6th International Conference on Advances in Experimental Structural Engineering
11th International Workshop on Advanced Smart Materials and Smart Structures Technology
August 1-2, 2015, University of Illinois, Urbana-Champaign, United States

Hybrid Simulation Based on Finite Element Analysis of a Continuous Gird Bridge with Fiber Reinforced Polymer composition

Hongxing JIA [1], Shizhu TIAN [2], Yuanzheng LIN [3]

1 *PhD candidate, School of Civil Engineering, Harbin Institute of Technology, China.*
E-mail: hongxing_6468@163.com
2 *Professor, School of Civil Engineering, Harbin Institute of Technology, China.*
School of Civil Engineering, Suzhou University of Science and Technology, China.
E-mail: tianshizhu@mail.usts.edu.cn.
3 *P.G, School of Civil Engineering, Suzhou University of Science and Technology, China.*
E-mail: linww429@163.com.

ABSTRACT

Hybrid simulation, a general technique to obtain the response of overall structure under ground motion, which is the improvement of traditional seismic test technique, has become one of the world's most advanced seismic testing methods currently. In the hybrid simulation, according to the distribution of nonlinear behavior, the structure model is divided into the numerical and the experimental elements, the experimental element can be regarded as a special numerical element as well, through integration and combination between different types of element, the hybrid model of the overall structure can be analyzed. The comparative hybrid tests were performed on a continuous girder bridge retrofitted with/without fiber reinforced polymer (FRP) composite sheets in axial direction are presented, taking piers of this bridge as the experimental substructure, the rest of bridge was simulated by OpenSees. The comparison between the test for the piers with/without FRP composite sheets shows that load carrying capacity and seismic performance of the retrofitted bridge has been promoted than one that had not been strengthened by FRP composite jacket.

KEYWORDS: *Hybrid simulation, Experimental element, a continuous girder bridge, Fiber reinforced polymer, OpenSees*

1. INSTRUCTION

The study of repair, strengthening and retrofitting for the existing bridges is of great significance in decades, on account of design code updating and the material aging, not to mention the tremendous destructive effects of the earthquakes, many existing bridges need strengthening or reinforcement. Owning to the advent of strengthening technology and building materials, great progress has been made in the structural strengthening and retrofitting field. Fiber reinforced polymer (FRP) composites is widely used in engineering retrofitting industries for several superiority over other materials, including light weight, high strength, high modulus, corrosion resistance, designable, and so on.

Experimental research related to FRP composite materials have been demonstrated to provide a strong support to promote the application. Shekih et al. (2001) tested 28 columns with circular or square section under quasi-static cyclic loading, based on a comparison of the moment-curving response of the critical sections of the FRP-retrofitting specimens with those of similar companion specimen with FRP, it can be concluded that the retrofitting of columns with FRP can substantially improve the deformation capacity and their ductility. Haroun et al. (2005) conducted testing program on reinforced concrete RC bridge circular and square column with insufficient lap-splice length, results show that he cyclic performance of composite-jacketed bridge columns with poor lap-splice details was significantly improved, despite the improvement of a circular jacketed column’s seismic behaviour is more dramatic than the square jacketed column. Gu et al. (2010) tested 17 circular concrete columns under combined lateral cyclic displacement excursions and constant axial load to study the factors that influence the performance of FRP reinforced concrete circular columns, such as axial load level, aspect ratio, FRP jacket confinement stiffness, the fracture strain, amount of confining FRP material and so on. Kumar et al. (2014) presented the shaking table performance of two RC specimens with different volumetric reinforcement ratios, which had moderate high shear and flexural damage, repaired using FRP composite sheets, and made conclusion that the repair using FRP could be considered as a permanent strengthening solution of RC bridge columns.

However, in the above tests, experimental methods used are mainly quasi-static testing method and shaking table testing method. These seismic experimental method have some certain shortcoming. Firstly, the specimens in quasi-static tests are subjected to a predefined history of loading and displacements in a lower rate by actuators, the response of the specimens obtained in these tests can be regarded as just an approximation, not reflect the overall structural response under an actual seismic event accurately. Secondly, the limited capacity and size of the shaking table, the reduced scale specimens in shaking table tests are also restricted following dynamic similitude laws. Moreover, the balancing weight is always lacking in shaking table tests, and as a result, size effect and insufficient artificial mass significantly affect the accuracy of the results. Thirdly, in these tests about bridge columns repaired with fiber reinforced polymer jackets, just the bridge components, mainly, piers were tested in experimental study, it was unable to takes into account the overall seismic performance of FRP reinforced bridge structure.

On the other hand, hybrid simulation, formerly also called the pseudo-dynamic testing method or online hybrid testing method, can be regarded as an advanced experimental method, combining the numerical analysis and physical testing together by means of substructure test technology. The overall structure in accordance with their characteristics or research focus is divided into several subassemblies, simply grouped into two categories: numerical and experimental substructures. Numerical substructures whose behavior is well-understood or linear can be simulated by means of finite element analysis. Experimental substructures whose behavior is complex or highly nonlinear, are difficult to be analyzed by calculation. Through reasonable boundary conditions coupled and coordination, after developing the hybrid model of the overall structure, seismic response of whole structure can be obtained by solving the overall structure of the equations of motion (Schellenberg et al., 2009, Elkhoraibi et al., 2007, Yang et al., 2009). In this study, attention is exclusively focused on the hybrid simulation of a continuous RC girder bridge retrofitted by FRP jacket subjected to seismic ground motion.

2. MODELLING AND EXPERIMENTAL SETUP

2.1 Prototype structure and retrofitting procedure

In this hybrid simulation, the prototype bridge used as reference was a 4-span RC highway bridge, the bridge superstructure was a reinforced concrete main girder whose length is 80m, and the substructure was double-column piers with circular cross section whose diameter was 1m, the total height was 4m. Transverse cap beam girder was located upper the piers and their length was 6m, the middle bearing support was fixed while the others were sliding. The prototype continuous girder bridge is presented in Figure 2.1. Because this bridge had been constructed for many years, the seismic performance was unable to satisfy the present current bridge design code, retrofitting with FRP composite was a good choice, the Retrofitting procedure with FRP jackets in the plastic hinge region of piers was adopted to apply retrofitting, as shown in the Figure 2.2. Under the actual earthquake, the plastic hinge of columns was potential to occur at the bottom of the pier in the longitudinal direction, so the constraint regions consisted of primary-secondary zone, the primary zones were located at the bottom end of piers, while the secondary zones were at the periphery of the primary regions, its thickness were only about half of primary ones. The height of the primary-secondary strengthening regions were 500mm, 1/8 of the total height of piers.

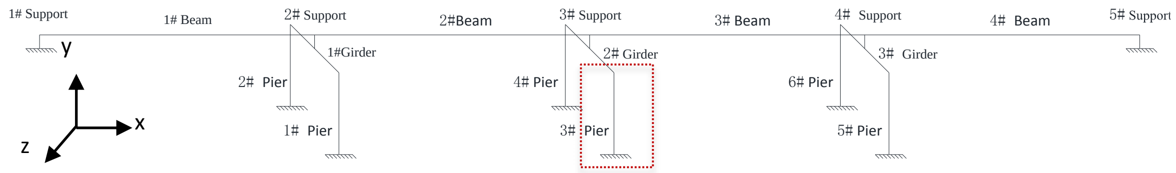


Figure 2.1 The prototype continuous girder bridge

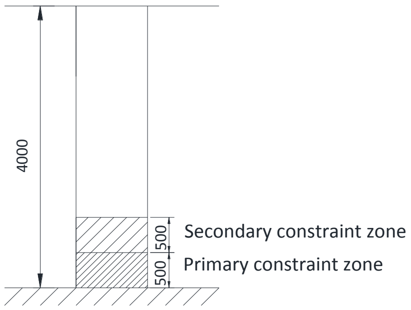
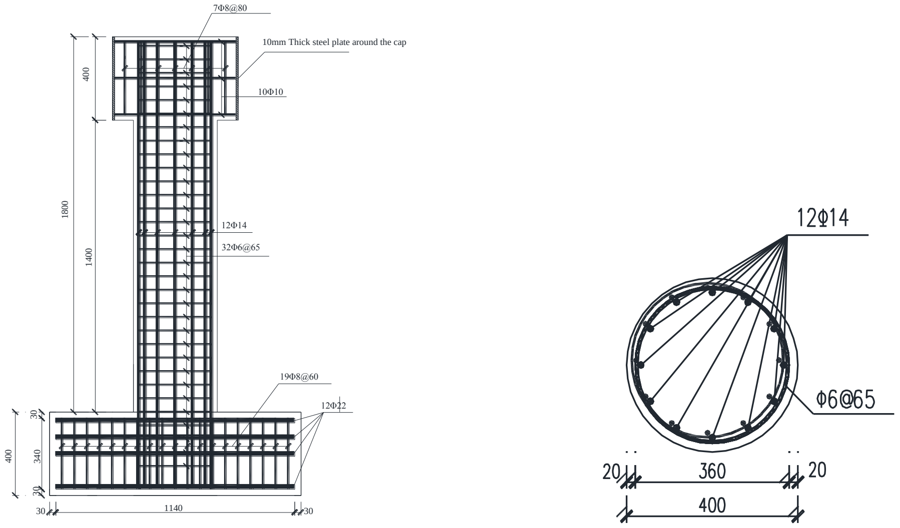


Figure 2.2 Retrofitting procedure with FRP jackets in the plastic hinge region

2.2 Hybrid model

It is ideal to a construct a full-scale model for this program, nevertheless, the size of the studied bridge renders this construction difficult, in the past post-earthquake damage surveys, the vulnerability of piers were greater than the deck and the beam. In fact, the deck and beam remained elastic even the piers had lost the capability, so, in this project, the investigated bridge was divided into an experimental substructure consisting the 3$^{\#}$ pier and a numerical substructure including the other piers and deck. After coordinating by the boundary conditions, the hybrid model of overall bridge structure was developed. The length scaling factor was 1/2.5, the specimen of the piers were 1800mm, consisting the height of the column cap, 400mm, Properties of reinforced steel and concrete in specimens are shown in Table 2.1, and the dimensions and reinforcements of the specimens are presented in Figure 2.3.



(a) Dimensions of the specimen of the pier (b) Reinforcements of the pier body

Figure 2.3 Dimensions and reinforcements of the specimen

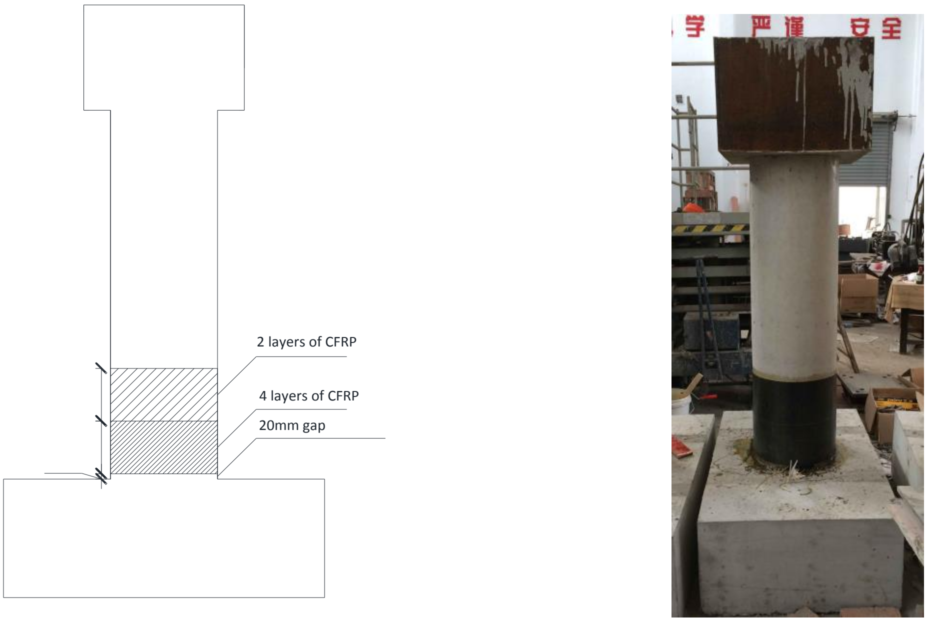
As the first phase of this program, in detail, only the performance of the overall bridge in the longitudinal direction under different ground motion was considered as case study, excepting the bottom end of the piers retrofitted by FRP composite sheet, other parts of the specimen kept same, schematic and photo of the retrofitting procedure with FRP jackets in the plastic hinge region of the pier is shown in Figure 2.4. Based on the stress–strain model for concrete confined by wrapped FRP (Lam and Teng, 2003), in the primary zone, the pier was wrapped with four layers of CFRP (Carbon Fibre Reinforced Plastics), and the secondary strengthening regions contained 2 layers of CFRP. At least 20mm gap between the foundation and the CFRP reinforced region boundary was reserved to keep CFRP cloth from affecting by the vertical pressure directly (Xiao, 1999). Parameters of composite CFRP sheets were summarized in Table 2.2.

Table 2.1 Properties of reinforced steel and concrete in specimens

Steel diameter (mm)	Type	Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Elastic modulus (N/mm^2)
14mm	HRB335 (longitudinal steel)	364	522	2.0×10^5
6mm	HPB300 (stirrup)	323	486	2.0×10^5
Concrete strength grade	Cubic compressive strength (N/mm^2)	Cylinder strength (N/mm^2)	Elastic modulus (N/mm^2)	Poisson ratio
C30	34.1	26.9	3.16×10^4	0.2

Table 2.2 Parameters of composite CFRP sheets

Nominal thickness (mm)	Tensile strength (N/mm^2)	Elastic modulus (N/mm^2)	Elongation ratio (%)
0.167	3417	2.43×10^5	1.7



(a) Schematic of the retrofitting procedure with FRP jackets (b) Photo of a pier retrofitted with FRP jackets

Figure 2.4 Schematic and photo of the retrofitting procedure with FRP jackets in the plastic hinge region of the pier

Table 2.3 Ground motions used for testing specimens

Testing ID	Ground motion	Peak acceleration	Specimens type
1A	E1 for seismic intensity 7	0.046g	Original pier without FRP
2B	E2 for seismic intensity 7	0.22g	Original pier without FRP
1C	E1 for seismic intensity 7	0.046g	Retrofitted with FRP
2D	E2 for seismic intensity 7	0.22g	Retrofitted with FRP

The different scaled versions of the ground motion recorded of 1940 El Centro Earthquake were used as the seismic ground motion for testing specimens, Table 2.3 gives the peak acceleration and sequence of ground motions used for testing.

2.3 Hybrid simulation set-up

The data communication of hybrid simulation set-up during a hybrid simulation performed is shown in Figure 2.5. The hybrid simulation set-up architecture based MTS electro-hydraulic servo system(JIA et al, 2013) at Jiangsu key laboratory of structural engineering (JKLSE) comprised finite element software, OpenSees(PEER, 2015) or Matlab(CAI et al, 2014), OpenFresco (Schellenberg et al, 2007), Data interface application programs of MTS, MTS 793 test control system and the data acquisition system.

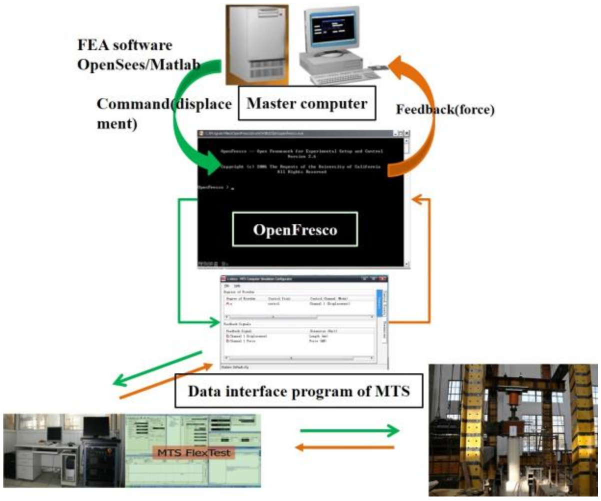
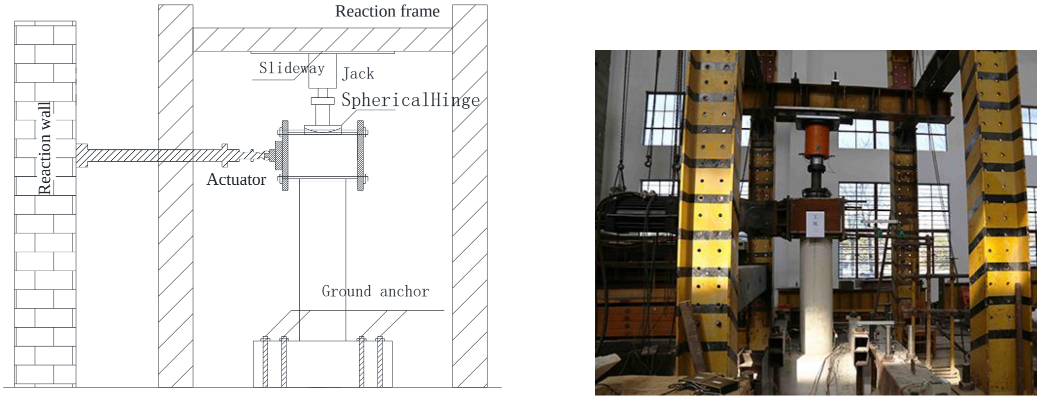


Figure 2.5 Global architecture of the hybrid simulation set-up.

The experimental setup consisted of the horizontal relative displacements and a constant vertical load of 246 KN, one servo hydraulic actuator was employed to impose the horizontal relative displacements at the column cap with displacement control method, in order to compare the calculated displacement with the order displacement, a LVDT displacement transducer was fixed to measure the horizontal relative displacements of the piers, moreover, resistance strain gauge was placed at the surface of the longitudinal bar, concrete and CFRP, schematic and photo of the experimental setup is presented in Figure 2.6.



(a) Schematic of the experimental setup (b) photo of a pier in testing configuration

Figure 2.6 Schematic and photo of the experimental setup

3. EXPERIMENTAL RESULTS

3.1 Failure mode

Under E1 for seismic intensity 7, there was nearly no significant cracks on the surface of the pier with/without CFRP, until the deformation reached a peak. And with the displacement decreasing, cracks were closed gradually. The cracks were mainly horizontal cracks which occurred in the tension side of the pier uniformly and disappeared completely as soon as the test was finished. Under E2 for seismic intensity 7, the cracks developed more severely than one under E1, the homogeneous cracks appeared horizontally not only at the bottom end of the pier, but also at the pier body, the width of maximum crack was about 1mm, as shown in Figure 3.1. When the peak displacement reached, there was a little spalling concrete and plastic hinge at the bottom end of the pier, by contrast, there was no significant damage at the surface of the pier retrofitted with CFRP.

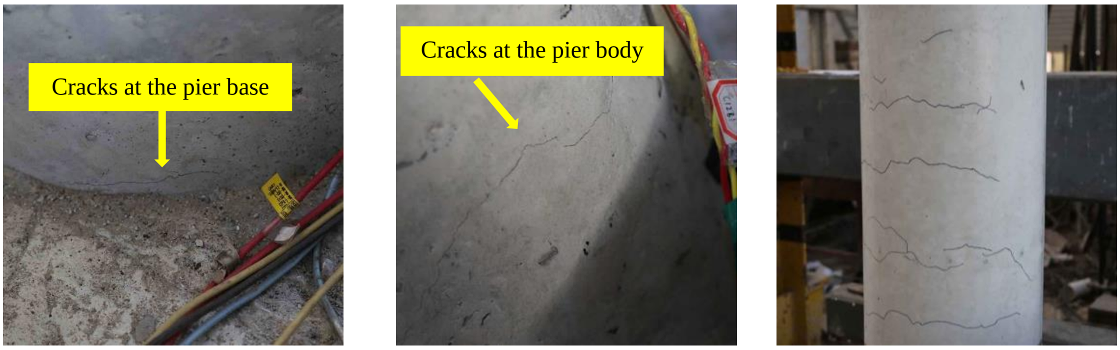


Figure 3.1 Damage state of the pier without FRP sheets under E2 for seismic intensity 7

3.2 Experimental results analysis

Displacement history of the piers under E1 and E2 for seismic intensity 7 are shown in Figure 3.2 and Figure 3.3. The peak displacement of the pier with/without FRP sheets under E1 for seismic intensity 7 reached 10.3mm, 9.3mm respectively, by contrast, ones were -72.4mm and -44.5mm under E2 for seismic intensity 7. From the loop, it is obvious that the peak displacement was less after retrofitting with CFRP composition sheets.

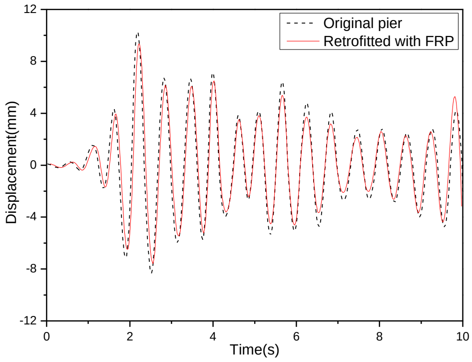


Figure 3.2 Displacement history of the piers under E1 for seismic intensity 7

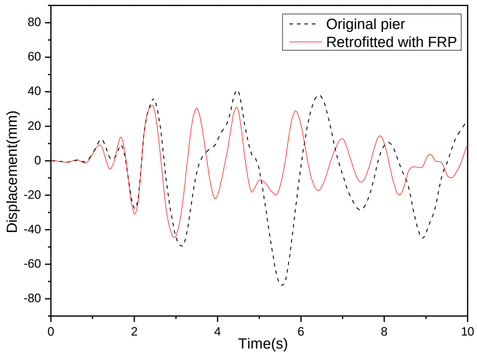


Figure 3.3 Displacement history of the piers under E2 for seismic intensity 7

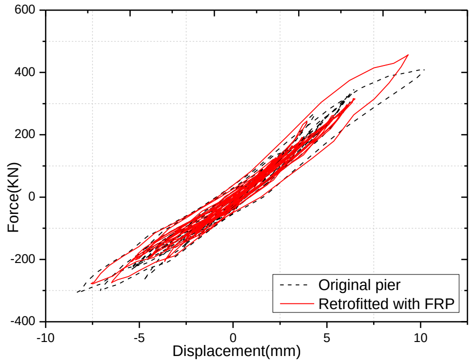


Figure 3.4 Hysteresis loop of the piers under E1 for seismic intensity 7

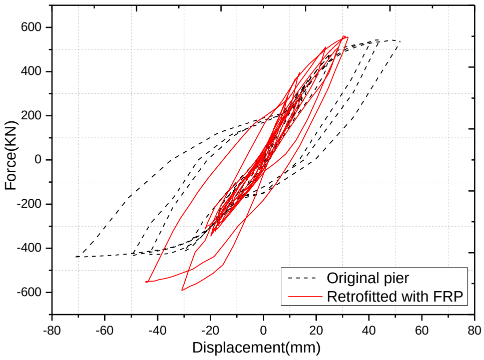


Figure 3.5 Hysteresis loop of the piers under E2 for seismic intensity 7

Figure 3.4 shows the hysteresis loop of the piers under E1 for seismic intensity 7, from the loop, it was evident that the initial stiffness of the piers which was no matter retrofitted or unreinforced were basically identical, but the energy-dissipating capacity of the pier has been improved after retrofitting with FRP composition sheet. On the other hand, as shown in Figure 3.5, the seismic performance of pier retrofitted with CFRP composition sheets was enhanced than one without FRP composition.

4. CONCLUSION

In this paper, the hybrid simulation of an existing continuous girder bridge with FRP composition jacket was conducted to investigate the strengthening and retrofitting effects. In the hybrid simulation, the mid-span pier was treated as experimental element which was tested in the laboratory, meanwhile, the other piers and the deck, beam was analysed in finite element analysis software. Through integrating and coupling between different substructures, the response of whole bridge under a variety of ground motion was able to obtain. By comparing the results of the hybrid simulation of the bridge with/without retrofitted by FRP composition jacket, some observations were summarized as follows:

(1) The effectiveness of hybrid simulation implementation adopted to the bridge structure was ascertained, and the favourable stability and consistency properties has been verified as well. Hybrid simulation can be viewed as the advanced form of traditional seismic testing method. The biggest advantage over the other testing method is the overall structure can be tested in a large proportion, even the prototype model can be investigated instead of only some structural members can be studied in the laboratory.

(2) For RC continuous gird bridge, the approach of retrofitting with FRP jackets in the plastic hinge region of piers is an effective way on the pier reinforcement. The seismic performance of the overall bridge is also improved, not only the usage of reinforcement material can be less when compared to the approach that the entire pier was wrapped with FRP composition sheet.

REFERENCES

1. CAI X. J., TIAN S. Z. (2014). MTS-OpenFresco-MATLAB hybrid simulation system construction and verification test. Earthquake Engineering and Engineering Dynamics, 34(01):117-122.
2. Elkhoraibi T., Mosalam K. M. (2007). Generalized hybrid simulation framework for structural systems subjected to seismic loading, PEER Report 2007/101, Pacific Earthquake Engineering Research Center, University of California, Berkeley.
3. Gu D. S., Wu G, Wu Z. S., et al (2010). Confinement effectiveness of FRP in retrofitting circular concrete columns under simulated seismic load. Journal of Composites for Construction, 14(5): 531-540.
4. Haroun M., Elsanadedy H. (2005). Fiber-reinforced plastic jackets for ductility enhancement of reinforced concrete bridge columns with poor lap-splice detailing, Journal of Bridge Engineering, 10(6): 749-757.
5. JIA H. X., CAI X. J, TIAN S. Z. (2013). Hybrid simulation testing technology with OpenFresco framework. Sichuan Building Science, 39(04):209-212.
6. Kumar P., Mosalam K., Abbasi S., et al (2014). Reinforced concrete bridge columns repaired with fiber-reinforced polymer jackets, Proceedings of the Structures Congress, Boston, Massachusetts, United States: 429-440.
7. Lam L., Teng J. G. (2003). Design-oriented stress–strain model for FRP-confined concrete. Construction and Building Materials, 17(06): 471-489.
8. Pacific Earthquake Engineering Research Center (2015). Open System for Earthquake Engineering Simulation -Home Page, http://opensees.berkeley.edu, 5/14/2015.
9. Schellenberg, A., Mahin S. A., Fenves G. L. (2009). Advanced implementation of hybrid simulation, PEER Report 2009/104, Pacific Earthquake Engineering Research Center, University of California, Berkeley.
10. Sheikh S. A., Bayrak O. (2001). Seismic behaviour of FRP-retrofitted concrete columns, Proceedings of the Structures Congress. Washington, D.C., United States.
11. Yang T. Y., Stojadinovic B., Moehle J. (2009). Hybrid simulation of a zipper-braced steel frame under earthquake excitation, Earthquake Engineering & Structural Dynamics, 38(1): 95-113.
12. Xiao Y., Wu H., Martin G. R. (1999). Prefabricated composite jacketing of RC columns for enhanced shear strength. Journal of Structural Engineering, 125(3): 255-264.