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Self-Centering Prestressed Concrete Pier Considering the Effect of Vertical Earthquake Motions with External Aluminum Dissipators

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Abstract: A prototype self-centering prestressed concrete (SCPC) bridge pier and conventional reinforced concrete (RC) pier with similar backbone curves are designed and modeled. The objective of this study is to investigate the seismic performance of the SCPC bridge pier considering the effect of vertical earthquake ground motions. Under a severe vertical earthquake motion, the RC pier damage is much greater than the SCPC pier. The SCPC bridge pier shows a great capability in reducing residual drift at the top of the structure, therefore, the probability of bridge survival is increased. In this study, the external aluminum bars were used to reduce the seismic energy impacts on the bridge pier structure. In addition, the averages of the maximum and residual drifts of bridge piers under a set of 20 earthquake ground motion records impact with different vertical-to-horizontal peak acceleration ratios on the bridge seismic response are presented. The results are compared with the case of horizontal-only excitations, to clarify the effect of the vertical earthquake on the SCPC and RC bridge pier. Hence, the designers can find good solutions for structures in earthquakes resistance.

Keywords: Self-centering, reinforced concrete, external dissipator, maximum drift, residual drift

1. Introduction

With a significant number of bridges are located in highly seismic regions, several studies have been under investigation recently with the goal of mitigating the effects of earthquakes. One strategy is to design bridge pier technology with self-centering behavior induced by unbounded post-tensioned. The SCPC bridge pier systems are designed to create a gap opening at the bottom of the piers to respond to the lateral force-drift during severe earthquakes without developing inelastic deformations and large residual displacements. Therefore, these bridge systems have been effectively used in reducing seismic damage under unidirectional earthquakes. However, the performance of the SCPC bridge pier system is not fully analyzed under the effect of vertical earthquake ground motion components. In the present study, the models of SCPC and RC bridge piers were used, have been investigated and developed by Guo et al. (2015), then simulated by Zhiliang Cao et al. (2016). Numerical analyses have been carried out to investigate the seismic behavior of the SCPC bridge piers under the effect of the vertical earthquake ground motions. In order to do that, the Opensees software has built two models of bridge piers with sufficient characteristics of two kinds of piers which are the RC pier

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and SCPC pier. Subsequently, the effect of the vertical earthquake ground motion files has been applied to the models and results will be investigated to assess the seismic behavior of the SCPC and RC pier. This study clarifies the effectiveness of the SCPC system during severe vertical directional earthquakes effect and compares it with the bridge structures using conventional RC systems.

2. Analytical model

2.1 Self-Centering Prestressed Concrete Bridge Pier Validation

To validate the self-centering bridge pier model, in the previous study, Zhiliang Cao et al (2016) experimented to consider the behavior of the SCPC and RC bridge pier specimens under cyclic loading. The 15 experiments were executed to study how the various parameters affect the specimen's response. The authors observed the crushing of the RC bridge pier specimens at the bottom. And the fracture of the SCPC bridge pier occurs in the external aluminum bars where they can replace after the earthquakes. The self-centering capability of the SCPC bridge pier specimens is clearly shown when the maximum residual drifts after tests are 2.5% for the RC bridge pier specimens and 0.21% for the SCPC bridge pier specimens.

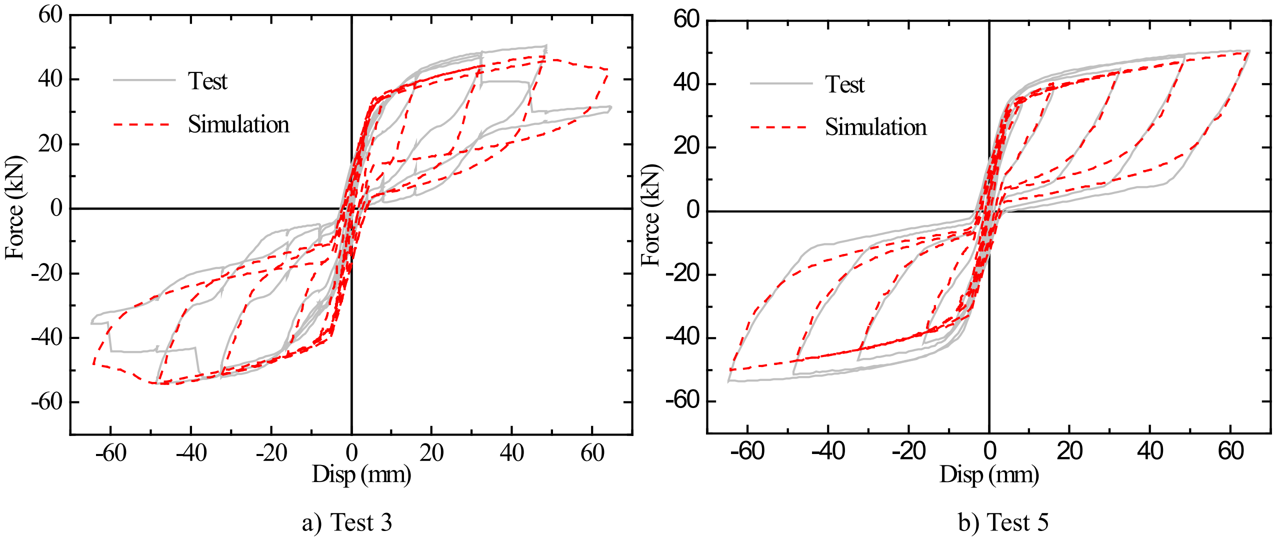


Fig. 1 - Comparison between test results and numerical simulation

The comparison between test results and numerical simulation is shown in fig 1, from this figure, a good agreement is reported. Therefore, the model of the SCPC bridge pier is simulated in this study has high practical value. And the model can simulate the behavior of the bridge piers under the effect of the severe earthquake ground motions.

2.2 Prototype Bridge Pier

A conventional reinforced concrete bridge pier and a self-centering prestressed concrete pier prototype are simulated by Zhiliang Cao model (fig. 2 and 3) [2], which experiences severe vertical earthquake motions in this study. To highlight the performance of the SCPC bridge pier under this kind of earthquake.

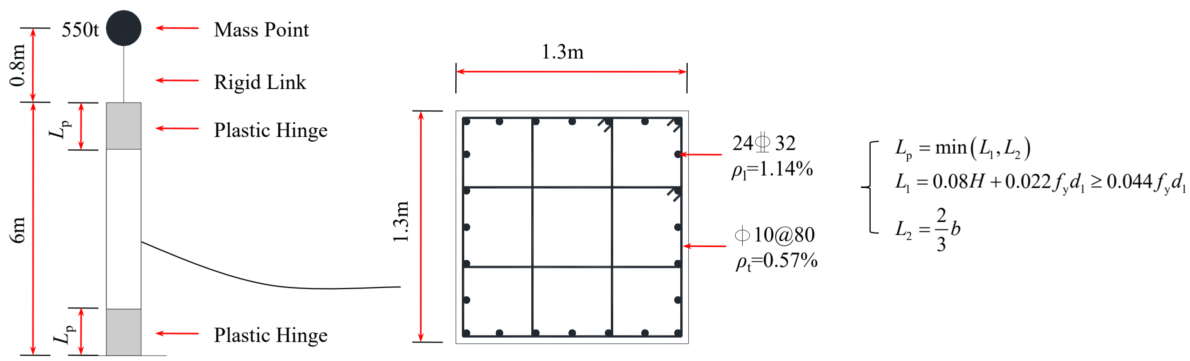


Fig. 2 - The conventional prototype bridge pier

A prototype RC pier that is designed (fig. 2) with 6 meters is the height of the RC pier (H). In this analysis, only the single bridge pier is calculated and analyzed, to execute the accuracy analysis of the RC pier performance under the earthquake motions, the self-weight of the superstructure (P = 550t) is included in the model [2]. The RC pier in this study is designed with the axial compression ratio N = 10%. The pier section (Ag) is a square with an edge of 1.3m (b). the longitudinal reinforcement bars in the pier are 24 with 32mm in diameter (d1) of the bar and distributed as fig. 2. Besides, the transverse reinforcement bars are steel bars with 10mm diameter and 80mm spacing along the pier [2]. The cover concrete is 40mm, the reinforcement bars ratios are 1.14% and 0,57% with longitudinal and transverse bars and yield strengths are 400 and 335 Mpa, respectively [2]. The plastic hinges of the pier are described in fig. 2, following Scott and Fenves (2006) the length of the plastic hinge (L) according to the formula (fig. 2).

The RC bridge pier is placed on good quality soil to ensure the impacts of earthquake ground motions are accurately reflected and sufficient on the RC pier. The concrete material is looked up from ACI 318-14 “building code requirements for structural concrete”, design and durability requirement for concrete. The concrete material is detailed performed in the model to execute the analysis behavior of the pier under the effect of earthquake ground motion files.

Table 1 - Presents the primary parameter of the core concrete material

Parameter	Concrete compressive strength at 28 days (N/m²)	Concrete strain at maximum strength	Concrete crushing strength (N/ m²)	Concrete strain at crushing strength	Tensile strength (N/ m²)
Parameter value	-28.4e6	-0.003	-5.68e6	-0.009	3.35e6

Following Chang and Mander (1994) model, under the impact of external force, the longitudinal reinforcement bars go through three different working states: elastic branch, yield branch, and strain hardening branch. From these states, the longitudinal reinforcement bar parameters are carried out to use in the software.

Table 2 - Presents the detailed parameter values of the longitudinal reinforcement steel bars

Parameter	Yield stress in tension (N/m²)	Ultimate stress in tension (N/m²)	Initial elastic tangent (N/m²)	The tangent at initial strain hardening (N/m²)	Strain corresponding to initial strain hardening	Strain at peak stress
Parameter value	400e6	592e6	2.01e11	0.615e10	0.0156	0.078

The SCPC pier will be simulated to have a similar backbone to the RC pier, to assess the potential capability of this system in earthquake resistance (Fig. 3).

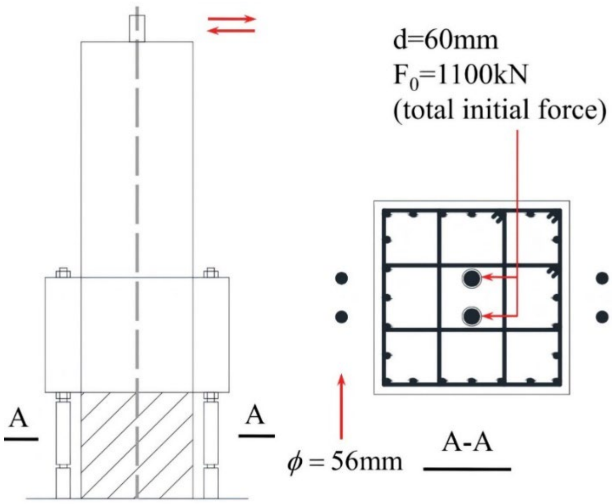


Fig. 3 - The SCPC design

2.3 The External Energy Dissipators System for SCPC Bridge Pier

In this study, the energy dissipators (EDs) aluminum bars will be changed, there are two bars on the west and east sides of the column respectively, to dissipate the seismic energy input in the transversal direction, and each bar is 0.25m away from the column edge, instead of four bars in the previous study. This change of the SCPC model will reduce the capability of the pier in energy dissipators. Therefore, the effect of vertical earthquake motions on structure will be clarified. The EDs bars are in a difficult situation to reduce earthquake energy under the vertical earthquake motions. These results are shown in fig. 6, which reports the effect of the vertical component on the SCPC system. In the model, the corbel is simulated with the 500mm height and the sufficient strength capability to anchor the EDs under the effect of earthquake ground motions without corbel damage. The bottom anchorage of the EDs is connected with the threaded rod embedded in the foundation. The alloy aluminum bars were used to be energy dissipator bars in this study. the aluminum bars have a diameter is 100mm for each bar and 56mm for the reduction diameter segments with 800mm of the length. The diameter reduction of the aluminum bars leads to plastic deformation concentrates, the maximum strain value of this segment is 15%.

Table 3 - Presents the detailed parameter values of the EDs aluminum bars

Parameter	Yield strength (N/m²)	Initial elastic tangent (N/m²)	Yield offset	The parameter to control the transition elastic to plastic	The limited value of strain
Value of parameter	130e6	6.62e10	0.004	6.8	0.15

2.4 The Unbounded Post-Tensioned Tendons for SCPC Bridge Pier

To mitigate the earthquake damage on the bridge piers, the SCPC system is used with the self-centering capability that leads to the reduction of the residual deformation in the pier. Under the impact of seismic force, the pier undergoes two-stage; first, when the earthquake intension is smaller than a certain level, the behavior of the SCPC pier is similar to the RC pier. The second stage happens when the seismic amplitude is large enough, the gap at the bottom opens due to the pier rotates, in this case, the tendons in the pier elongates and pull the pier returns to the original position after the earthquake [40]. This study uses the unbounded post-tensioned tendons for maintaining the self-centering capability of the pier. The length of the tendon element between two anchorages is 7,5m with 60mm of diameter. The slip between tendons and the pier at the top of the pier should be considered and prevented.

Table 4 - Presents the detailed parameter values of the unbounded post-tensioned tendons

Parameters	Tangent (N/m²)	Strain at the material reaches the plastic state in tension	Strain at the material reaches the plastic state in compression	The initial strain	The limited value of strain	The cross-sectional area of the element (m²)
Parameter values	4.4e10	0.05	- 0.05	-0.00452	0.0245	2.83e-3

3. Earthquake Ground Motions

To consider the response of bridge piers under different earthquakes, that occur in the world, there are 20 ground motion earthquake records which are selected from the ngawest2.berkeley.edu website. The impact of these different 20 earthquake records with different characteristics will report meaningful results to conclude the behavior of the bridge piers and show the dangers of the vertical ground motion earthquakes to structures. This kind of earthquake needs to be considered and calculated carefully for structures, especially the regions with a high occurred probability of strong earthquakes.

Table 5 presents the 20 ground motion earthquakes records characteristics, the characteristics for earthquake selection were as follow:

(1) The magnitude of the earthquake: $6.5 \leq Mw \leq 8$.

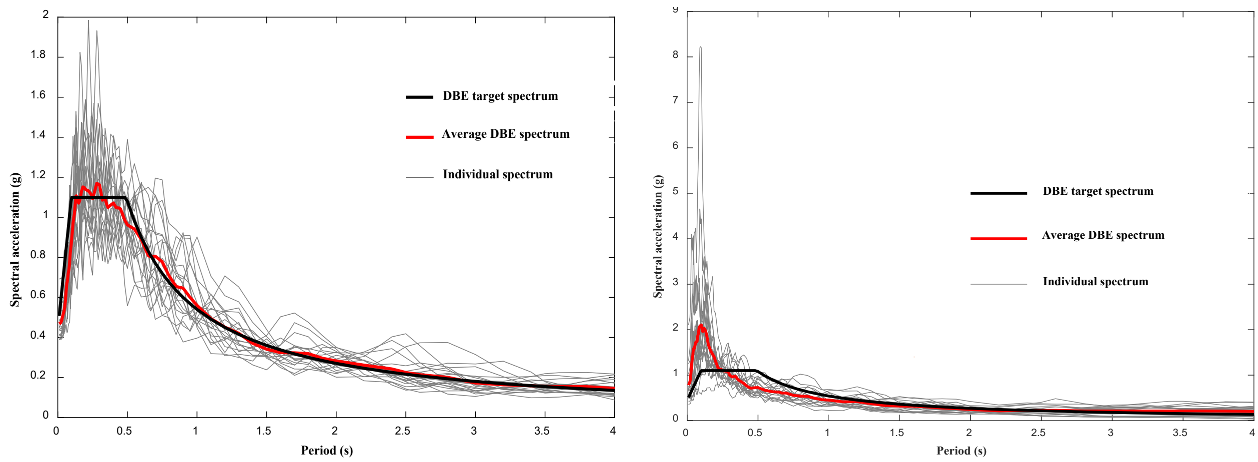
(2) The fault rupture length: $10 \leq Rrup \leq 100\ (km)$.

(3) The soil type was selected for the foundation of the station site in this test is the stiff soil site (soil type D). $180 \leq Vs30 \leq 360$ (m/s).

The damping ratio of 5% was chosen for the first-mode spectral acceleration Sa (T1, 5%).

Table 5 - Characteristics of selected earthquake records

No.	Event name	Year	Station name	Magnitude	PGA (g)	Periods (s)
1	Imperial Valley-06	1979	Delta	6.53	0.26	101
2	Imperial Valley-06	1979	El Centro Array #13	6.53	0.12	40
3	Superstition Hills-02	1987	El Centro Imp. Co. Cent	6.54	0.26	60
4	Superstition Hills-02	1987	Westmorland Fire Sta	6.54	0.21	60
5	Loma Prieta	1989	Fremont - Emerson Court	6.93	0.15	40
6	Northridge-01	1994	Compton - Castlegate St	6.69	0.1	40
7	Northridge-01	1994	LA - Baldwin Hills	6.69	0.19	40
8	Northridge-01	1994	LA - Pico & Sentous	6.69	0.14	40
9	Kobe_ Japan	1995	Sakai	6.9	0.15	199
10	Chi-Chi_ Taiwan	1999	CHY088	7.62	0.18	90
11	Hector Mine	1999	Desert Hot Springs	7.13	0.08	108
12	El Mayor-Cucapah_ Mexico	2010	MICHOACAN DE OCAMPO	7.2	0.43	100
13	El Mayor-Cucapah_ Mexico	2010	Westmorland Fire Sta	7.2	0.16	187
14	El Mayor-Cucapah_ Mexico	2010	Bonds Corner	7.2	0.24	250
15	El Mayor-Cucapah_ Mexico	2010	Meloland_E Holton Rd.	7.2	0.23	304
16	El Mayor-Cucapah_ Mexico	2010	Holtville Post Office	7.2	0.19	250
17	Darfield_ New Zealand	2010	DORC	7	0.09	62
18	Darfield_ New Zealand	2010	Kaiapoi North School	7	0.33	74
19	Darfield_ New Zealand	2010	Styx Mill Transfer Station	7	0.17	72
20	El Mayor-Cucapah_ Mexico	2010	Westside Elementary School	7.2	0.27	201



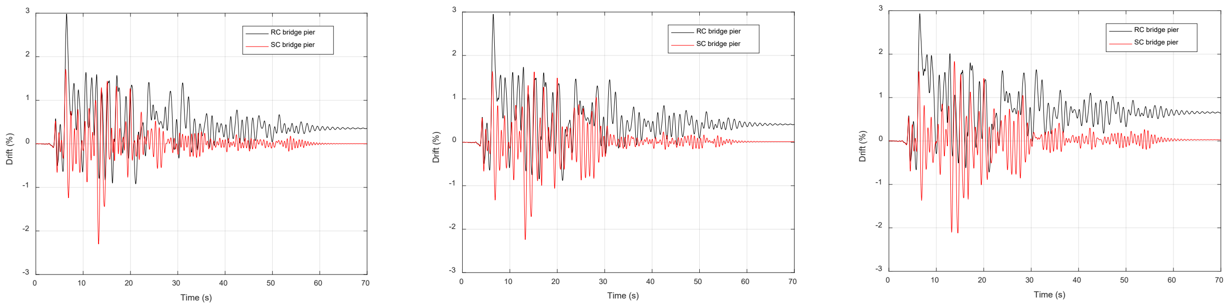
a) Horizontal spectral acceleration. b) Vertical spectral acceleration.

Fig. 4 - Scaled mean spectrum of 20 ground motions

The design basis earthquake (DBE) is chosen to be the seismic hazard level corresponding to 10% probability exceed in 50 years. The earthquake records are linearly scaled to match the DBE target spectrum. Figures 4a and 4b show the spectral accelerations of 20 ground motion files and their mean spectra for DBE seismic hazard. The effect of the vertical earthquake ground motions on the structure changes very much under the change of spectral acceleration. To get the great capability of the SCPC bridge pier systems under the effect of the vertical components, a great ratio between the vertical and horizontal components should be carried out. In this study, the target spectral acceleration of the horizontal component is adopted to becomes the target spectral acceleration of the vertical component. Therefore, the effect of the vertical earthquake ground motions on the structure should be significant.

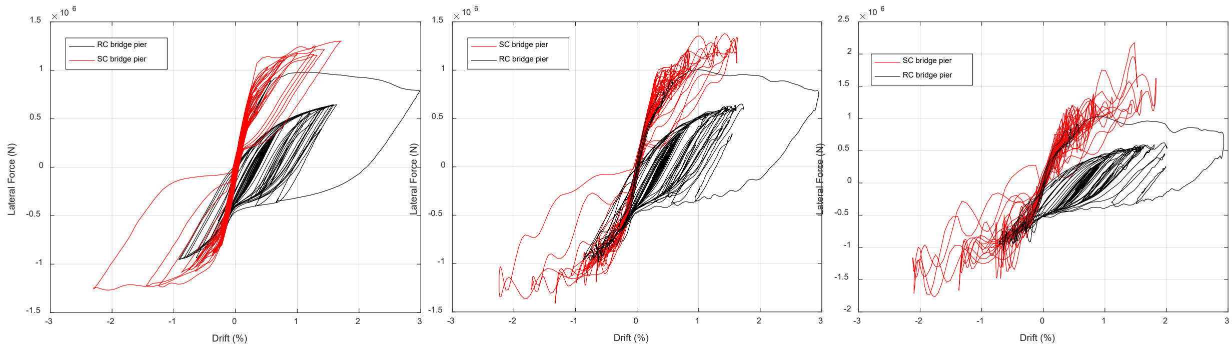
4. Performance Evaluation of Bridge Piers

Within the scope of this test, the most dangerous factor that affects the cantilever bridge pier is the drift factor; besides, the energy dissipator capability of the pier system is also an important part to reduce the damage of the piers.



a) H-Earthquakes only   b) scaled factor H/V = 1   c) scaled factor H/V = 0.4

Fig. 5 - The RC and SCPC bridge piers drift time histories under the effect of the earthquakes



a) H-Earthquakes only   b) scaled factor H/V = 1   c) scaled factor H/V = 0.4

Fig. 6 - The bridge piers lateral force-drift relationship under the effect of the earthquake ground motions

The Superstition Hills-02 earthquake with the station record is Westmorland Fire Sta, was used to simulate the earthquake on the piers with a different kind of earthquake, unidirectional and horizontal combined vertical ground motions. In both cases, the SCPC system showed the ability to outperform the conventional pier system. The maximum drift of the SCPC and RC piers under unidirectional are 2.3% and 2.98%, respectively. while the maximum drift under the vertical ground motion impacts is 2.24%, 2.12% for SCPC pier and 2.95%, 2.93% for RC pier (fig. 5). This difference is caused by the loss of self-centering control in the RC pier system (fig. 6). Under unidirectional earthquake, the drift of the RC pier tilted completely to one side, led to the maximum drift of the RC is much larger than the SCPC pier system.

Table 6 - The drift of bridge piers

Drift	H earthquakes (1)		H+V earthquakes (2) Scaled factor ratios (H/V) (3)			
			1		0.4	
	RC pier	SCPC pier	RC pier	SCPC pier	RC pier	SCPC pier
Residual drift (%)	0.36	0.013	0.414	0.015	0.65	0.0292
Maximum drift (%)	2.98	2.3	2.95	2.24	2.93	2.12

Note: (1) horizontal motions only; (2) combination of horizontal and vertical motions; (3) Horizontal Motions are preserved.

The residual drifts of the SCPC pier are 0.013% under unidirectional earthquake record and 0.015%, 0.03% under the impact of the vertical earthquake component, the changing of the SCPC residual drift is insignificant. Contrary to the SCPC pier, the seismic behavior of the RC pier under earthquakes leads to large damage to the bridge structure. Under unidirectional earthquakes, the residual drift of this system is 0.36%. This results in a starting point for the need for remodeling. Under the impact of the earthquake including the vertical ground motion, the residual drifts are 0.414% and 0.65%, the combination of the horizontal and vertical component impact on the conventional structure induces the great residual drift. Table 6 shows that the increased Vertical Component leads to a significant change in the residual drift of the RC piers but the maximum drift does not change significantly. The increased vertical earthquake motions cause the damage to increase quite fast, the repair work has to be carried out for the whole of the bridge pier, even demolished the conventional pier.

The energy dissipator aluminum bars work very well under the unidirectional earthquake effect. While the EDs bars experience difficulties in dissipating seismic energy during the effect of vertical motions (fig. 6). Therefore, the SCPC pier residual drift became larger than unidirectional earthquake ground motion but still within the allowable limit. Although the energy dissipator capability of aluminum bars is greatly affected, the result of the breaking of dissipators is not shown and the SCPC pier still shows the excellent ability to maintain a normal working post-seismic.

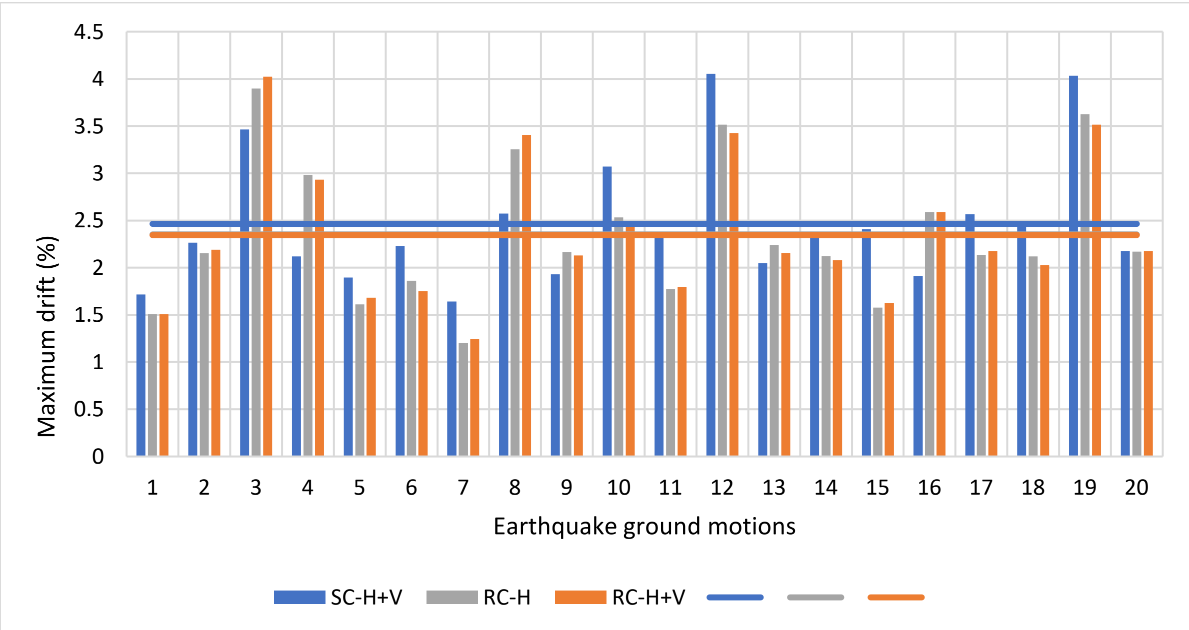


Fig. 7 - The bridge piers maximum drift under H and H+V ground motions

Fig. 7 depicts the maximum drift of bridge piers under 20 ground motion earthquake records impact. From this figure, the average maximum drift is 2.46% for the SCPC system under the effect of vertical direction ground motion, 2.35%, and 2.345% for the RC pier under unidirectional (H), horizontal and vertical combination (H+V) directional ground motions, respectively. Hence, the result shows the average maximum drift of the SCPC system is larger than the RC conventional system, but the great self-centering capability pulls the pier back to the original position, then reduces the damage of maximum drift on the bridge pier. The maximum drifts of RC pier under H and H+V earthquake are almost the same, but the residual drift of the RC bridge pier under H+V ground motion is much larger than this system under unidirectional ground motion record (fig. 8).

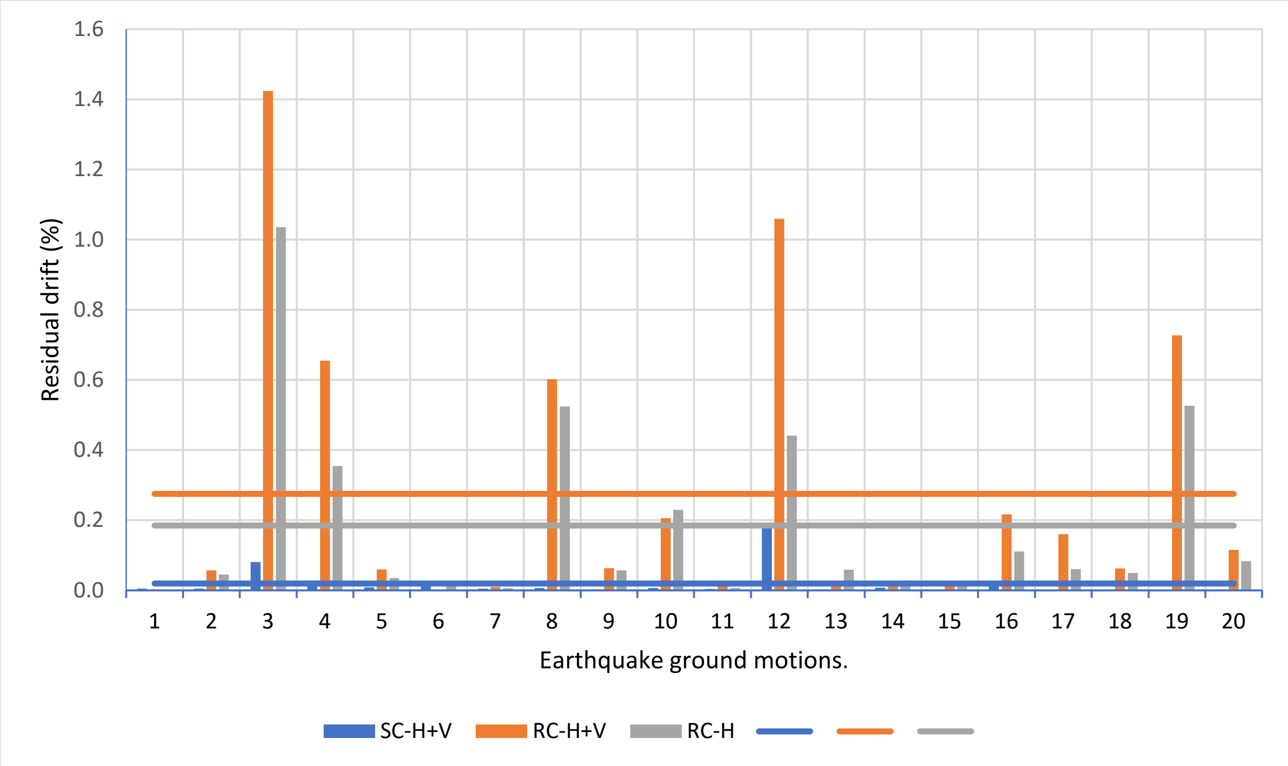


Fig. 8 - The bridge piers residual drift under H and H+V ground motions

The average residual drifts of bridge piers are 0.02%, 0.19%, 0.28% for the SCPC system under the earthquake ground motions including vertical components, the RC system under unidirectional, and the effect of vertical ground motions, respectively. Therefrom, the figure results in the great ability of the SCPC system under the effect of vertical earthquake motions, and shows the effect of the earthquake on the conventional bridge pier system, especially under the impact of the vertical earthquake. The vertical component does not lead the bridge pier to increase the maximum drift but the up and down movements of the ground result in loss of stability of structures and a significant decline of the structure self-centering.

5. Summaries and Conclusions

This study investigated the seismic performance assessment of the self-centering bridge pier considering the effect of vertical earthquake ground motions. The SCPC bridge pier and RC bridge pier are experienced under the systematical earthquake's impact. The SCPC pier system with the combination of external energy dissipator aluminum bars, unbounded post-tensioned tendons would be investigated. After the analysis, the systematic comparisons would be presented to highlight the great capability of the SCPC pier system. Finally, a set of 20 ground motion files effect on two bridge piers are figured out to evaluate and compare the response of the two bridge piers. The general conclusions in this study after investigation are summarized and presented as below:

(1) Under the effect of severe vertical earthquake motions, the SCPC bridge pier shows great capability in the residual drift reduction. The residual drift of the SCPC pier system is small, insignificant, and minimally changed when experiences the two earthquakes. While the RC bridge pier results in large residual drifts, especially under the effect of vertical earthquake motions.

(2) The vertical earthquake motions do not lead to the significant change of maximum drift but it causes more instability or imbalance in the structure than the unidirectional earthquake. Hence, the energy dissipator bars are in a difficult situation when dissipating the seismic energy and result in a larger residual drift in the RC pier.

(3) The ratio of scaling factors between vertical and horizontal ground motions affects the behavior of structures significantly. Therefore, the vertical earthquake component needs to be considered and calculated carefully to predict the damage of severe earthquakes on structures. Hence, the designers can find good solutions for structures in earthquakes resistance.

(4) Note that in this paper, the bridge with a single SCPC pier instead of multiple SCPC piers is investigated, while the drift of bridges with multiple or frame SCPC piers requires further investigation in future study.

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