

Influence of Steel and Carbon Fiber Reinforcement Bars on Seismic Performance of Precast Segmental Bridge Columns

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Abstract: A new design method aiming at improving construction efficiency and incorporating new materials is proposed, in which the effect of substituting partial ED bars with carbon fiber bars in precast segmental bridge piers on the lateral strength and damage level is investigated. The simulation is first taken to validate the proposed method by comparing with the pseudo static test results. Then study is focused on the effect of substituting partial ED bars with carbon fibre reinforced bars on the response of piers under the loading of pseudo static cyclic load and seismic ground motion. The results show that adding carbon fiber reinforcement bars can enhance the lateral strength of column, and increase the effective stiffness, as well as decrease the equivalent viscous damping ratio and hysteretic energy dissipation. It is found that carbon fibre reinforcement bars help keep the column survival under the ground motion with high intensity. The discussion is made on the column response under ground motion using an absolute energy method. The input energy and hysteretic energy absorbed in the four specimens under the three ground motion are also analyzed, which leads to the conclusion that, the increase of input energy is inversely proportional to the increase of the hysteretic energy of columns.

Key words: prefabricated construction; precast segmental column; seismic response; carbon fibre reinforcement; energy dissipation

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Precast construction is widely used in the world for accelerated project schedule and innovative design that yield safe and economic scheme of bridges or buildings^[1]. This construction manner has been used in girders or columns of viaducts and overseas bridges in China^[2]. Constructing of bridge columns with prefabricated component has several advantages including reducing site construction work, accelerating bridge construction, mitigating traffic jam in urban area, improving work zone safety, reducing life cycle costs and environmental impact^[3-4]. Although precast construction is proved practical in low earthquake intensity area, its spreading to high intensity area is greatly concerned.

Under the earthquake excitation, the bridge column is expected to form plastic hinge near the base in common monolithic column design philosophy. But in precast

segmental bridge columns, the joint opening will prevent the forming of plastic hinge. Hence the energy dissipation ability of precast segmental bridge column is weak in comparison with the monolithic case^[1]. Several researchers investigated the seismic performance of precast segmental bridge columns through model test and numerical simulation^[5-8]. Among these studies, Ou proposed an energy dissipation bars scheme^[8].

Composite material such as fiber-reinforced polymer and fibre-reinforced bars is increasingly used in design and retrofit of earthquake resistant structures which has advantage of high strength, high elastic modulus, and high fatigue resistance and erosion prevention. Zhu^[9], Fahmy^[10] and Xie^[11] proposed different systems of composite material as reinforcement for aseismic bridge columns.

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Tab. 1 Material property

MPa

Concrete	Steel reinforcement bar		Prestressing tendon		Carbon fibre bar	
compression strength	Yield strength	Ultimate strength	Yield strength	Ultimate strength	Elastic modulus	Ultimate stress
45	454	665	1 682	1 852	227 535	3 930

The present study mainly deals with the seismic response of precast segmental bridge columns under the loading of cyclic reversal lateral load and ground motion records with partial conventional steel reinforcement energy dissipation bars be replaced by carbon fiber bars.

1 The precast segmental bridge column specimen

The precast segmental bridge column of the present study is from the test database of literature [8]. The specimen C5C-UB was composed of foundation, column segments and bent cap, as illustrated in Fig. 1. The column segments were stacked one on the other, then prestressing strands were post-tensioned through section hollow, and energy dissipation (ED) bars were set in the ducts embedded in concrete section, at last the ED bar ducts were grouted. The energy dissipation bars were left unbonded for a length of 400 mm in the foundation near the base joint. The design details of the specimens can refer to literature [8]. The material property was shown in Tab. 1. The carbon fibre bar was assumed to be used in some specimens listed in Tab. 2, and the material property was suggested by Bank [12].

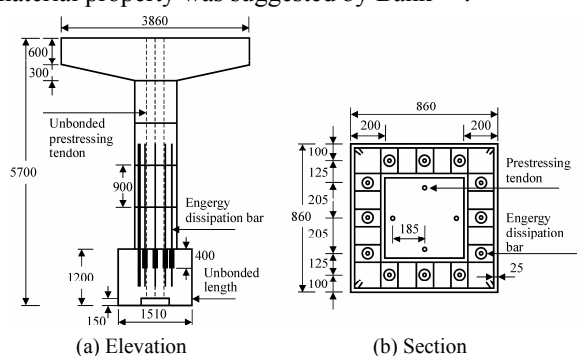


Fig. 1 Scheme of column test specimen (Units: mm)

2 Model discretization

2.1 Material model

The concrete material is simulated with the Kent-Scott-Park model with loading and unloading stiffness degradation, which has simple form and high calculation efficiency. This model was first proposed by Park and

Kent [13], and was later revised by Scott [14]. The stress and strain relation is comprised by three parts, parabolic ascending part, linear descending part and the horizontal part. The stress-strain relation of concrete can refer to literature [14]. Fig. 2(a) shows a typical hysteretic stress-strain curve of confined concrete.

The energy dissipation bars utilize the Giuffre-Menegotto-Pinto material model [15]. In this steel model, linear distribution of strain along the depth of section is assumed (plane section assumption), excluding bond slip during all the loading history, and local buckling of steel bars. Fig. 2(b) shows a typical hysteretic stress-strain curve of steel reinforcement.

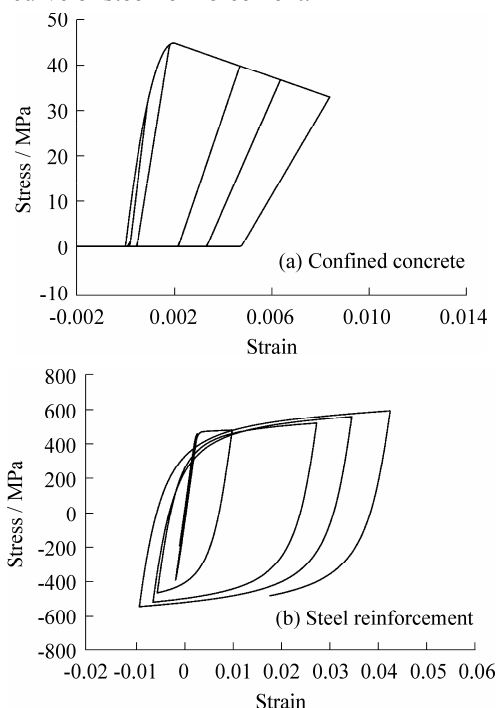


Fig. 2 Typical stress-strain hysteretic curves

The post-tensioned tendon is assumed to conform to bilinear elastic-plastic material model, the second stiffness was properly chosen according to the test data [8]. The carbon fibre bar is assumed to respond in linear elastic manner under axial tension or compression load.

2.2 Fibre beam-column element

The section of beam-column element was divided into a number of fibres, assuming the plane section remain plane, neglecting the crack of concrete and bond-slip of

steel reinforcement (these two effects were considered through modifying the stress-strain relation), and overlooking the shear deformation. Every section was divided into a number of fibres to simulate the variation of concrete and steel reinforcement area along the element length. With these section fibres, section stiffness and resistant force can be derived through integration.

2.3 Finite element model

The precast segmental bridge column specimen was modeled with OpenSees program: an open source software for seismic response simulation developed by the University of California Berkeley. The column was modeled with beam-column elements, the element section was discretized into concrete fibres and steel reinforcement fibres as illustrated in Fig. 3. The unbonded post-tensioned tendons were modeled with truss elements. The foundation to segment or segment to segment joints were not explicitly modeled, the opening of joints were involved in the stress-strain relationship of concrete material by overlooking its tension strength.

3 Model validation

The response of precast segmental bridge column specimens under the cyclic reversal pseudo static load was modeled with the finite model of Fig. 3. The comparison between the simulation results and the test results were illustrated in Fig. 4. The force-displacement curve was shown in Fig. 4(a). The simulation result agreed well with the test result, except the negative post-yield stiffness and residual displacement which has some discrepancies with the test data. The tendon force, joint opening and the equivalent viscous damping of simulation also agreed well with the test results. Although some discrepancies existed between the simulation and test results, the finite model can capture the main features of the column response, thus it can be used to precast segmental bridge column seismic response simulation.

4 Segmental bridge columns with carbon fiber reinforcement as ED bars

In order to investigate the effect of carbon fibre reinforcement in reducing the damage level of precast segmental bridge columns under the hysteretic load and

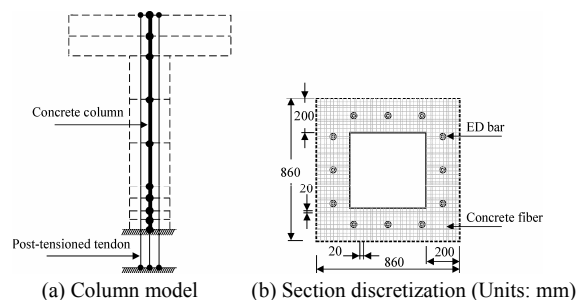


Fig. 3 Column finite element model

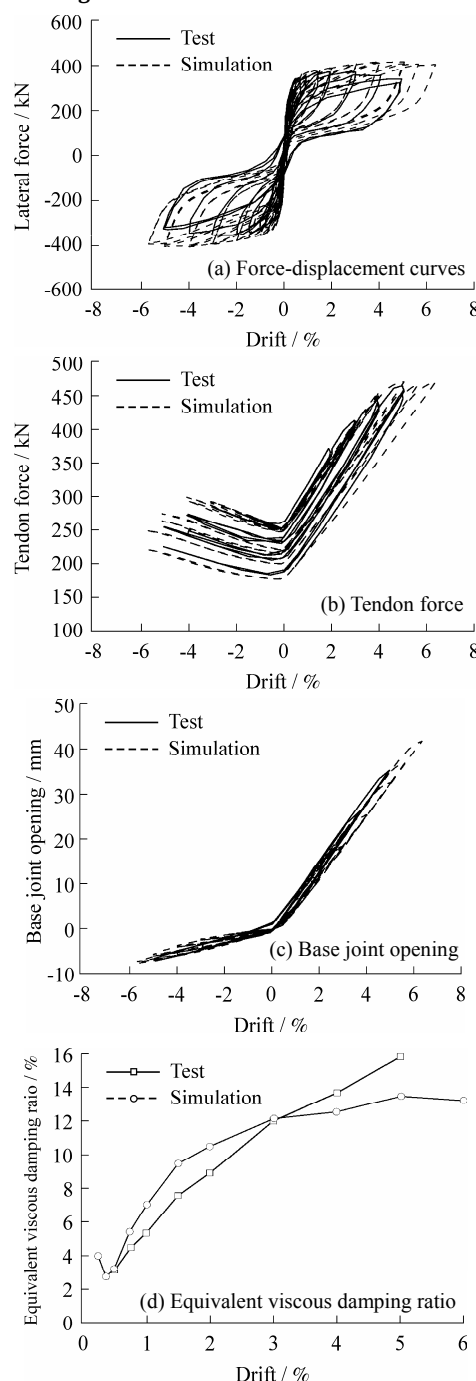


Fig. 4 Comparison between the simulation and test results

ground motions, three specimens were assumed based the specimen C5C-UB^[8]. The specimen C5C-UB was designated as S1, specimen S2 was one ED bar be replaced by carbon fibre reinforcement with the same area in each side of loading direction (2 bars in total), specimen S3 was 4 ED bars be replaced by carbon fibre reinforcement, specimen S4 was 6 ED bars be replaced by carbon fibre reinforcement. The other parameters such as the tendon ratio, tendon stress and gravity load ratio remain unchanged. The parameters of the four specimens were illustrated in Tab. 2.

Tab. 2 Specimens and parameters

No.	ED bar ratio/%	Carbon fiber ratio/%	Tendon ratio/%	Tendon stress/MPa	Gravity load ratio/%
S1	0.50	0.000	0.21	925.1	10.0
S2	0.417	0.083	0.21	925.1	10.0
S3	0.333	0.167	0.21	925.1	10.0
S4	0.250	0.250	0.21	925.1	10.0

4.1 Response under pseudo static cyclic loading

The response of specimens S2 to S4 under the cyclic hysteretic load was calculated and was compared with the simulation results of S1, as illustrated in Fig. 5. (1) The force-displacement curves are shown in Fig. 5 (a). With increasing of carbon fibre reinforcement, the ultimate lateral strength increased prominently. The lateral strength of specimen S1 is 397.9 kN at 6% drift, from S2 to S4 the lateral strength is 734.2 kN, 927.4 kN,

1 092.8 kN respectively. The post-yield stiffness of specimens S2 to S4 was relatively higher compared with the results of S1. The carbon fiber bars are efficacious in enhancing the ultimate lateral strength of columns. (2) As illustrated in Fig. 5(b), with increasing of lateral displacement, the effective stiffness of the four specimens decreased nonlinearly. High ratio of carbon fibre reinforcement contributed to high effective stiffness. This is meaningful in controlling the maximum displacement for a given lateral force of column under seismic impact. (3) The equivalent viscous damping is illustrated in Fig. 5(c). The damping ratio dropped from about 13% for specimen S1 to about 2% for specimen S4 with the increasing of carbon fibre amount. Adding carbon fibre bars tends to lower the viscous damping ratio. (4) The accumulated energy dissipation was shown in Fig. 5(d). The hysteretic energy dissipation decreases with increa-

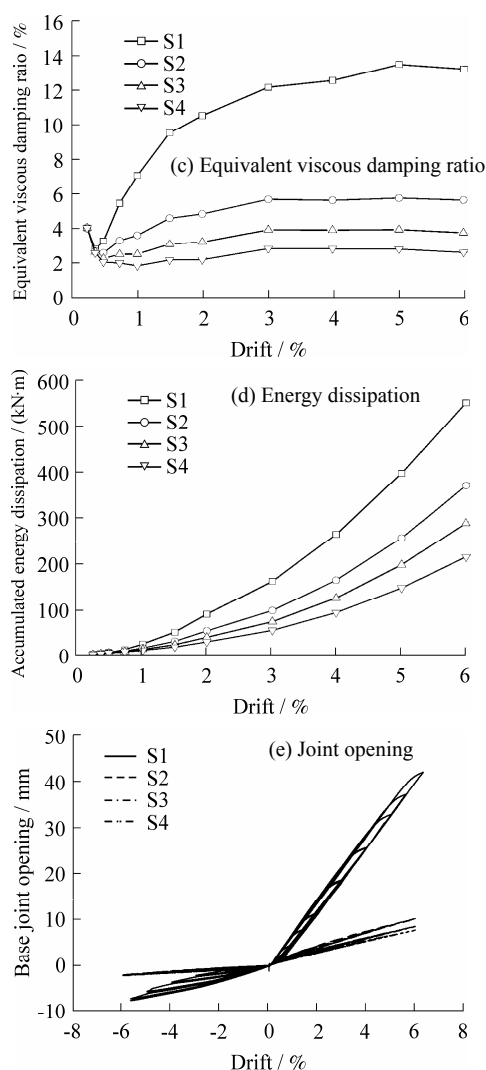
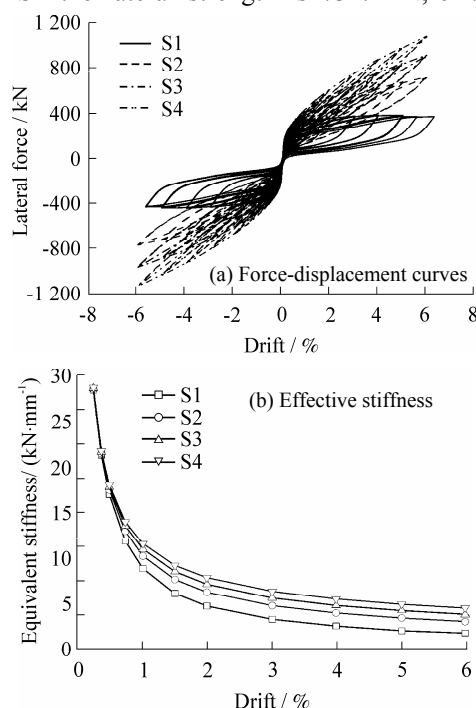


Fig. 5 Pseudo static test simulation results

sing of carbon fibre amount. The energy dissipation for specimen S1 to S4 is 555.3 kN·m, 372.2 kN·m, 288.9 kN·m and 215.2 kN·m respectively at 6% drift. This is caused by the linear elastic stress-strain relation of carbon fibre, which almost has no yield stress, thus leads to small hysteretic cycle area to dissipate energy. (5) The base joint opening was illustrated in Fig. 5(e). Due to the crush of concrete in the compression toe, the opening in the compressive side is negative. The positive joint opening is much bigger than the negative value. From specimen S1 to S4, the maximum base joint opening is 42.3 mm, 10.1 mm, 8.4 mm and 7.7 mm at 6% drift respectively. The effect of carbon fibre reinforcement in reducing joint opening is evident.

4.2 Response under ground motion records

In order to study the response of precast segmental bridge columns under the earthquake excitation, three history ground motion records were selected as the input load. The seismic waves were shown in Fig. 6. The response spectra of the three seismic waves were illustrated in Fig. 7. The features of the three earthquake ground motion records were shown in Tab. 3. The peak ground acceleration (PGA) of Mammoth Lakes (1983) was 0.149 8 g, while PGA of Landers (1992) was 0.151 5 g, and 0.376 4 g for Kocaeli (1999), which is in ascending order. The first vibration frequency of specimen S1 is about 2.78 Hz, and the period is about 0.36 s, as shown in Fig. 7. The response spectra of the three records were 161.1 gal, 404.8 gal, and 707.0 gal (1 gal=1 cm·s⁻²) respectively at the period of 0.36 s.

The time history response of the specimens S1 and S2 from Tab. 2 under the three earthquake ground motion records were shown in Fig. 8, Fig. 9 and Fig. 10 respectively. The peak response of column tip displacement, base shear and failure modes were shown in Tab. 3. PSC designates the Prestressed and Steel reinforced Column, PCC designates the Prestressed and Carbon fibre

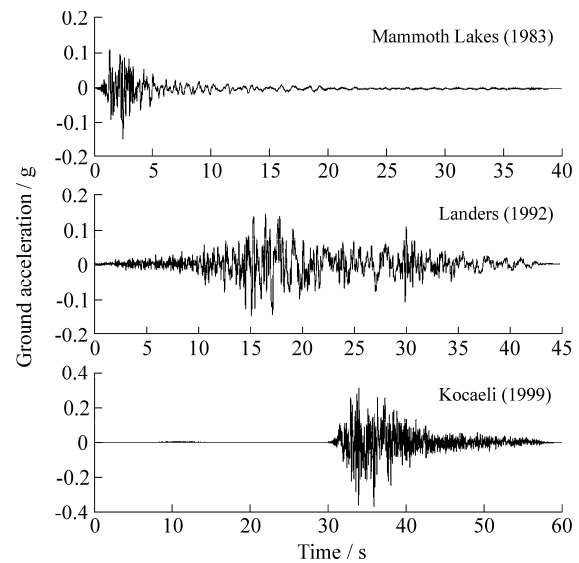


Fig. 6 Ground motion records

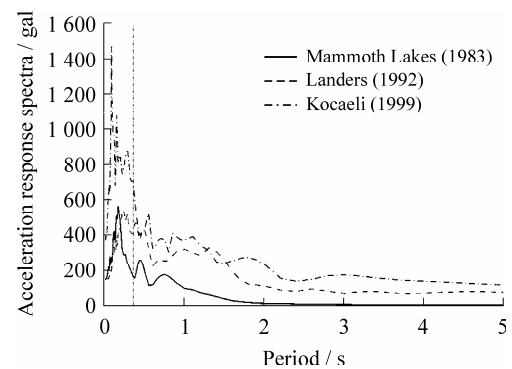


Fig. 7 Response spectra of ground motion records

reinforced Column. The parameters of PSC and PCC were the same as specimens S1 and S2 respectively as shown in Tab. 2. Under the excitation of Mammoth Lakes record, the response of PSC is bigger than that of PCC, as is shown in Fig. 8. This is caused by the frequency variation of the two columns. As the intensity of ground motion record increases, the PSC column was damaged under the act of Landers record and Kocaeli record, but the PCC column was still safe. The reason is that carbon fibre bars have high modulus and ultimate

Tab. 3 Seismic history response

Ground acceleration	Maximum ground acceleration / g	Column Type	Maximum base Shear / kN	Maximum tip Displacement / mm	Failure mode
Mammoth Lakes(1983)	0.1498	PSC	326.3	40.4	N/A
		PCC	329.0	25.2	N/A
Landers(1992)	0.1515	PSC	326.1	33.3	Concrete crush
		PCC	373.6	36.2	N/A
Kocaeli(1999)	0.3764	PSC	509.1	81.1	Concrete crush
		PCC	503.6	115.1	N/A

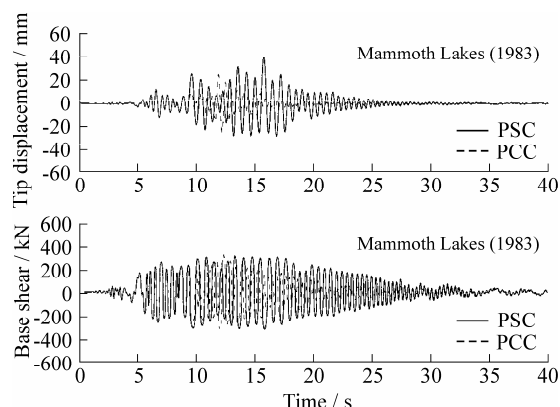


Fig. 8 Seismic response to Mammoth Lakes record

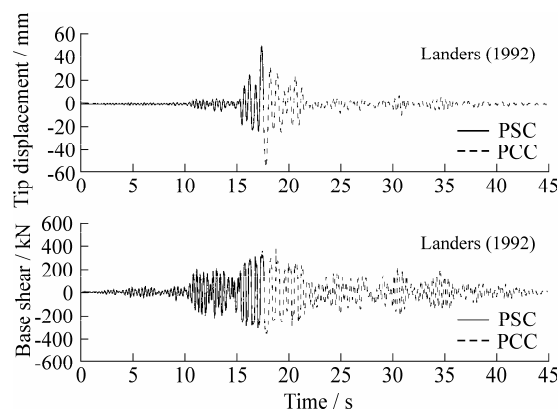


Fig. 9 Seismic response to Landers record

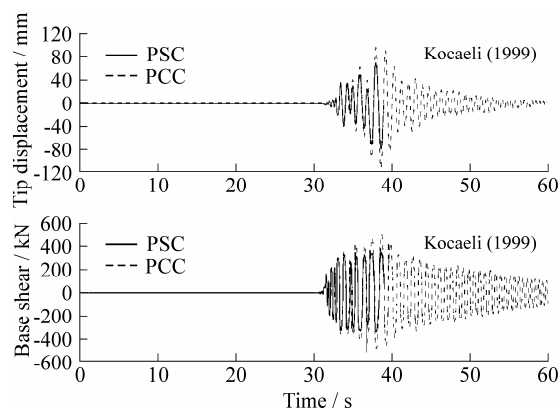


Fig. 10 Seismic response to Kocaeli record

stress compared with steel bars, the ultimate strength of the column is greatly increased, as shown in Fig. 5(a). The maximum base shear of PSC before the time of failure under the Landers record was 326.1 kN, which was lower than the pseudo static test ultimate lateral strength of 397.9 kN. But the maximum base shear of PSC under the Kocaeli record was 509.1 kN, which was much bigger than the pseudo static test ultimate lateral strength (397.9 kN). The maximum base shear of PCC under the Kocaeli record was 503.6 kN, which was lower

than ultimate lateral strength of 734.2 kN in pseudo static test. This reveals that the columns with partial carbon fiber bars can resist the earthquake like the intensity of Kocaeli record and still has some strength abundance.

4.3 Energy analysis

The failure of columns can be investigated from the energy input and dissipation as well. Unlike the traditionally strength and ductile design manner, an energy-based design method was proposed by Housner. He assumed that the energy demand during an earthquake can be predicted and the energy supply of a structure can be determined. A satisfactory design indicates that the energy supply of a structure should be larger than the energy demand of an earthquake. The energy input and dissipation of a structure during an earthquake can be calculated with an absolute energy method^[17].

The equation of energy of a SDOF structure under the act of earthquake can be written as:

$$E_k + E_\xi + E_s + E_h = E_i, \quad (1)$$

where E_k is the kinetic energy, E_ξ is the damping energy, E_a is the absorbed energy, it is composed of recoverable elastic strain energy E_s and irrecoverable hysteretic energy E_h , E_i is the input energy.

The input energy and hysteretic dissipation energy of the PSC and PCC columns under the excitation of the three ground motion records was calculated and illustrated in Fig. 11. From the figure, we can conclude that: (1) The input energy of Mammoth Lakes record increased very fast at the beginning, but the hysteretic energy dissipation increased relatively slowly. The input energy of PSC and PCC columns was almost the same, which is about 65.5 kN·m. The hysteretic energy of PSC (25.1 kN·m) is much bigger than that of PCC (7.2 kN·m). (2) The input energy of Landers record is about 789.7 kN at the end of excitation for PCC. But the PSC column was damaged at the time of 17.12 s. We can guess that the PSC and PCC column has the same input energy and the same hysteretic energy, but the PCC has higher strength and is survival after the earthquake. The total hysteretic energy of PCC is about 26.7 kN·m, which is about 1/29.6 of the input energy. This reveals that the PCC column has low hysteretic energy dissipation capacity, but high elastic strain energy. (3) The input energy of Kocaeli record is 6 519.0 kN at the end of excitation for PCC, which is about 100 times that of Mammoth Lakes record. The PSC column was damaged

at the time of 38.90 s. The total hysteretic energy of PCC is about 114.0 kN·m, which is about 1/57.2 of the input energy.

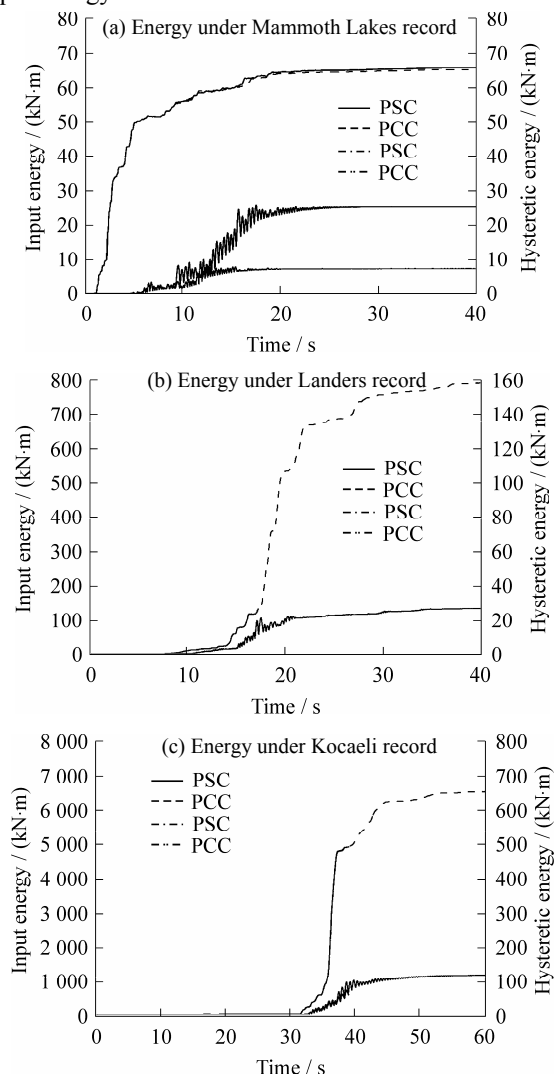


Fig. 11 Seismic energy input and dissipation

The results show the hysteretic energy of PCC increases slowly compared with the increasing of input energy. The hysteretic energy is part of the energy absorbed in structure. This means that with increasing of the intensity of earthquake, the absorbed energy increases slowly, and the ratio of hysteretic energy to input energy decreases abruptly.

5 Conclusions

From the results obtained in this study, the following conclusions can be drawn.

(1) The pseudo static test and seismic response of precast segmental bridge columns can be simulated by

the nonlinear program OpenSees with fibre beam-column element.

(2) With increasing of carbon fibre reinforcement, the ultimate lateral strength increased prominently. The lateral strength increased from 397.9 kN to 1 092.8 kN for specimens S1 to S4 at 6% drift.

(3) With increasing of lateral displacement, the effective stiffness of the four specimens decreased nonlinearly. High ratio of carbon fibre reinforcement contributed to high effective stiffness.

(4) The equivalent viscous damping ratio dropped from about 13% for specimen S1 to about 2% for specimen S4 with the increasing of carbon fibre amount.

(5) The hysteretic energy dissipation decreases from 555.3 kN·m to 215.2 kN·m at 6% drift for specimen S1 to S4 with increasing of carbon fibre amount. The linear elastic stress-strain material property of carbon fibre leads to small hysteretic cycle area of energy dissipation.

(6) By replacing partial steel reinforcement bars with the same area of carbon fibre bars, the base joint opening dropped from 42.3 mm to 7.7 mm for specimens S1 to S4.

(7) As the intensity of ground motion record increases, the PSC column was damaged under the act of Landers record and Kocaeli record, but the PCC column was safe after all three ground motion records. The reason is that carbon fibre bars have high elastic modulus compared with steel bars and the ultimate strength of the column is enhanced.

(8) The input energy increased with power order compared with the response spectra intensity. The hysteretic energy dissipation increased slowly compared with the increase amplitude of input energy.

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普通钢筋和碳纤维筋对预制节段桥墩抗震性能的影响

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摘要: 为了得到快速施工和利用新材料的预制节段桥墩设计方法, 研究了部分钢筋替换为碳纤维筋时预制节段桥墩的水平承载力和破坏等级. 首先通过与拟静力试验结果的比较证明了仿真分析的正确性, 然后研究了部分普通钢筋替换为碳纤维筋, 对拟静力循环荷载和地震地面运动分别作用时预制节段桥墩响应的影响. 结果表明: 碳纤维筋能提高桥墩水平承载力, 增大有效刚度, 降低等效粘滞阻尼比和滞回能量耗散. 地震时程计算表明: 部分普通钢筋替换为碳纤维筋时, 使得预制节段桥墩在较强烈地震地面运动下不倒塌. 利用绝对能量法分析了桥墩在地震地面运动下的能量吸收和耗散情况, 并主要研究了4种桥墩试件在3种不同地震地面运动作用下的输入能量和滞回能量耗散, 结果是随着桥墩输入地震能量的增大滞回能量耗散增长缓慢.

关键词: 预制施工; 预制节段桥墩; 地震响应; 碳纤维筋; 能量耗散

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