Research on seismic performance of design detailing based segmental prestressed concrete bridge pier

Hongyi Wei & Hao Wang & Tiantian Li & Zhiqiang Wang
Department of Bridge Engineering, Tongji University, Shanghai 200092, China

Feng Liu
Lin Tung-Yen & Li Guo-Hao Consultants Shanghai Ltd.

Ning Zhao
Shanghai Tunnel Engineering & Rail Transit Design and Research Institute

SUMMARY:
With the application of the segmental bridge piers in high earthquake risk zone, their seismic performances are increasingly concerned and investigated by the designers and researchers. A series of the pseudo-static tests were carried out in order to investigate the seismic performance of the segmental prestressed solid rectangular concrete bridge piers under different design detailing such as the number of pier segments, prestressed approaches (bonded, unbounded or both) and prestressed strands layout (in the section center or on the section edge). The result shows that the seismic performance of the segmental prestressed bridge pier is different from that of the integral pier. For the effect of the prestressed approaches, the prefabricated bonded prestressed concrete bridge pier has more energy dissipation capacity, while the unbonded one has less residual displacement. The specimen designed with both bonded prestressed strands on the section edge and unbounded in the section center not only has more ductility capacity, less residual displacement, but also has more energy dissipation capacity.

Keywords: Segmental prestressed concrete pier, Seismic performance, Pseudo-static test

1. INTRODUCTIONS

In recent years, there were many urban viaducts and light rail projects constructed now or in the future in China. Urban bridge constructions were governed by various constraints, and rapidity and green of construction was urgently becoming the needs. The precast assembly construction technology of bridge superstructure and piers has been applied in some long strait bridges built, such as East Sea Bridge (Wang et al., 2008), Hangzhou Bay Bridge, Hong Kong-Zhuhai-Macao Bridge, the various urban viaducts and rail transit viaducts. This construction method can be used to reduce the on-site construction time, minimize traffic disruptions and environmental impact, and improve the work zone safety, especially in busy city and bad environment.

With the application of the segmental assembly bridges piers in high earthquake risk zone, their seismic performances are increasingly concerned and researched by the designers and researchers.
Conventional reinforced concrete bridges are anticipated to suffer extensive damage and permanent deformations during and after a earthquake. More researchers have studied on the seismic performances of prestressed concrete solid bridge piers. The use of unbonded post tensioning in the center of section of the precast segmental columns to reduce residual displacement and improve the seismic response have been investigated by some researches (Mander and Cheng 1997; Hewes and Priestley 2002; Bilington and Yoon 2004; Sakai and Mahin 2004,Chung-chen chou and Yu-Chih Chen 2006; et al.). The result shows that these bridge column systems can produce significantly less damage and residual displacements compared with a traditional concrete column, and their seismic performance depends on the design details.

To get an overall understanding about the effect of design detail on the seismic performance of precast bridge piers, this paper investigates the effect of the number of pier segments, prestressed approaches (bonded, unbounded or both), prestressed strands layout (in the middle or at the edge of section) through the tests. Their seismic performance in terms of ductility, energy dissipation, self-centering capability and damage mechanisms are compared and analyzed.

2. TEST DESIGN

2.1. Specimen design

In order to investigate the seismic performance of the segmental prestressed concrete bridge piers with different design detailing, six pseudo-static tests of the single column solid rectangular pier specimens were designed. The main structural characteristics of each specimen were provided as following:

Specimen I-UBE was an integral cast-in-place prestressed concrete pier with the unbonded prestressed strands on the section edge. The layout of Specimen I-BE was same as the Specimen I-UBE but with bonded prestressed strands.

Specimen S-UBC-1, S-UBC-3, S-UBE-3 and S-H-3 were segmental precast prestressed concrete bridge piers. The first specimen had one segment and some shear keys and epoxy mortar at the joint between segment and pile cap, and the latter three specimens had three segments but no shear keys and epoxy mortar at every joint. For the prestressed system, specimen S-UBC-1 had unbonded prestressed strands in the section center. The specimen S-UBC-3 was same as specimen S-UBC-1. Specimen S-UBE-3 had unbonded prestressed strands on the section edge. Specimen S-H-3 had hybrid layout with bonded prestressed strands on the section edge and unbonded in the section center.

All specimens had an identical size. The size of column was 360×500×1240 mm. The pile cap was 1200 ×1200 ×500 mm. The loading end was 600×600×360mm. The effective height of specimen was 1750mm. To anchor the prestressing strands, there was a 500×120×1200 mm notch at each bottom of pile cap.

The concrete compressive strength was 63.6MPa. The longitude reinforcement yield strength was 335MPa. The stirrup yield strength was 235MPa. The prestressed strands were high-strength low relaxation strands (7Φ5 steel wires) with diameter of 15.24mm. The prestressed strand's yield strength was 1670MP. The layouts of the dimensions, reinforcements and prestressed strands of the test specimens were shown in Figure 2.1 and Table 2.1.

The ratio of axial compression corresponding to dead load and prestress were shown in Table 2.2.

Table 2.1. Description of specimens

Longitude reinforcement		Prestressed strands		Transverse steel	
Type	Reinforcement ratio	Type	Reinforcement ratio	Type	Transverse steel ratio
26-D10	1.13%	6×7D5	0.46%	D6@35mm	1.08%

Table 2.2. The ratio of axial compression

Dead load			Compression made by prestressed strands		
σ_c (MPa)	Axial compression ratio	Axial pressure (kN)	σ_c (MPa)	Axial compression ratio	Single strand tension(kN)
3.2	10%	422	3.2	10%	106

2.1. Test setup and loading history

The pseudo-static test setup was shown in Figure 2.2, in which the specimen was inverted when loaded. The top end of the specimen was fixed and the bottom end was supplied lateral cyclic loading by the actuator.

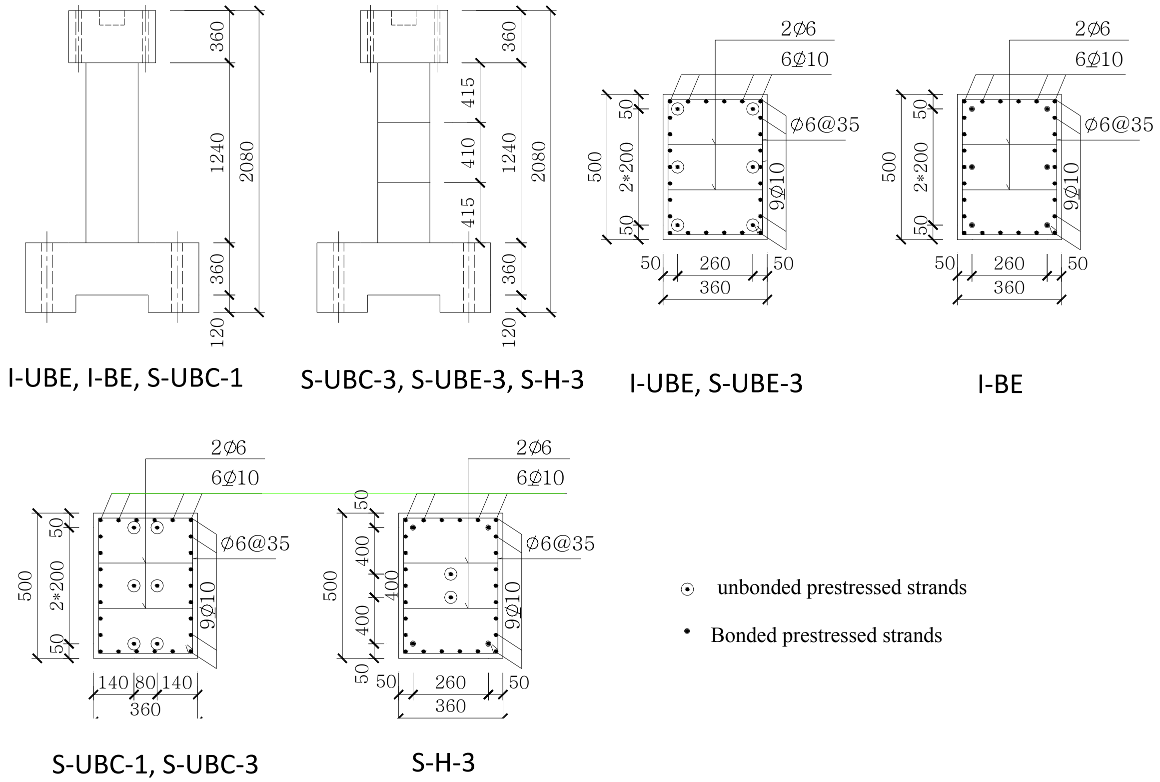


Figure 2.1. Specimen details

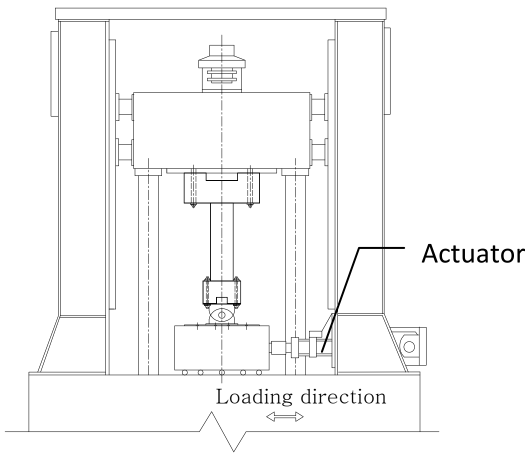


Figure 2.2 The experimental setup for specimen

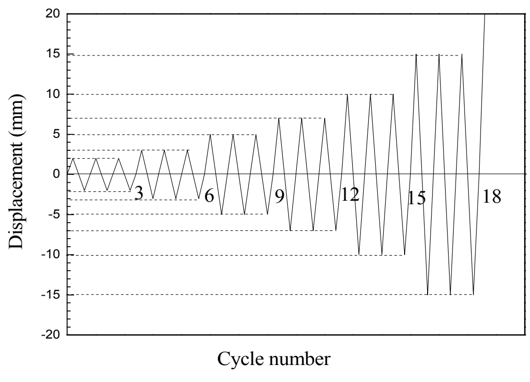


Figure 2.3 Loading history

The displacement-controlled loading cycle was shown in Figure 2.3. At the beginning, the displacement amplitudes were 2, 3, 5, 7, 10, 15mm respectively. Then the displacement was supplied with increments of 5mm. As soon as the specimen strength decreased to 85% of its maximum value, the loading process would be stopped.

3. TEST RESULTS AND DISCUSSION

According to the pseudo-static tests carried out under different design detailing, it is proved that the design parameters have a significant impact on the seismic performance of the segmental prestressed concrete bridge piers, which can be generalized as the following aspects:

3.1. Failure mode

The failure mode of the segmental precast prestressed concrete bridge piers was the failure of the joints, while the failure mode of the integral piers was the flexural failure of the plastic hinge region at the bottom.

Take the specimen I-UBE for example. With the supplied lateral displacement increasing, some failure characteristics at the bottom of the pier appeared gradually, such as the horizontal cracks, diagonal cracks, the concrete crushing and spalling, longitudinal reinforcement buckling and fracture. The final failure mode of specimen I-UBE is the typical flexural failure as shown in Figure 3.1.

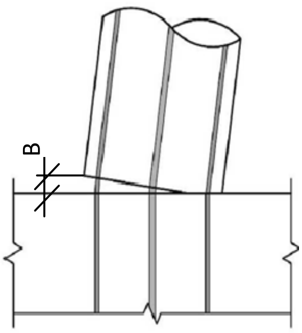


Figure 3.1 Observed failure mode of specimen I-UBE **Figure 3.2** Segmental specimen joint deformation form

For the segmental precast bridge pier, in spite of the precast segments number, the failure of specimen concentrated on the joints especially the one between pile cap and the first segment. The failure mode was the cover concrete spalling and the joints opening.

For example, during the test of the specimen S-UBE-3, the joints opened and closed alternately just as shown in Figure 3.2. The opening angle of the bottom joint (between pile cap and the first segment) was more significant than that of the upper joint (Figure 3.3). The angle of the bottom joint opening increased in a linear trend with the loading at the post-loading period. Figure 3.4 was the failure mode of the specimen S-UBE-3. The cover concrete near the bottom joint spalled severely but the core concrete and the cover concrete away from the joint stayed a comparatively sound state. Also, other joints suffered from much slighter failure.

Because the specimen S-UBC-1 only had one segment, the damage of the bottom joint was more serious than the specimen S-UBC-3.

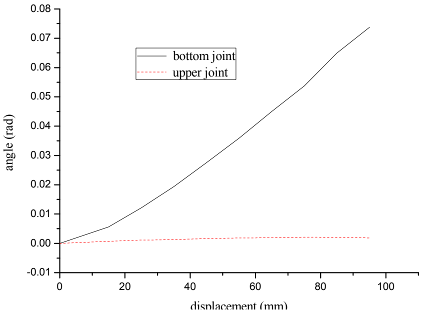


Figure 3.3 The angel of the joint opening **Figure 3.4** Observed failure mode of specimen S-UBE-3

The result in Figure 3.5 showed the different seismic performance clearly between segmental precast specimens and integral cast-in-place specimens. The hysteretic loops of the integral specimens were much plump spindle, whose energy dissipation capacity and residual displacement were larger. Corresponding to the integral specimen, the segmental specimens had the narrow hysteretic loop in flag shape, less energy dissipation capacity and less residual displacement. The specimen S-UBC-1 was special among segmental specimens. Its hysteresis loop was narrow but not obvious flag type. The hysteresis loop rotating around center with the displacement increasing made more residual displacement.

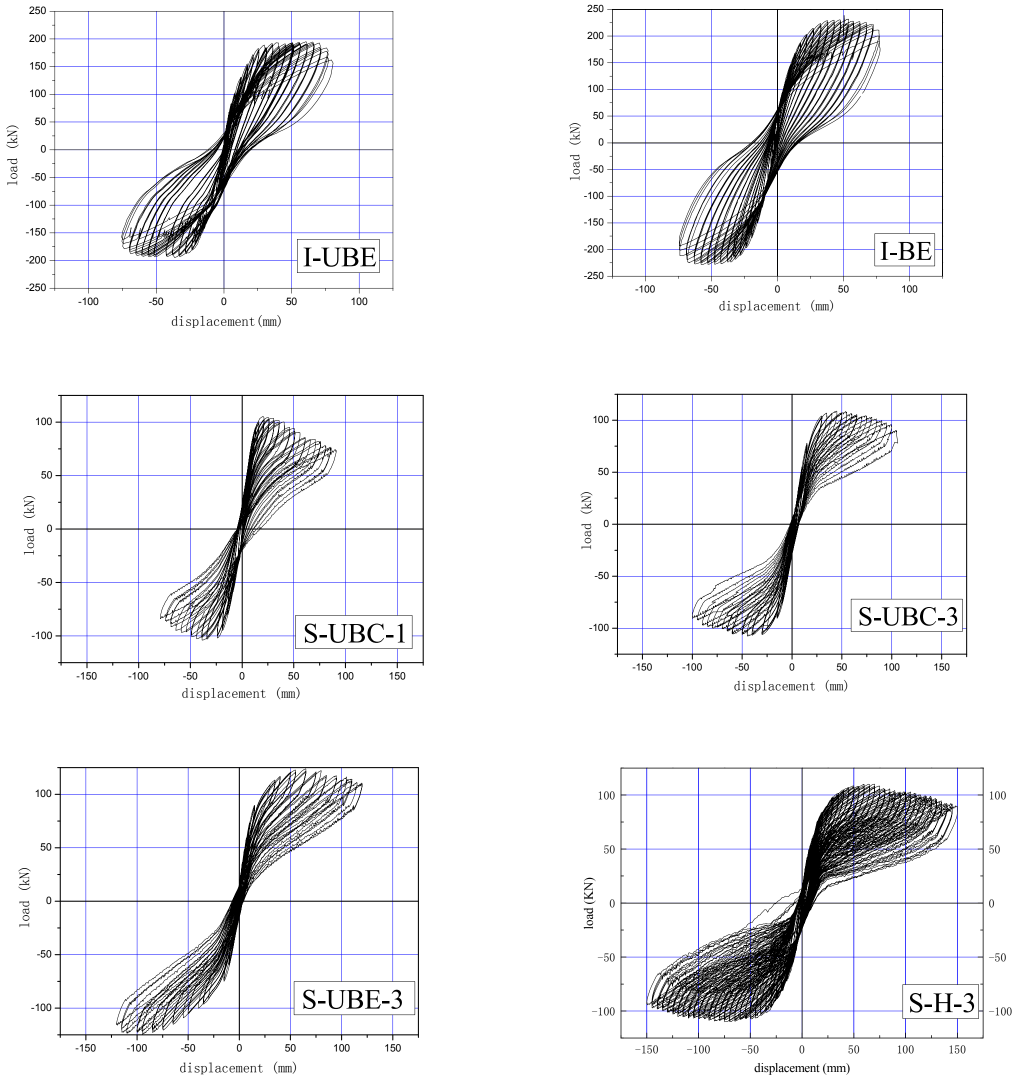


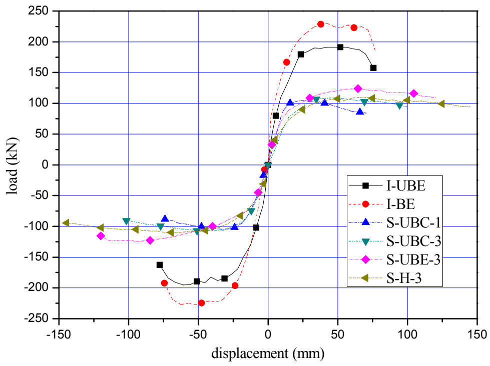
Figure 3.5 Load-displacement hysteretic curves of specimens

3.2. Envelope of a cyclic load-displacement curves characters

The envelope of cyclic load-displacement curves of all specimens were shown in the Figure.3.6.

Using the load-displacement curve in Figure.3.7, the idealized yield displacement U_y was defined as the displacement of the intersection point of the following two lines: the straight line that passes through the origin and B of the envelope curve, and the straight line that passes through P_{max} on the envelope curve and is parallel to the x-axis.

The ultimate displacement U_m was defined as the displacement that occurs when the strength of the descending branch of the load-displacement envelope curve became less than 0.85Pmax, as shown in the Figure 3.7.



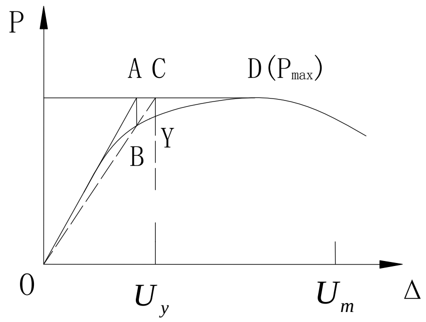


Figure 3.6 The envelope of cyclic load-displacement curve **Figure 3.7** Definition of displacement ductility

The yield force, idealized yield displacement, peak force, ultimate lateral force, ultimate displacement and ductility of envelope curves of specimens were listed in Table 3.1.

Table 3.1. The engineering parameters of envelope curve of segmental specimens

specimen	Yield		Peak		Ultimate		Displacement ductility μ_m
	Horizontal force（kN）	Displacement（mm）	Horizontal force（kN）	Displacement（mm）	Horizontal force（kN）	Displacement（mm）	
I-UBE	156.9	18.5	191.3	42.4	162.6	74.4	4.0
I-BE	203.4	22.2	229.7	42.9	195.3	75.6	3.4
S-UBC-1	96.1	14.0	104.3	25.3	88.6	73.9	5.3
S-UBC-3	91.4	17.7	107.0	51.0	91.0	99.9	5.6
S-UBE-3	91.8	17.1	123.8	64.6	105.3	128.7	7.5
S-H-3	79.6	17.8	110.1	69.4	93.6	146.4	8.2

Known from Figure.3.6 and Table 3.1, for the segmental specimens with three segments, the structural strength is on the slow process of strength decay after the rising stage. Comparing with the integral specimen, the segmental specimens have less strength but more ductility. The strength decay of the specimen S-UBC-1 is the most obvious.

For the effect of the prestressed approaches, the strengths of the specimen I-BE and specimen S-UBE-3 are more than that of the the specimen I-UBE and specimen S-UBC-3 respective, which explains the effect of the bonded prestressed strands and layout with the strands at the section edge on the strength increasing. The load-displacement envelope curve of the specimen S-H-3 also explains the fact mentioned above. The specimen S-H-3 with both bonded prestressed strands on the section edge and unbonded in the section center has less strength than the specimen S-UBE-3 but equivalent with the specimen S-UBC-3. The ductility capacity of the specimen S-H-3 is more than the specimen S-UBC-3 and specimen S-UBE-3.

3.3. Energy dissipation capacity

As known from the energy dissipation capacity–displacement curve (Figure.3.8), for segmental specimen, the relationship between energy dissipation capacity and displacement was almost in a linear and different from the integral specimen in a significant increase trend at the post-loading stage. At same displacement level, energy dissipation capacity of segmental specimen was much lower than integral specimen;

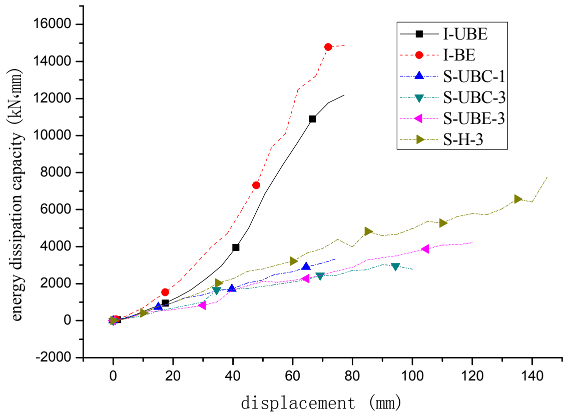


Figure 3.8 Energy dissipation capacity-displacement curve

Comparing the hysteretic energy dissipation respectively between the specimens I-BE and the specimen I-UBE, the specimen S-UBE-3 and the specimen S-UBC-3, the former is better than the later. This presents that the bonded prestressed strands and layout with the strands on the section edge could increase the hysteretic energy dissipation. For the segmental bridge piers, the specimen S-H-3 with hybrid prestressed strands is superior to other one on the hysteretic energy dissipation. For example, when displacement level was 105mm, the hysteretic energy dissipation of specimen S-H-3 was nearly 38% higher than specimen S-UBE-3.

On the influence of the segment number, the specimen S-UBC-1 is better than the specimen S-UBC-3 on the hysteretic energy dissipation.

Table 3.2 shows each specimen's total cumulative hysteretic energy EAD values.

Table 3.2. E_{AD} value

Specimen	I-UBE	I-BE	S-UBC-1	S-UBC-3	S-UBE-3	S-H-3
E_{AD} (kN·mm)	78957.9	102884.5	27234.5	30669.7	39934.2	110948.2

In addition, the equivalent viscous damping coefficient is also used to evaluate structural energy dissipation capacity.

Figure 3.9 is the equivalent viscous damping coefficient-displacement curve. For the integral cast-in-place specimen (I-UBE, I-BE), the equivalent viscous damping coefficient was in a rapidly growing trend with the displacement increased at the post-loading stage. For unbonded prestressed strands specimens with three segments(S-UBC-1, S-UBC-3), the equivalent viscous damping coefficient was in a reducing trend during the initial loading stage and kept at a small value during the middle and latter loading stage. The equivalent viscous damping coefficient of the specimen (S-H-3) was bigger than that of specimen (S-UBC-1, S-UBC-3) and its changing trend was plain. For specimens with single segment (S-UBC-1), equivalent viscous damping coefficient showed slightly reducing trend during the initiation of loading, then showed growth trend.

By comparing equivalent viscous damping coefficient of each specimen at the same displacement level, the specimen with bonded prestressed strands (I-BE) is better than the specimen with unbonded prestressed strands (I-UBE); the specimen with unbonded prestressed strands in the section center (S-UBC-3) is same as the one with unbonded prestressed strands on the section edge (S-UBE-3) and the specimen with hybrid prestressed strands (S-H-3) has more structural damping. When the displacement level was 105mm, the equivalent viscous damping coefficient of the specimen (S-H-3) was 1.6 times larger than the specimen (S-UBE-3). The structural damping of single segmental specimen was larger than multi-segment specimen.

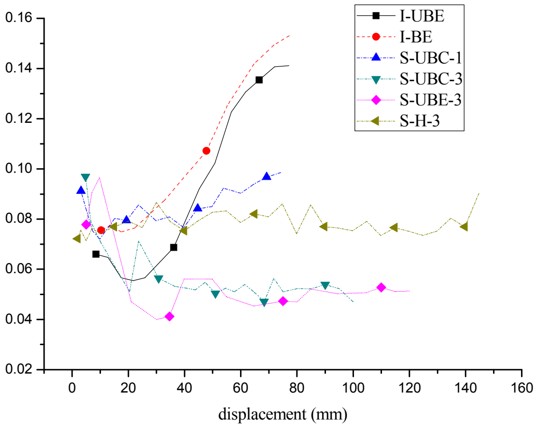


Figure 3.9 $\xi_{eq,h}$- displacement curve

3.4. The residual displacement and opening degree of the joint

Table 3.3 lists the residual displacement on a displacement level, which shows the multi-segmental specimen has less residual displacement and the unbonded prestressed strands can reduce the residual displacement. The residual displacement of single segment specimen S-UBC-1 is relatively larger.

Table 3.3 Residual displacement

Specimen	I-UBE	I-BE	S-UBC-3	S-UBE-3	S-H-3
Displacement level (mm)	70	70	100	100	100
residual displacement (mm)	19, -8.3	15, -18.7	6.4, -1.9	2.5, -5.9	7.5, -3.7

As mentioned above, the joints of the segments opened and closed alternately during the test. The opening width B (Figure 3.2) of the joint increased gradually with the test loading (Figure 3.10). In contrast, the joint opening degree of single segmental specimen S-UBC-1 was larger. For the multi-segmental specimen, increasing the number of segments will reduce the bottom joints opening degree and improve the structural ductility because of other joints opening.

Because the segmental rotation has not been constrained effectively by the unbonded prestressed strands in the section centre, the joint opening degree of specimen S-UBC-3 is larger than specimen S-UBE-3.

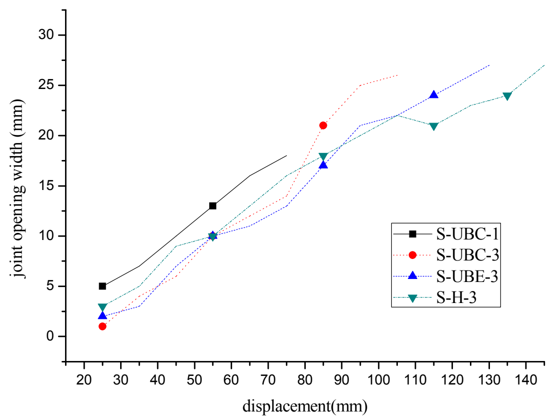


Figure3.10 the joint opening width - displacement

4. CONCLUSIONS

In order to investigate the seismic performance of the segmental prestressed concrete bridge piers, six solid section bridge pier specimens were tested using quasi-static test:

1. The seismic performance of the segmental prestressed bridge pier is different from that of the integral pier. The main failure is the opening of the joints, the spalling of the covering concrete and the crush of the confined concrete near the footing. The hysteretic curve is in flag shape. The segmental prestressed bridge pier has more ductility capacity, less residual displacement and relative less energy dissipation capacity.
2. For the effect of the prestressed approaches on the seismic performance, the bonded prestressed concrete bridge pier has more energy dissipation capacity and peak load, while the unbonded one has less residual displacement. The bridge pier with both bonded prestressed strands on the section edge and unbonded in the section center not only has more ductility capacity and energy dissipation capacity, but also has less residual displacement.
3. By investigating the influence of the number of segments on the seismic performance, the single segmental prestressed bridge pier has no special advantage except the energy dissipation capacity which is more than that of the multi-segmental pier.

ACKNOWLEDGEMENT

This research is financially supported by the National Science Foundation of China at the granted no. of (50508032 and 51178350), and their assistance is gratefully acknowledged.

REFERENCES

Wang Zhiqiang, Ge Jiping, Wei Hongyi, 2008. Seismic Performance of Prestressed Concrete Bridge Column of East Sea Bridge, Journal of Tongji university (natural science) , Vol.36 (11), 1462-1466, (in Chinese)

Mander J.B., and Cheng C.T. (1997a). Seismic design of bridge columns based on control and reparability of damage. Technical Rep. NCEER-97-0013, National Center for Earthquake Engineering Research, Buffalo, State University of New York.

Mander J.B., and Cheng C.T. (1997b). Seismic resistance of bridge piers based on damage avoidance design. Technical Rep. NCEER-97-0014, National Center for Earthquake Engineering Research, Buffalo, State University of New York.

Hewes J.T. (2002). Seismic design and performance of precast concrete segmental bridge columns. Ph.D. Dissertation, San Diego, University of California.

Billington S.L. and Yoon J.K. (2004). Cyclic response of unbonded post-tensioned precast columns with ductile fiber-reinforced concrete. Journal of Bridge Engineering, ASCE, 9:4, 353-363.

Sakai, J. and Mahin, S. A. (2004). “Analytical investigations of new methods for reducing residual displacements of reinforced concrete bridge columns.” PEER-2004/02, Pacific Earthq. Engrg. Res. Center, Univ. of California at Berkeley, California.

Chung-Che Chou and Yu-Chih Chen. (2006). Cyclic tests of post-tensioned precast CFT segmental bridge columns with unbonded strands. Earthquake engineering and structure dynamics, 35,159-175.

Wang Zhiqiang, Ge Jiping, Wei Hongyi, Liu Feng, 2009. Recent development in seismic research of segmental bridge columns, Earthquake engineering and engineering vibration, Vol. 29 (4), 147-154, (In Chinese).

Ge Jiping, Wei Hongyi, Wang Zhiqiang, 2008. Seismic Performance of Precast Segmental Bridge Column Under Cyclic Loading, Journal of tongji university , Vol. 36 (7), 894-899, (In Chinese).