PSEUDO-DYNAMIC TEST STUDY ON SEISMIC BEHAVIOR OF CFST BUILT-UP COLUMN WITH RC WEB AT THE DIFFERENT INTENSITY OF GROUND MOTIONS

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Abstract

The CFST built-up column with RC web (CFST-RC column) is a new composite structure proposed on the basis of CFST lattice column. Compared with the CFST lattice column, the RC web in the CFST-RC column can reduce the compressive stress of the CFST limbs and the overall shear deformation; it can also improve the stability, ultimate bearing capacity, and energy dissipation capacity of the whole structure. In this paper, a pseudo-dynamic test of two 1/8-scaled CFST-RC columns was performed. The seismic records obtained from the 2008 Wenchuan Earthquake and the 1995 Kobe Earthquake were selected as input ground motions to study the seismic behavior of the CFST-RC column under the action of different intensity of ground motions. The results show that the CFST-RC columns had good seismic performance, and the structure was in the elastic state when subjected to the intensity-8 frequent, basic, rare and extremely rare earthquakes. Under the action of the intensity-9 rare earthquake, the RC web began to crack and CFST limbs yielded and the structure entered the elastoplastic working state. With the increase of the peak ground acceleration, the shear cracks on the RC web and the maximum response displacement at the top were greatly increased, and the yield ring gradually formed in the plastic hinge region at the bottom of the CFST limb. However, there was no obvious structural damage until the end of the test. CFST-RC column has a great application prospect in bridge engineering in high-intensity areas in China.

Keywords: CFST built-up column, RC web, pseudo-dynamic test, seismic behavior, intensity of ground motion

1. Introduction

Compared with the traditional RC columns with the same bearing capacity, the CFST built-up columns have lighter self-weight and larger flexural rigidity, and are more suitable for the working conditions with larger load eccentricity or slenderness ratio. Located in seismic region with intensity 8 of Chinese intensity scale, the Ganhaizi Bridge shown in Fig. 1 adopts CFST truss girder as its superstructure and CFST battened built-up columns as its substructure with a height of 20 to 107 meters [1].

Fig. 1 – Panorama of the Ganhaizi Bridge

In regard to the seismic performance of CFST built-up columns, previous experiment conducted by Kawano [2], Yang [3], Huang [4], and Yuan [5] suggests that the CFST built-up columns exhibit good hysteresis energy dissipation capacity and deformation capacity; however, these columns connected by lacings or battens are more susceptible to shear than the traditional RC columns, the effect of shear distortions can be significant and should be carefully considered in the seismic design.

The CFST built-up column with RC web (hereafter CFST-RC column for short) is a new composite structure. Compared with the conventional CFST laced or battend built-up column, the RC web in the CFST-RC column can reduce the compressive stress of the CFST limbs and the overall shear deformation; it can also improve the stability, ultimate bearing capacity, and energy dissipation capacity of the whole structure. Yadav [6] has carried out quasi-static tests on CFST-RC column which showed that this type of column has excellent seismic resistant properties.

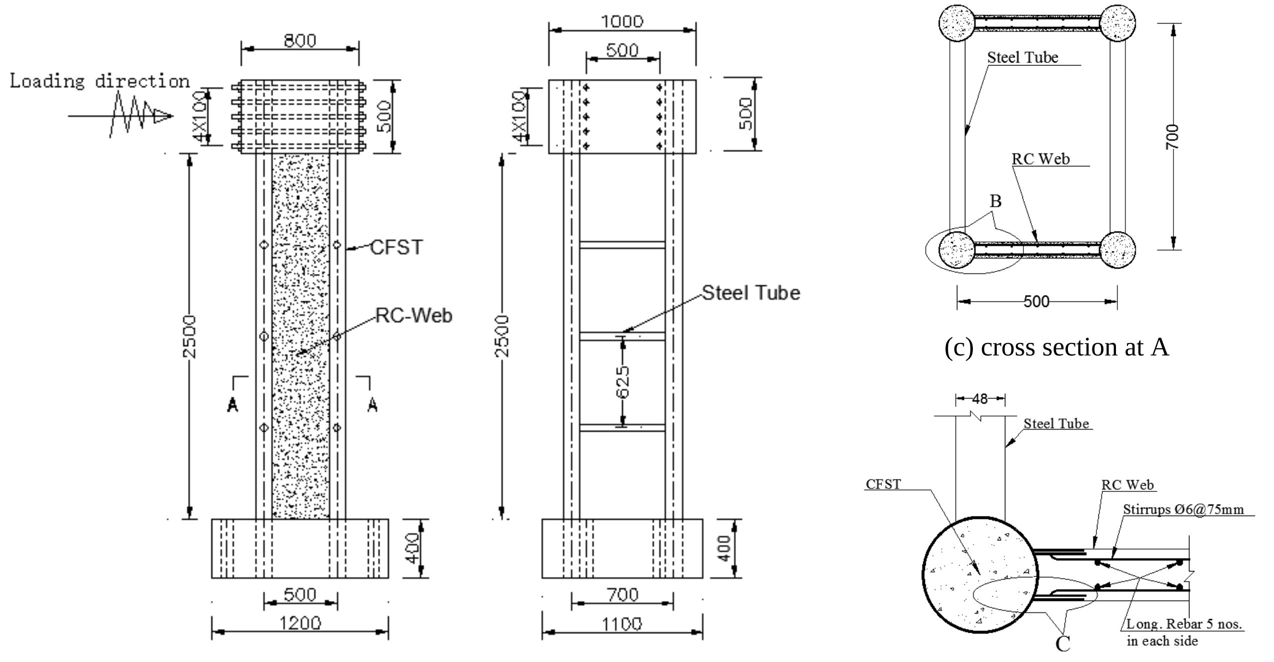
Limited research has been conducted for investigation of seismic behavior of CFST–RC columns in strong earthquakes. Therefore, in order to investigate the actual seismic responses of the CFST-RC column, a pseudo-dynamic test of two 1/8-scaled CFST-RC columns was performed in this study. The seismic records obtained from the 2008 Wenchuan Earthquake and the 1995 Kobe Earthquake were selected as input ground motions to study the seismic behavior of the CFST-RC column under the action of different intensity of ground motions.

2. Experimental Program

2.1 Test specimen

To ensure the continuity and integrity of the research, the two test specimens used in this study have the same geometric dimensions and materials as in the previous study [6]. The height of the selected actual pier is 24m, and the outer diameter of the CFST limb is 813mm. According to the experimental conditions of the laboratory of Fuzhou University, the test specimens consisting of four CFST limbs, of which the outer diameter of the Q235 steel tube is 114mm and the wall thickness is 2mm, are designed and manufactured using the 1:8 scale ratio of the actual bridge pier. The specimens are fixed at the footing, similar to actual bridge piers.

The total height of the specimens is 3400 mm including a 400mm-high column footing and a 500mm-high column cap. The center-to-center distance of two CFST limbs is 700mm in the transverse direction connected by hollow steel tubes with 48mm diameter and 2mm thickness at the spacing of 625mm. The center-to-center distance between two CFST limbs is 500mm along the loading direction connected by RC web of uniform thickness. The thickness of RC web is 50 mm, reinforced with two layers of ø6 mm bars and stirrups of ø6 mm bar spaced at 50mm. C50 grade of concrete is used for both infill in the steel tube and RC-web. For the column footing and the column cap, C30 grade of concrete is used. 2mm-thick and 50mm-wide steel plates are welded with the steel tube for the connection between the CFST and the RC web. Transverse rebars are welded with steel plate. The details of specimens are illustrated in Fig. 2.



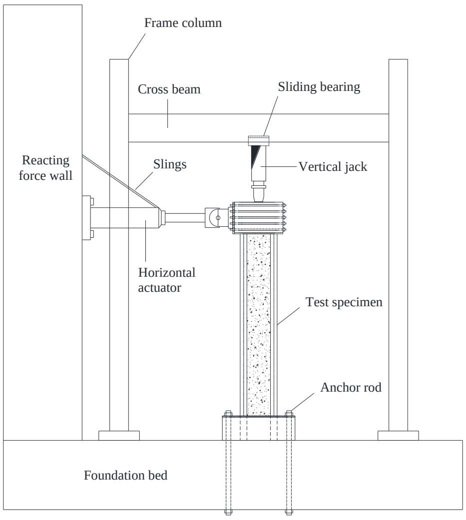
(a) longitudinal elevation (b) transverse elevation (d) detail drawing at B

Fig. 2 – Details of CFST-RC column specimen (unit: mm)

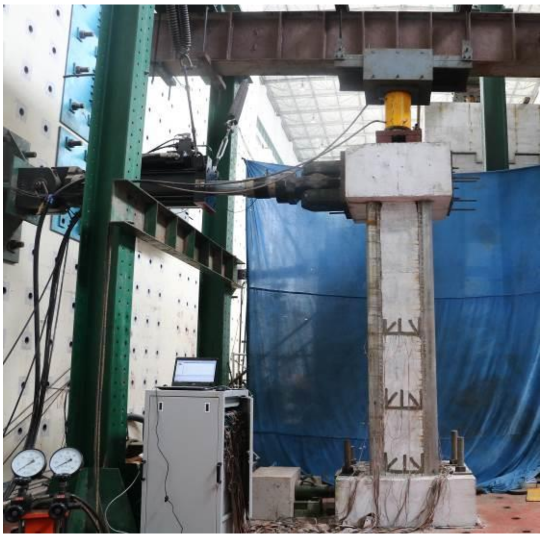
2.2 Test setup

Fig. 3 shows the general arrangement of the loading system for the pseudo-dynamic test of the CFST-RC column specimen in the laboratory. The axial compression load and the cyclic horizontal seismic load are respectively applied by a 1000kN hydraulic jack and a 1000kN MTS electro-hydraulic servo actuator on the top of test specimens. The upper end plate of the vertical jack is connected to a sliding bearing. As the column cap of specimen shifts laterally, the hydraulic jack and sliding bearing move synchronously along the cross beam, so that the hydraulic jack will always apply a constant vertical load to the center of the cross-section of the column cap. The column cap and the horizontal actuator are tightly linked together by 5 pairs of connecting rods and then the horizontal repeated load can be applied to the centroid of the column cap of the specimen. Huang [7] calculated the dead load from superstructure acting on 25 numbers piers of the Ganhaizi Bridge. It is found that the dead load on the piers ranges from 12% to 17% of its capacity. For this study, the ratio of the applied axial load to the nominal axial compressive capacity is taken as 0.15, that is $N = 0.15N_u = 0.15 \times \sum (A_{cfst} f_{cfst} + A_{rc} f_c) = 459$kN.

Certain amounts of steel strain gauge are used to measure the strain of steel tube, which are placed at the bottom, 1/8th, 1/4th and 1/2nd height of the columns. To measure the strain of RC web, the concrete strain gauges are arranged at the same height as the steel strain gauges. A total of five displacement transducers are used to measure the fixity of base and the displacement in transverse direction of the column.



(a) Schematic view



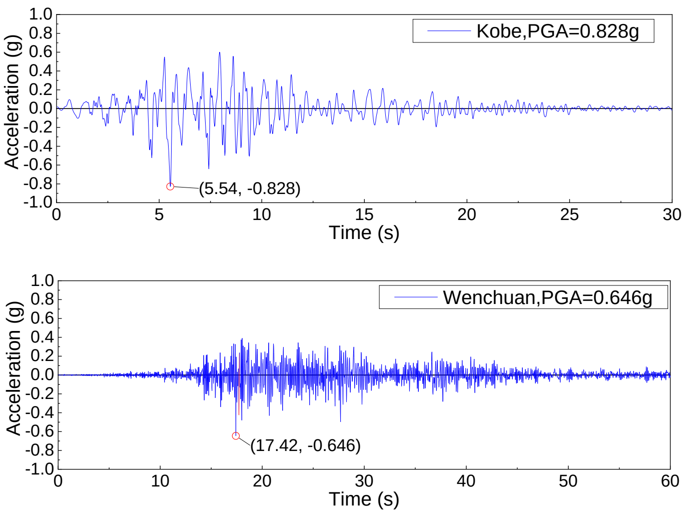
(b) Real scenario

Fig. 3 – Arrangement of the loading system

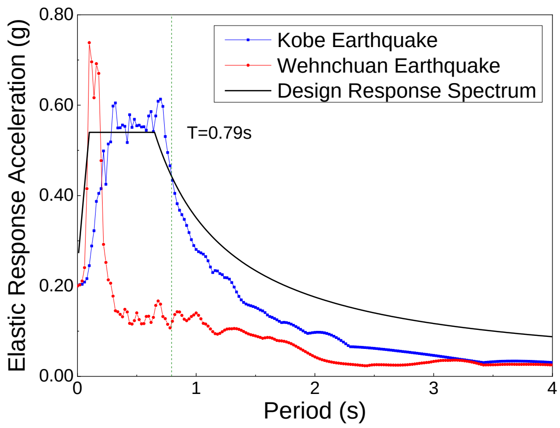
2.3 Input parameters in pseudo-dynamic test

The pseudo-dynamic test is a widely used alternative to the shaking-table test, in which the structural displacements caused by the earthquake are calculated by computers using a stepwise integration procedure and applied quasi-statically to the test specimen. The resulting restoring force of the test specimen is measured and fed back to the analysis model as part of the input for the next calculation step.

The seismic fortification intensity of the Ganhaizi Bridge is 8 degrees, the design basic seismic acceleration value is 0.20 g, the site category is Class III, and the site characteristic period is 0.65 s. In this study, the seismic records obtained from the 2008 Wenchuan Earthquake and the 1995 Kobe Earthquake were selected as input ground motions. The PGA of these two records are gradually increased from PGA=0.05g to correspond to different intensity ground motions. The acceleration time histories of actual ground motions are presented in Fig. 4.



(a) Acceleration records



(b) Acceleration response spectrum of input ground motions with PGA=0.20g

Fig. 4 – Input ground motions of pseudo-dynamic test

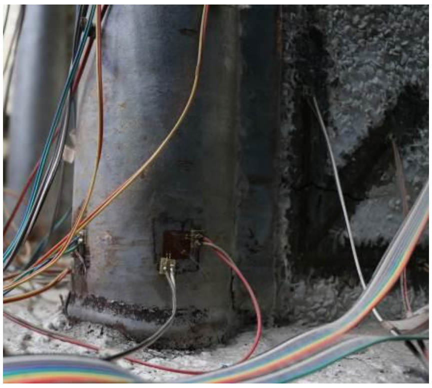
The test specimens were scaled according to actual bridge piers with a length scale factor S of 8. According to the principle of dynamic analogy, the mass, initial stiffness, damping coefficient, and natural period of actual bridge piers for numerical analysis are determined. The damping ratio ζ is set to 0.035, and the initial stiffness of the test specimen k_0 is obtained in the pre-cyclic loading test with amplitude of 1mm. In the pseudo-dynamic loading test, the actual bridge pier with natural period of 0.79s is modeled as a one-degree-of-freedom system, and the Newmark-β method (β = 1/4) is applied to solve the corresponding equation of motion for displacement.

3. Results and Discussions

3.1 Failure patterns

Fig. 5 illustrates the failure patterns of CFST-RC specimens at the end of pseudo-dynamic loading tests. As shown in the figure, the main failure patterns of the test specimens are local buckling deformation at the bottom of CFST limb and oblique shear cracks on RC webs. In the process of the loading conditions with PGA smaller than 1.0g, there was no damage to the test specimens; when the PGA of loading condition reached 1.0g, cracks began to appear on the RC web, and a slight local buckling deformation began to occur at the bottom of the CFST limb; with the increase of PGA, the cracks on the RC web continuously increased and expanded, and the local buckling deformation of the steel pipe became more and more obvious; however, until the end of tests (maximum PGA = 2.4g), the specimens did not have obvious damage and showed good seismic performance.

(a) Cracks on RC web



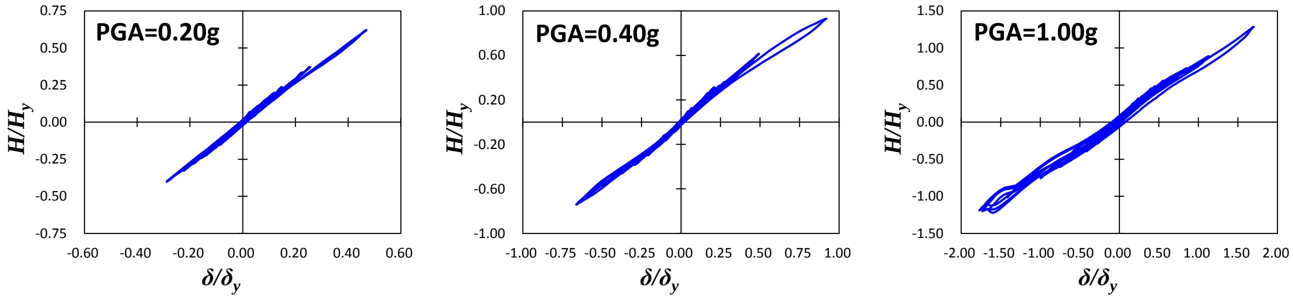
(b) Local buckling ring at the bottom of CFST limb

Fig. 5 – Failure patterns of CFST-RC specimens after pseudo-dynamic tests

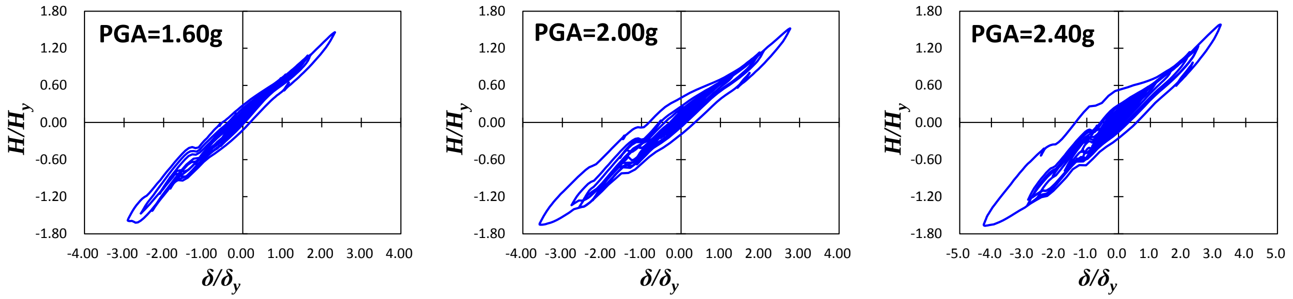
3.2 Hysteretic curves

The load-displacement hysteresis curves of two specimens under the seismic actions of Kobe Earthquake and Wenchuan Earthquake with different intensities are shown in Fig. 6 and Fig. 7. Due to space limitations, only some typical loading conditions are listed in the figure. The load and displacement in the figure are normalized using the yield load P_y = 141.3kN and the yield displacement δ_y = 11.0mm obtained from the previous quasi-static loading test in literature [6].

It is clearly shown in Fig. 6 and Fig. 7 that compared with Wenchuan Earthquake, the seismic response of the CFST-RC specimen caused by Kobe Earthquake was more obvious, and the hysteresis curve shape of the specimen was also plumper. Moreover, the hysteresis curves of the test specimen were basically linear before 9 degrees of rare earthquake conditions, indicating that the structure was in an elastic working state or the plastic development was not obvious. With the increase of PGA, the steel tube at the bottom of CFST limb began to yield, and cracks also appeared in the RC web, and the stiffness of the structure gradually decreased.

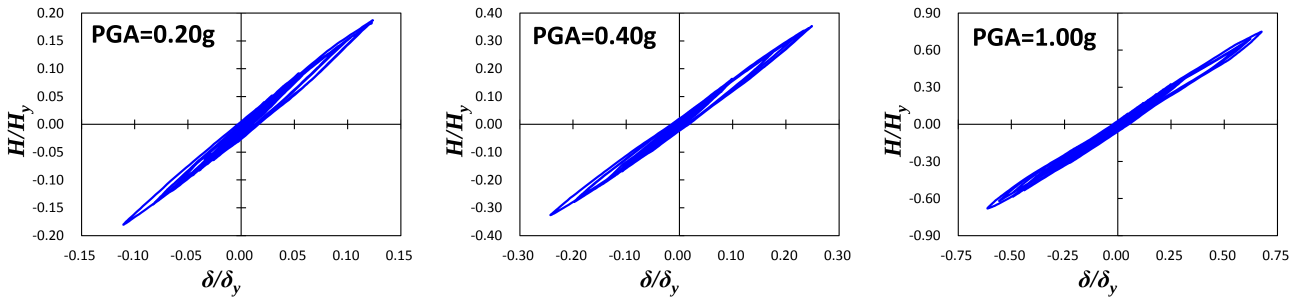


(a) PGA=0.20g (b) PGA=0.40g (c) PGA=1.00g

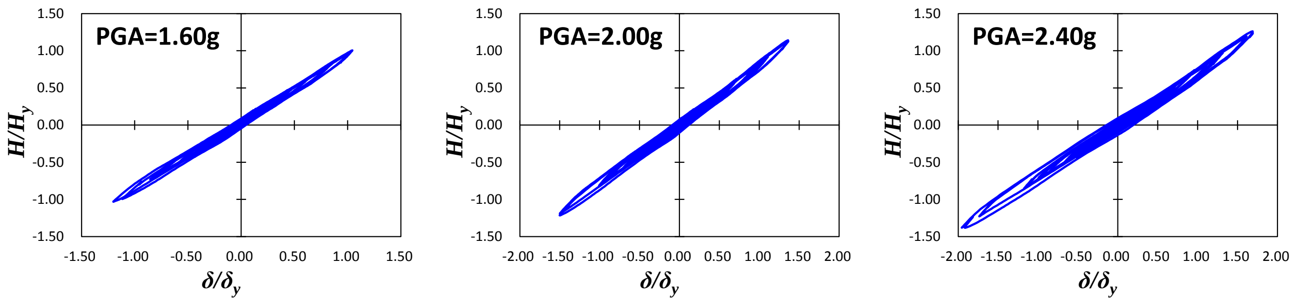


(d) PGA=1.60g (e) PGA=2.00g (f) PGA=2.40g

Fig. 6 – Hysteretic curves of the CFST-RC specimen under the seismic actions of Kobe Earthquake



(a) PGA=0.20g (b) PGA=0.40g (c) PGA=1.00g



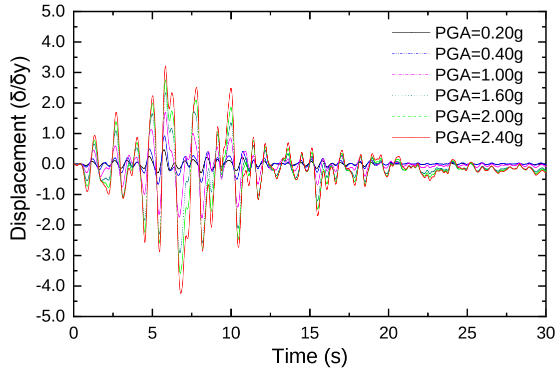
(d) PGA=1.60g (e) PGA=2.00g (f) PGA=2.40g

Fig. 7 – Hysteretic curves of the CFST-RC specimen under the seismic actions of Wenchuan Earthquake

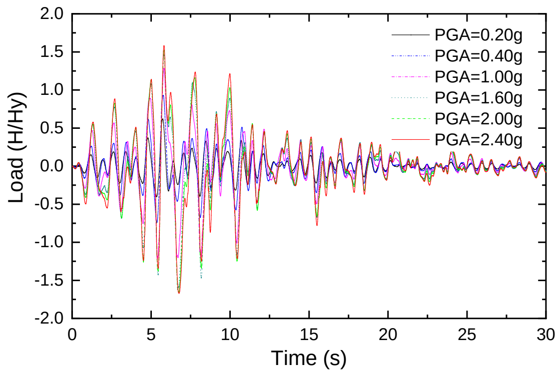
3.3 Time-history curves

The time-history curves of the lateral displacement at the top of the column, the lateral load at the bottom of the column, and the accumulative dissipated energy under Kobe and Wenchuan Earthquakes are plotted in Fig. 8 and Fig. 9, respectively, where the dissipated energy is normalized using the energy unit E_y = 1/2$P_y\delta_y$ = 777.2 kN·mm.

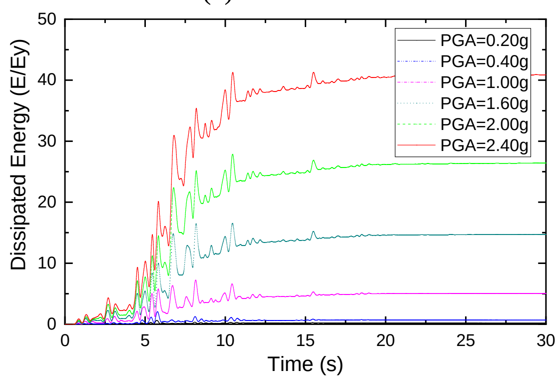
By comparing the time-history curves of CFST-RC columns under the seismic actions of Kobe Earthquake and Wenchuan Earthquake, the difference in ground motion characteristics has a significant effect on the seismic response of the structure. It can be seen from Fig. 4(b) that the first-order natural vibration period of the actual CFST-RC column pier is 0.79s, which falls near the characteristic period of the response spectrum of ground motion of Kobe Earthquake, while the ground motion of Wenchuan Earthquake has more short-period components, and the seismic response near 0.79s is rather small.



(a) Lateral displacement

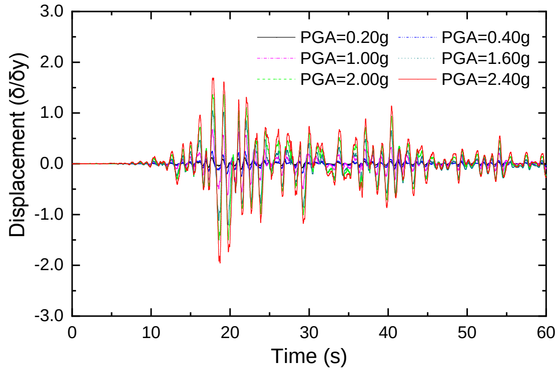


(b) Lateral load

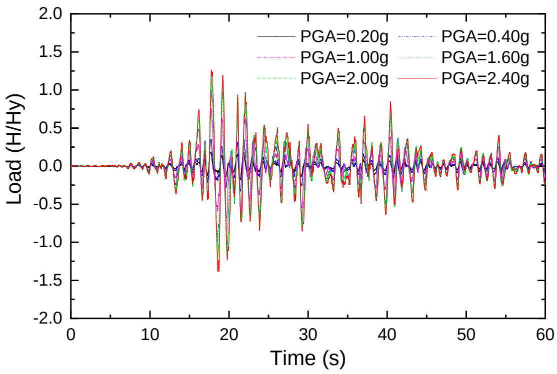


(c) Accumulative dissipated energy

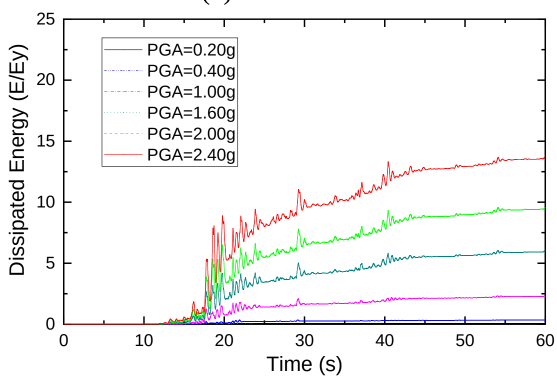
Fig. 8 – Time-history curves of Kobe Earthquake



(a) Lateral displacement



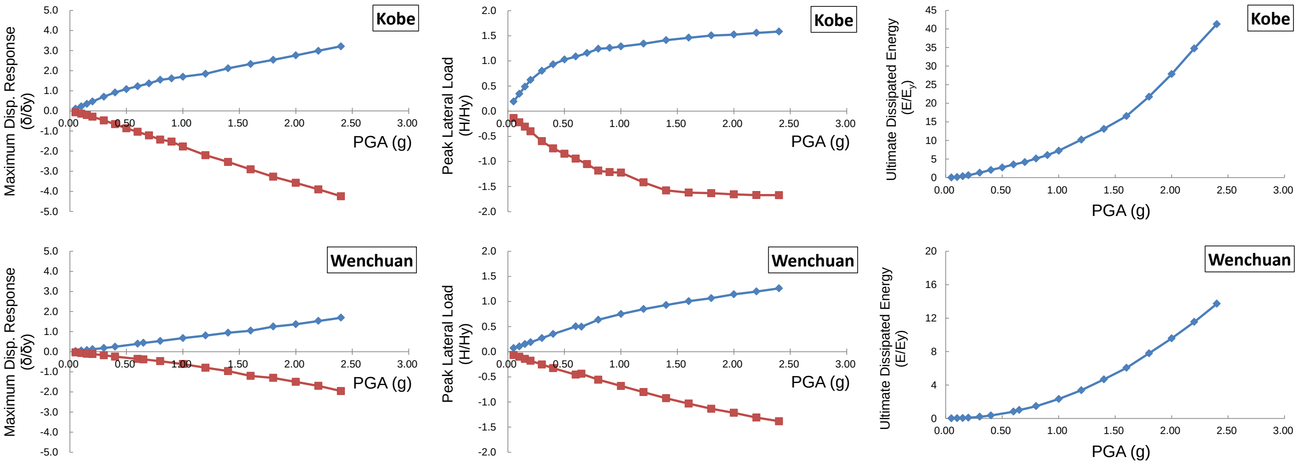
(b) Lateral load



(c) Accumulative dissipated energy

Fig. 9 – Time-history curves of Wenchuan Earthquake

Fig. 10 illustrates the maximum displacement response, the peak lateral load, and the ultimate cumulative dissipated energy of CFST-RC columns under different intensity of ground motions. It is not difficult to see that as the PGA of the input ground motion was gradually increased, the maximum displacement response increases nearly linearly, and the structure enters the elastoplastic phase from the elastic working state, which causes the increase rate of the peak load to gradually slow down, especially after the PGA of Kobe ground motion reaching 1.60g, the peak lateral load of the test specimen gradually reaches the structural bearing capacity; moreover, as the elastoplastic deformation of the structure increases, the area enclosed by the hysteresis curve also increases, and the seismic energy dissipated by the structure increases significantly.



(a) Maximum displacement response (b) Peak lateral load (c) Ultimate dissipated energy

Fig. 10 – Change of seismic performance index with increase of ground motion intensity

4. Conclusions

A pseudo-dynamic test of two 1/8-scaled CFST-RC columns was performed by using the seismic records obtained from the 2008 Wenchuan Earthquake and the 1995 Kobe Earthquake to study the seismic behavior of the CFST-RC column under the action of different intensity of ground motions. The main conclusions of this study can be summarized as follows:

(1) The CFST-RC column has shown good seismic performance, and the structure was in the elastic state when subjected to the intensity-8 frequent, basic, rare and extremely rare earthquakes.

(2) When the PGA of loading condition reached 1.0g (corresponding to intensity-9 rare earthquake), the RC web began to crack and CFST limbs yielded and the structure entered the elastoplastic working state; with the increase of PGA, the shear cracks on the RC web were greatly increased, and the yield ring gradually formed in the plastic hinge region at the bottom of the CFST limb; however, until the end of test, the specimens did not have obvious damage.

(3) With the increase of PGA, the maximum response displacement at the top increased nearly linearly, and the cumulative dissipated energy grew nonlinearly; while the peak lateral load gradually reaches the bearing capacity of the structure.

5. Acknowledgements

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6. References

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