inclination angle equal or larger than 7°, while for the lower inclination of 4° the larger residual displacement occurs, indicating that the seismic resilience of bridges is not adequately ensured for specimen F-4.

Since the large friction coefficient of concrete surfaces requires to use large inclination, the sliding on the inclined part could cause a large vertical displacement (δ_z) provoking a significant difference between the superstructure and the approach slab, which is important in design, particularly for detailing of the bridge expansion joint. The time history response of δ_z is evaluated trough Figs. 6e to 6h. As shown in Figs. 6e and 6f, specimens F-18 and F-11 exhibit large δ_z which is close to 7 mm for both cases. Although large inclination causes increase of δ_z during excitation, δ_z becomes zero at the end of motion since the system returns to the flat surface due to the large restoring force. On the other hand, lower inclination of specimen F-4 shows very small δ_z during excitation; however, the low restoring force of F-4 causes the system to stop on the inclined surface dealing with a vertical residual displacement as shown in Fig. 6h. The large residual vertical displacement can introduce an irregularity in height between the superstructure and the slab approach. Therefore, in terms of shear force and residual displacement, specimens F-11 and F-7 exhibited better behaviors as observed through Figs. 4 to 6.

3.4 Rotation of superstructure

Flat sliding system often causes the large residual displacement at the end of excitation. In this proposed system, although the residual displacement is minimized with the use of an inclined surface, the flat surface can cause rotation (α) of the superstructure during excitation as described in Fig. 3b. Due to the bi-directional motion, α during excitation could cause variations between the sliding displacements on the left and right sides of the bridge, where α is calculated as $\tan^{-1}$ of the ratio between the relative transverse displacement measured as D4–D5 to 1200 mm as shown in Fig. 3b.

From the time history response, α is observed to be nearly 10×10^{-3} rad for specimens F-18 and F-11, as shown in Figs. 7a and 7b, respectively. Whereas for specimens F-7 and F-4, α increases considerably to 15×10^{-3} rad as confirmed in Figs. 7c and 7d, respectively. Specimen F-4 exhibits various fluctuations of α during the course of motion as shown in Fig. 7d. The larger α is observed at 9 seconds after which α decreased to 10×10^{-3} rad; however it does not return near to zero. It is evident that a low inclination of specimens may exhibit small δ_z at the expenses of a large α at the end of excitations. The shaking table test results demonstrated that although δ_z is larger during excitations for specimens F-18 and F-11, the sliding displacement exhibited a circular path, minimizing rotation of the superstructure at the end of excitations. Moreover, specimen F-11 demonstrated better reduction in shear forces compared to specimen F-18.

Finally, the shear forces and residual displacements can be reduced using the proposed low-cost system to ensure the seismic resilience of RC bridge piers. The plastic deformations traditionally accepted in the capacity design methodology [8] can be eradicated through the friction energy dissipation of the flat-inclined surface.

4. Conclusions

A novel low-cost friction sliding system has been developed using concrete and steel materials to improve the seismic resilience of bridges. The bi-directional excitation test was performed to demonstrate the effectiveness of the system with different inclinations. The most important conclusions are as follow.

1. An RC bridge pier provided with a spherical flat-inclined surfaces can improve seismic response due to the sliding between concrete and steel surfaces, dissipating seismic energy through friction. The system depends essentially on its geometry to reduce the shear forces and the residual displacements.
2. Large inclination of 25° transmitted the larger shear force and the low inclination of 4° leads to large horizontal and vertical residual displacements. Specimens with an intermediate inclination of 11° exhibited good hysteresis response with a stable system at the end of excitations.
3. The system with the inclinations of 25° and 18° exhibited large shear forces at the boundary between the flat surface and the inclined part. In addition, the experimental results demonstrated that the hysteretic behaviors subjected to a bi-directional excitation may be different from those subjected to a uni-directional motion. The bi-directional excitation induced a large circular motion for specimen with the inclination of 11°.

5. Acknowledgements

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6. References

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