The Fifth International Bridge Seismic Workshop (5IBSW)
Hunan University, Changsha, China, June 5-7, 2026

UHPC-Connected Novel Precast Bridge Pier: Structural Configuration and Seismic

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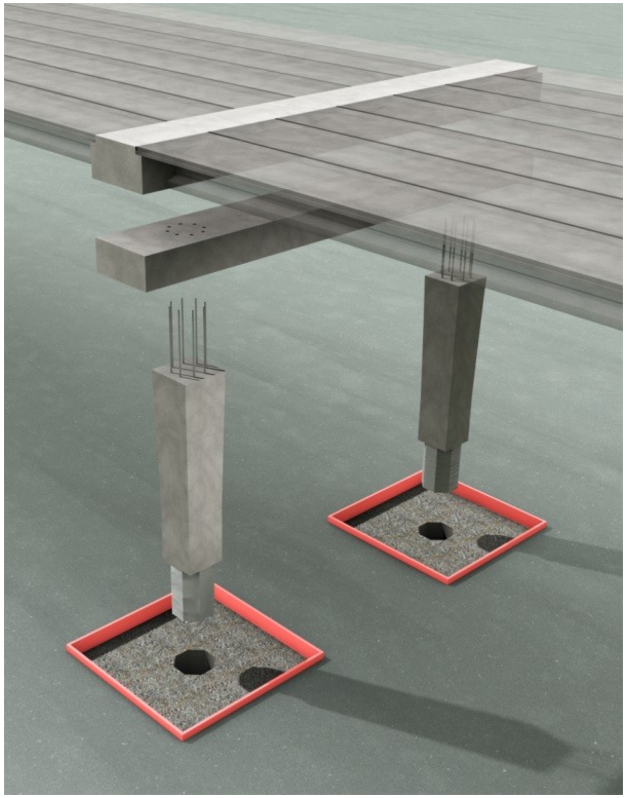
Outline

1. Introduction
2. Configuration of precast piers with UHPC connections
3. The bond-slip performance
4. Seismic performance of precast piers with UHPC connections
5. Conclusions

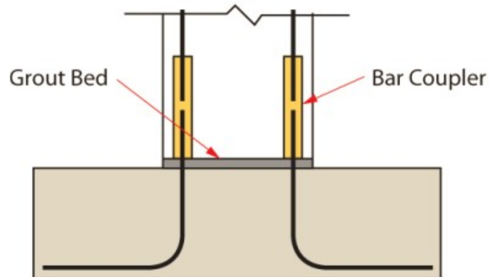
1、Introduction

- ✓ At the end of the last century, due to the need for rapid replacement of a large number of bridges without disrupting traffic, the United States began systematic research on precast assembled bridge substructures to achieve the goal of fully precast bridge construction.

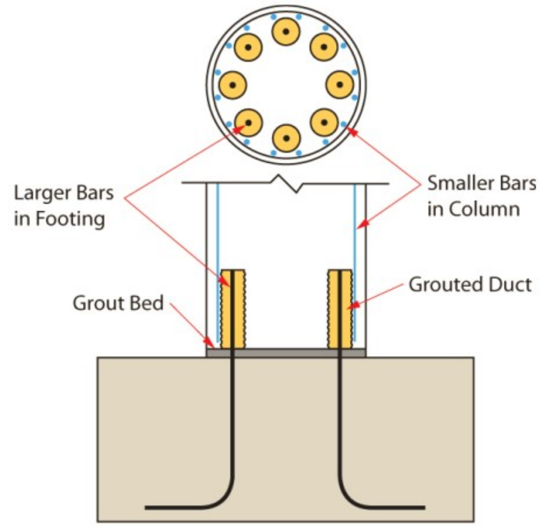


1、Introduction

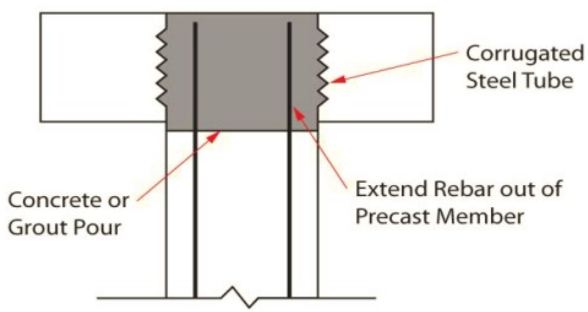
✓ Various connection details for precast assembled bridge piers have been developed.



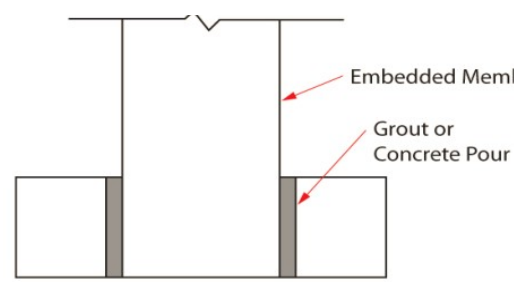
Grout sleeve connection



Grout-filled corrugated duct connection



Pocket connection

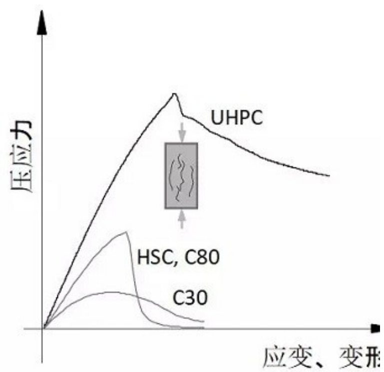


Socket connection

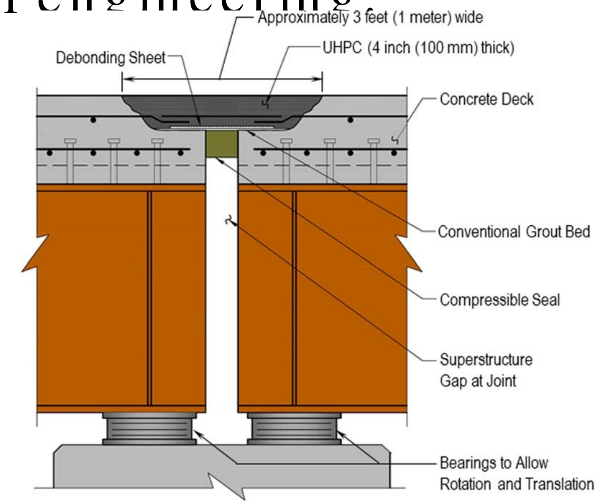
1 、 Introduction

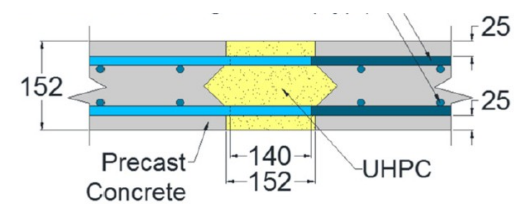
✓ In the past decade, UHPC materials with excellent properties such as high strength and durability have been widely applied in bridge and structural engineering.

- High strength, high toughness, high durability;
- high bond strength with reinforcing steel.

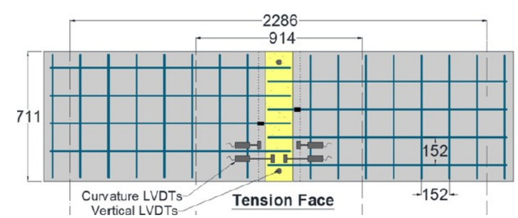


(a) 单轴压缩





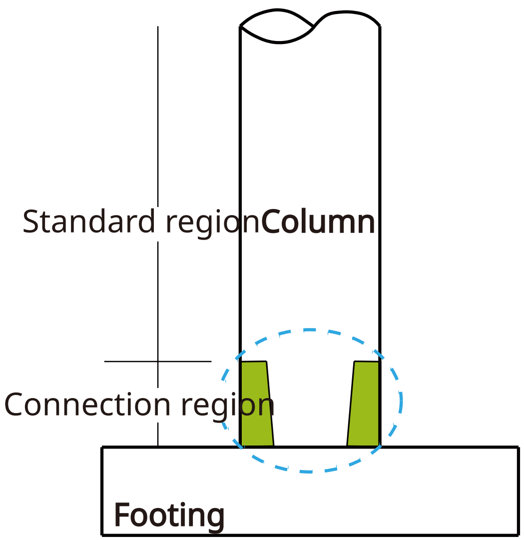
(b)



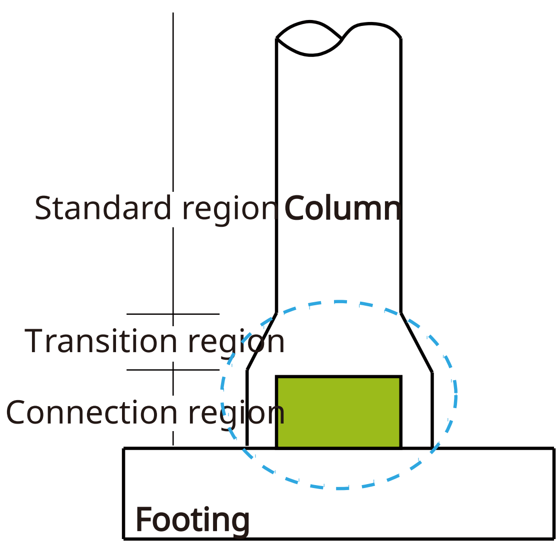
2 Configuration of precast piers with UHPC connections

✓ Two connection details are developed by utilizing the high strength and good anchoring performance of UHPC: the ring UHPC connection and the enlarged base UHPC connection for precast bridge piers.

- Shorter connection length
- Simple construction process
- Reliable connection with good seismic performance



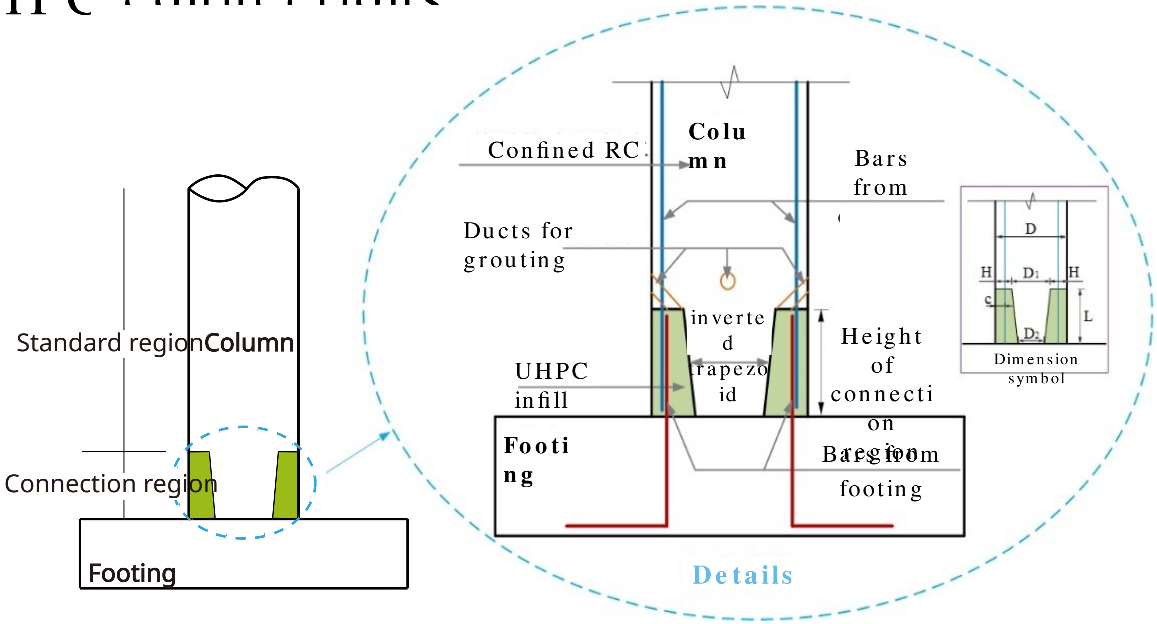
Precast pier with ring UHPC connection



Precast pier with enlarged base UHPC connection

2 Configuration of precast piers with UHPC connections

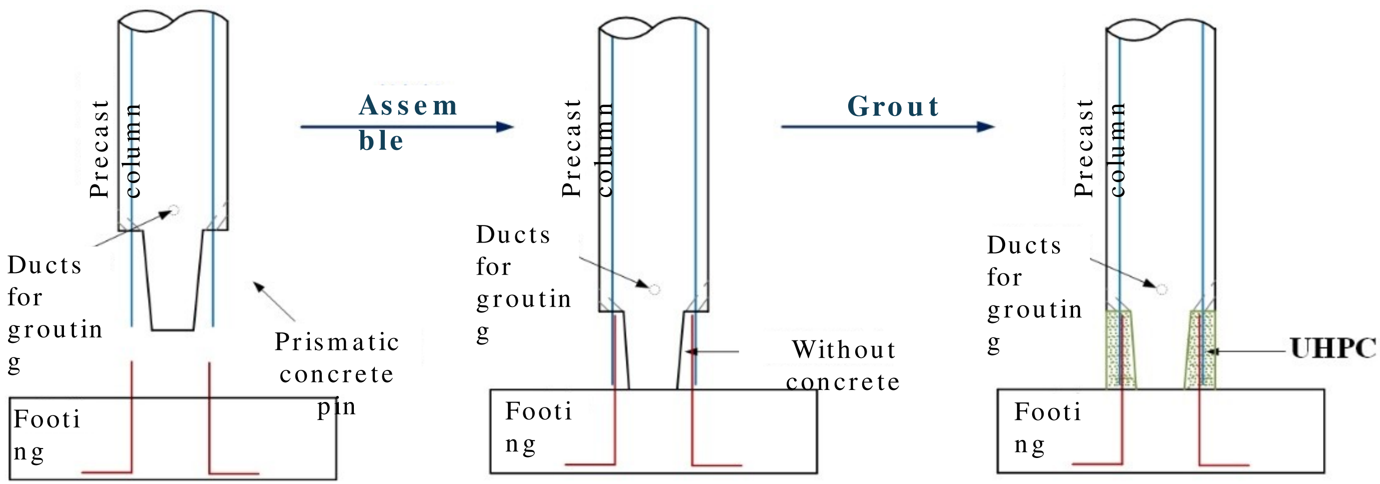
✓ Structural details of precast assembled bridge piers with ring UHPC connections



- The pier base is designed as an inverted trapezoid, reserving the lapping position for column reinforcement and pile cap reinforcement.
- Eliminating the need for additional scaffolding to support the column
- The UHPC connection segment at the pier base enhances the stiffness and strength of the section, shifting the plastic hinge

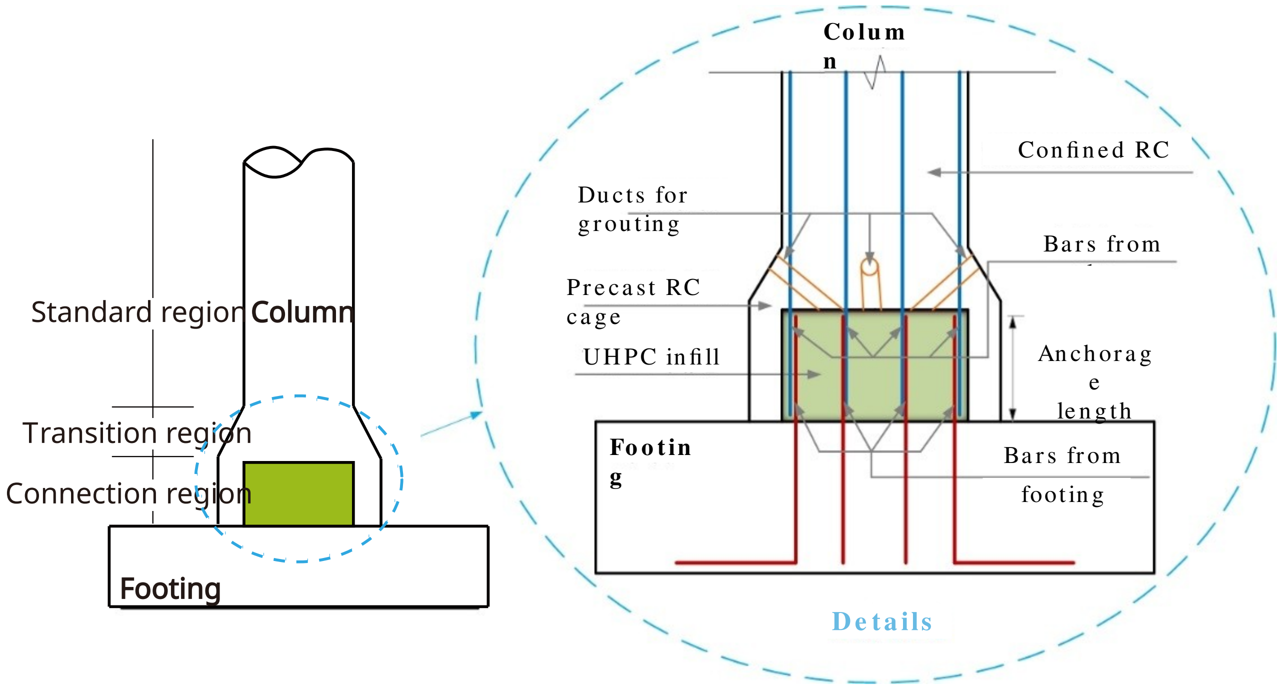
2 Configuration of precast piers with UHPC connections

✓ Construction of precast assembled bridge piers with ring UHPC connections



2 Configuration of precast piers with UHPC connections

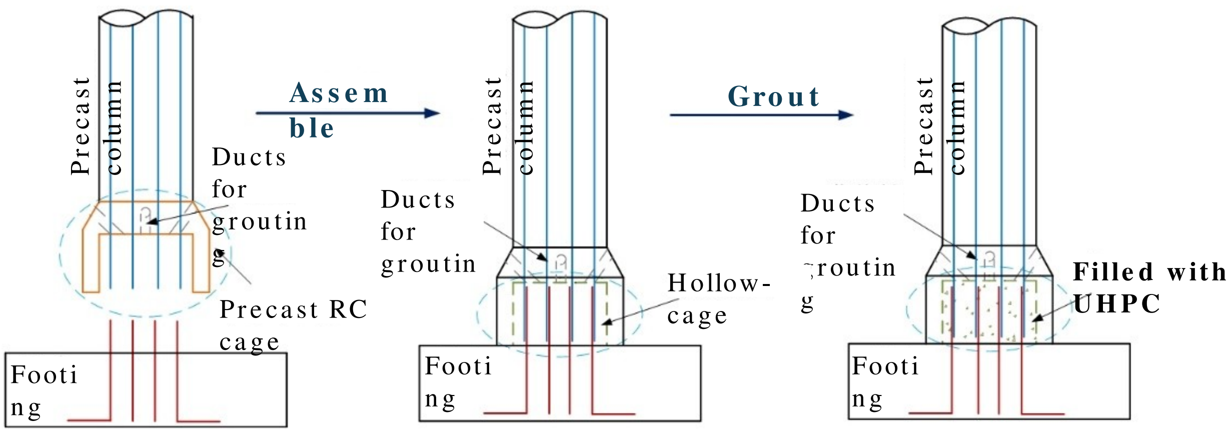
✓ Structural details of precast assembled bridge piers with enlarged base UHPC connections



- The hollow area of the enlarged pier base provides sufficient connection space for reinforcement lapping.
- Serves as a grouting formwork for UHPC casting, ensuring reliable internal reinforcement anchorage.
- The UHPC connection segment enhances the section stiffness and strength, shifting the plastic hinge upward under seismic action and preventing damage at the connection.

2 Configuration of precast piers with UHPC connections

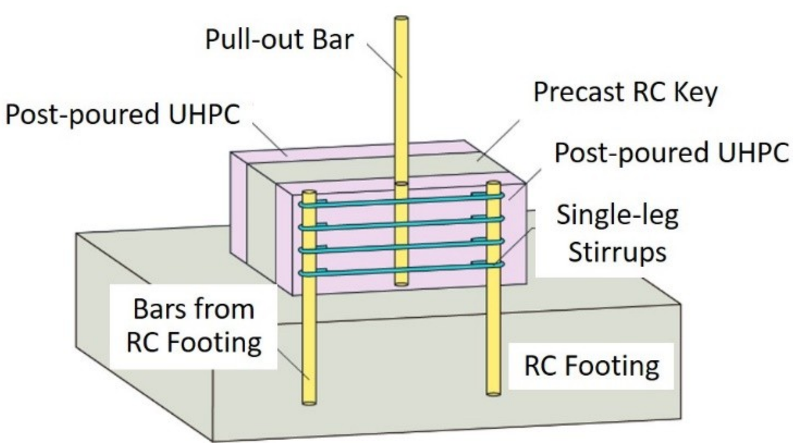
✓ Construction of precast assembled bridge piers with enlarged base UHPC connections



3 The bond-slip performance

✓ UHPC-connected precast piers utilize the bond between rebars and UHPC to achieve rebar splicing. The bond-slip performance between rebars and UHPC is the main factor affecting the performance of UHPC-connected precast piers.

✓ To investigate the bond-slip performance between rebars and UHPC, pull-out tests with stirrup confinement were conducted.



- The test model consists of three parts: a UHPC specimen, a precast concrete tenon, and a concrete bearing platform. Single-leg stirrups were arranged in the UHPC specimen.

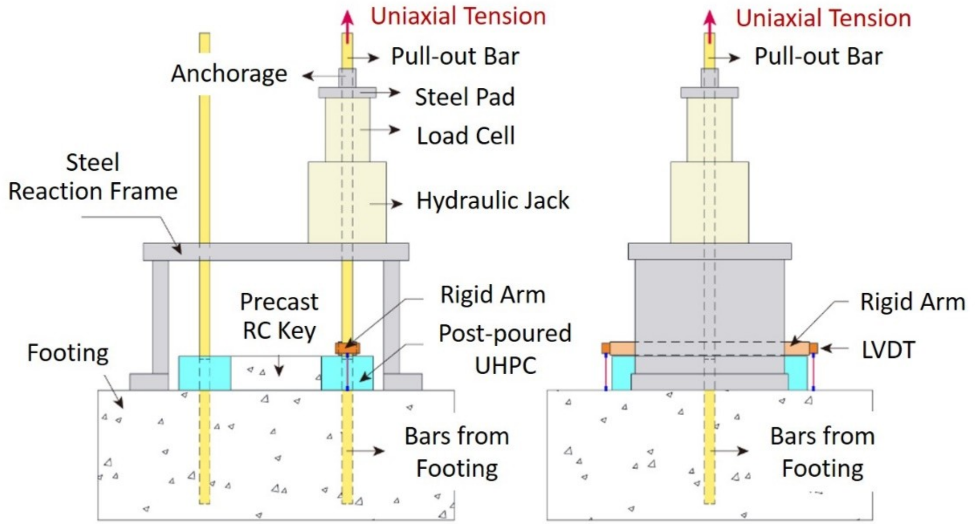
3 The bond-slip performance

✓ Based on two design variables—stirrup ratio and rebar anchorage length—a total of 12 sets of UHPC specimens were designed.

Category	Group	Rebar anchorage lengthl_d (d_b)	stirrup ratioρ_{sv} (%)
1	1	**3.0**	**0**
	2		**0.4**
	3		**0.8**
2	4	**6.0**	**0**
	5		**0.4**
	6		**0.8**
3	7	**8.0**	**0**
	8		**0.4**
	9		**0.8**
4	10	**12.0**	**0**
	11		**0.4**
	12		**0.8**

- The UHPC is of UC120 type. Both rebars and transverse stirrups are HRB400 steel bars.

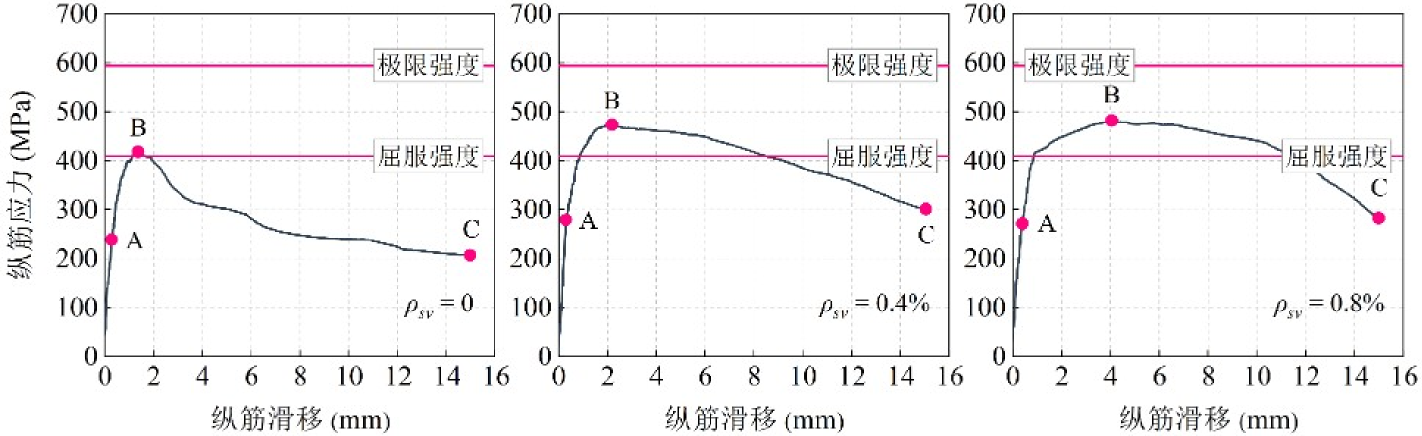
3 The bond-slip performance



Pull-out tests for the bond-slip performance between steel bars and UHPC

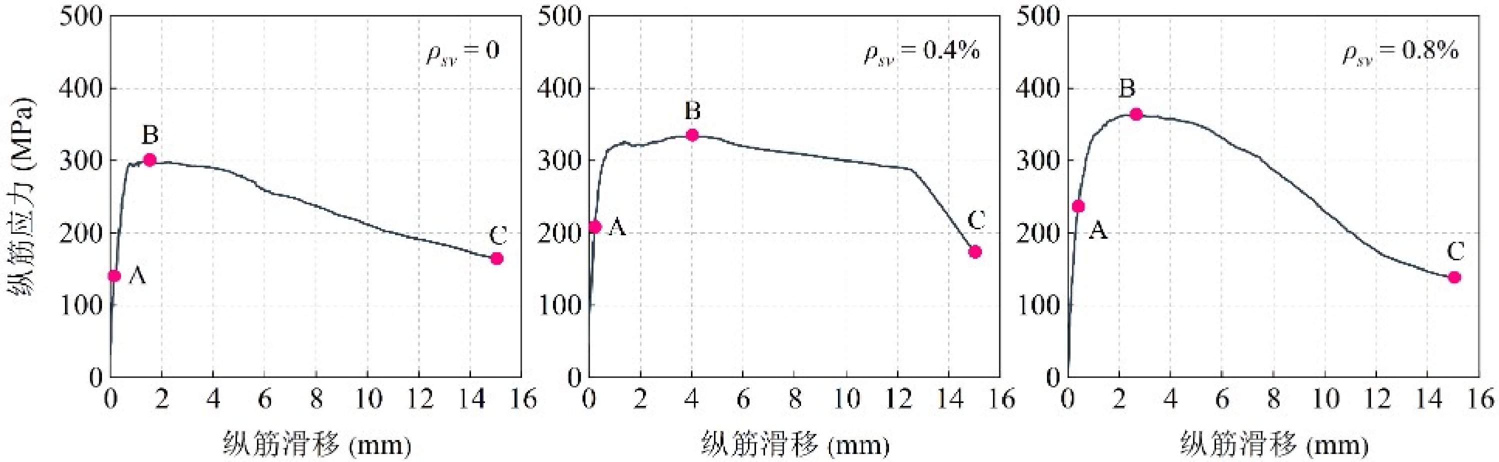
3 The bond-slip performance

✓ When the anchorage length was $6d_b$, splitting failure occurred. As the stirrup ratio increased from 0 to 0.4% and 0.8%, the peak stress of the pulled rebar increased by 11% and 18%, respectively.



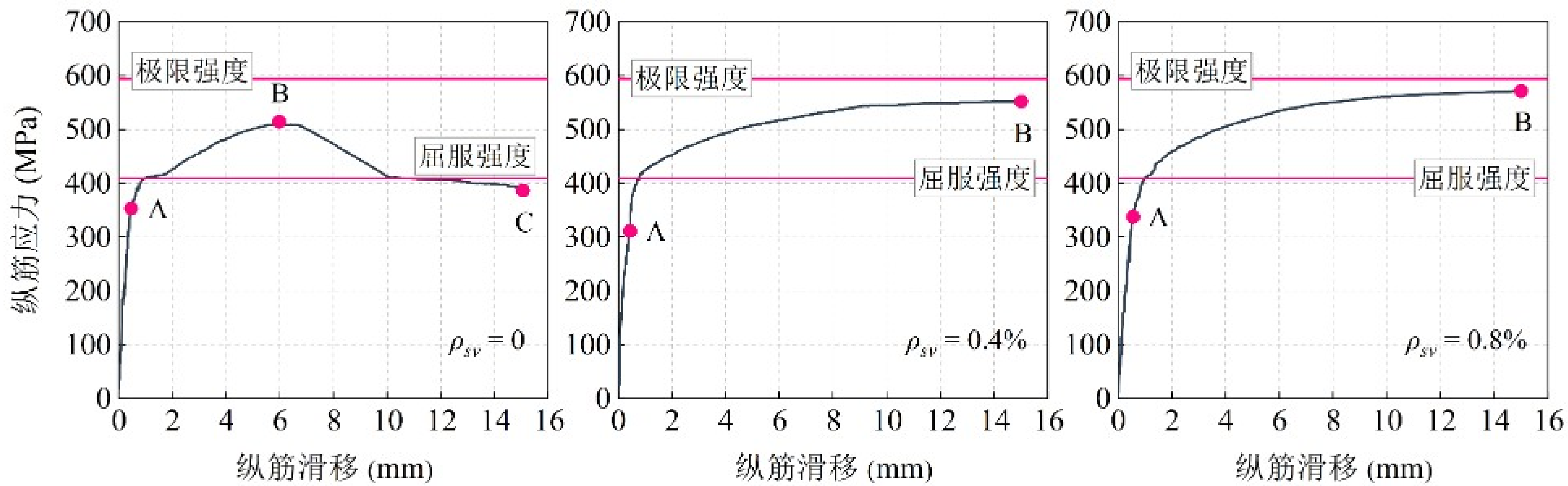
3 The bond-slip performance

- ✓ When the anchorage length was $8d_b$, splitting failure occurred. As the stirrup ratio increased from 0 to 0.4% and 0.8%, the peak stress of the pulled rebar increased by 17% and 18%, respectively.



3 The bond-slip performance

- ✓ When the anchorage length was $12d_b$, specimens with stirrup ratios of 0.4% and 0.8% exhibited rebar fracture failure. As the stirrup ratio increased from 0 to 0.4% and 0.8%, the peak stress of the pulled rebar increased by 4% and 8%, respectively.



3 The bond-slip performance

Comparison of bond strength among UHPC specimens with different design variables

l_d (d_b)	ρ_{sv} = 0	ρ_{sv} = 0.4%		ρ_{sv} = 0.8%	
	σ_{bc} (MPa)	σ_b (MPa)	σ_b / σ_{bc}	σ_b (MPa)	σ_b / σ_{bc}
3	181.9	181.9	1.00	181.2	1.00
6	309.4	343.0	**1.11**	363.8	**1.18**
8	420.8	489.9	**1.16**	491.3	**1.17**
12	532.2	552.8	**1.04**	572.8	**1.08**

Comparison of rebar slip among UHPC specimens with different design variables

l_d (d_b)	ρ_{sv} = 0	ρ_{sv} = 0.4%		ρ_{sv} = 0.8%	
	s_{max} (mm)	$s_{max,b}$ (mm)	$s_{max,b}$ / s_{max}	$s_{max,b}$ (mm)	$s_{max,b}$ / s_{max}
3	3.8	4.4	**1.14**	4.1	**1.08**
6	1.1	2.4	**2.25**	2.7	**2.52**
8	1.6	3.8	**2.38**	5.8	**3.63**
12	9.2	15.0	**1.63**	15.0	**1.63**

3 The bond-slip performance

✓ Furthermore , the database of bond strength (without stirrups) comprises 237 specimens was established. Regression analysis was performed using the genetic programming-orthogonal least squares algorithm.

✓ The obtained unconfined bond strength (without stirrups) σ_{bc} is

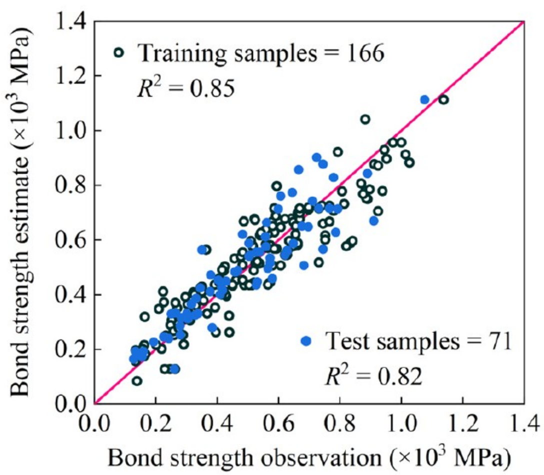


Fig. 3. Comparison between observed and estimated bond strengths.

$$\hat{\sigma}_{bc} = 79.25\frac{l_{em}}{d_b}\left[\frac{c_{so}/d_b}{\sqrt{f_{tU}}} - 0.14\right] - 78.44\frac{l_f/d_f}{\ln d_b \cdot \ln f_{tU}} - 22.99d_b + 1515.97$$

Table 1
Database for bond strength.

Variable		Min	First quartile	Median	Third quartile	Max	Mean	Standard deviation
Input	d_b / mm	10.0	16.0	16.0	22.0	36.0	18.8	6.1
	σ_{sy} / MPa	428.4	455.0	517.0	869.0	924.0	635.0	196.8
	f_{cU} / MPa	70.7	94.5	115.1	135.0	205.0	115.2	25.7
	f_{tU} / MPa	5.3	6.5	6.8	8.9	19.2	7.8	2.2
	l_f / d_f	59.1	63.5	63.5	63.5	78.9	63.8	3.1
	l_{em} / d_b	3.0	6.0	7.8	8.4	18.1	7.6	2.9
	c_{so} / d_b	0.5	1.2	1.8	2.1	3.3	1.8	0.7
	c_{si} / d_b	0.1	1.0	2.2	2.5	9.0	2.0	1.4
Output	σ_{bc} / MPa	128.0	350.1	521.0	663.8	1137.7	531.0	227.7

3 The bond-slip performance

- Based on results of pull-out tests with stirrup confinement of this study and thirteen samples recorded in the study by Ma et al., adjustment factor representing the effect of stirrup confinement on the bond strength could be regressed as：

$$\hat{\kappa}_{tr} = -414.84\rho_{sv}(t_{sl} - 0.019) + 1.00 \geq 1.00 \qquad 0 \leq \rho_{sv} \leq 2.3\%$$

- The design bond strength can be further expressed as

$$\sigma_b = \kappa_{tr}\,\sigma_{bc}$$

4 Seismic performance of precast piers with UHPC connections

4.1 quasi-static test

✓ To investigate the seismic performance of precast piers with UHPC connections, quasi-static tests were designed and conducted on ten test models

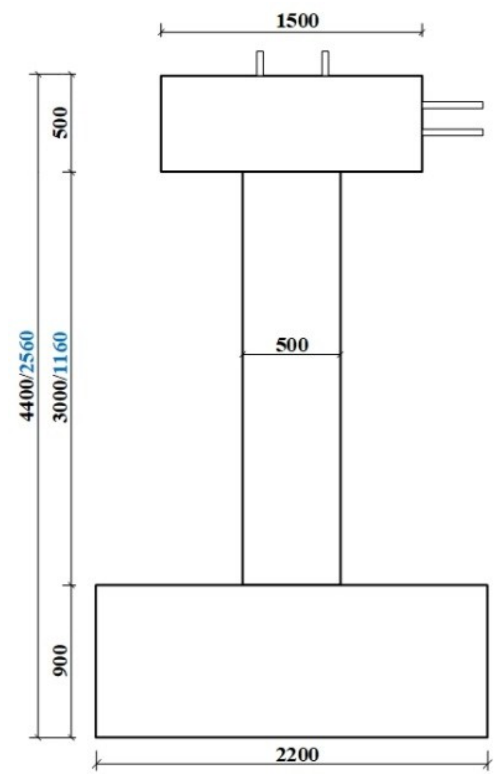
Bridge pier models （10）

Bridge pier type

- UHPC-connected precast bridge pier （8）
- Cast-in-place bridge pier （2）

Research parameters

- Pier height
- Length of the UHPC connection segment (rebar anchorage length)
- Stirrup ratio of the UHPC connection segment



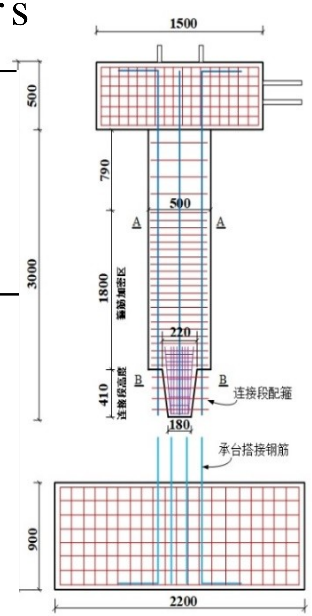
Pier height： 3000mm/1160mm

Pier cross-section： 500mm x

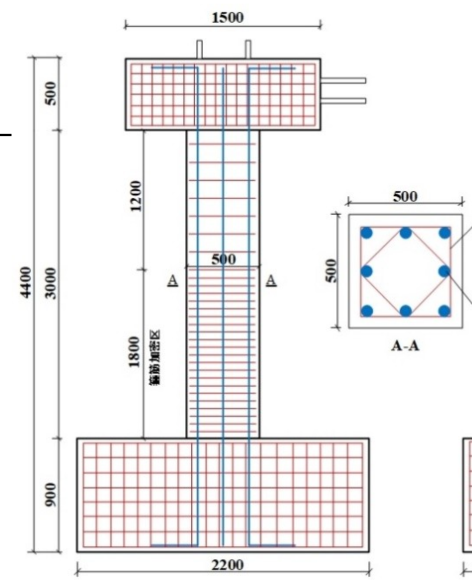
4 Seismic performance of precast piers with UHPC connections

- Design parameters of UHPC-connected precast piers

Specimen ID	Pier height (shear span ratio)	Connection length (anchorage length)	Stirrup ratio of the connection segment
G12D-0	3000mm （6）	410mm （12d）	0
G12D-0.4	3000mm （6）	410mm （12d）	0.4%
G12D-0.8	3000mm （6）	410mm （12d）	0.8%
G10D-0.8	3000mm （6）	350mm （10d）	0.8%
G8D-0.8	3000mm （6）	290mm （8d）	0.8%
G6D-0.8	3000mm （6）	230mm （6d）	0.8%
L12D-0.8	1160mm （2.3）	410mm （12d）	0.8%
L12D-0.4	1160mm （2.3）	410mm （12d）	0.4%

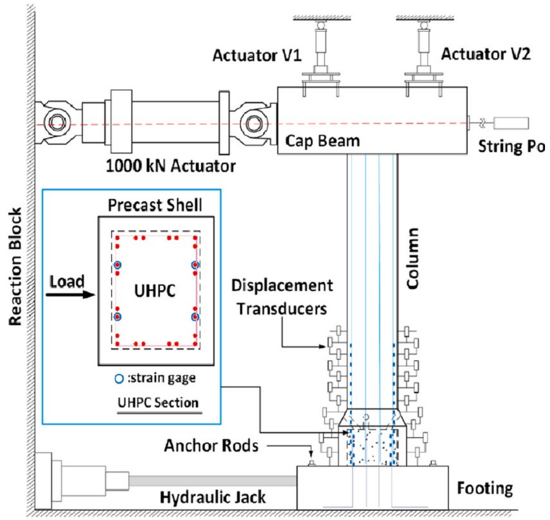


- Two additional cast-in-place pier models were designed with same cross-sectional dimensions and rebar ratios to the UHPC-connected piers. The heights of the two cast-in-place piers are 3000 mm (GCIP) and 1160 mm (LCIP), respectively.



4 Seismic performance of precast piers with UHPC connections

- Test device and loading protocol



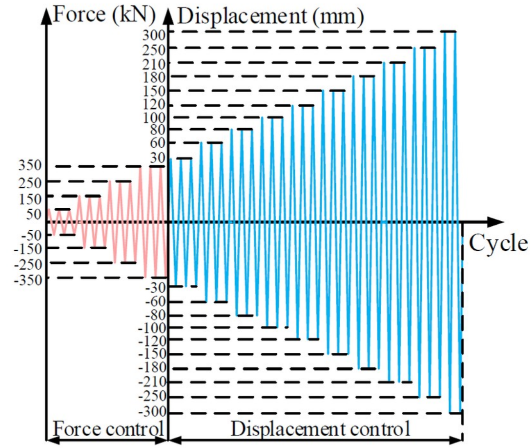
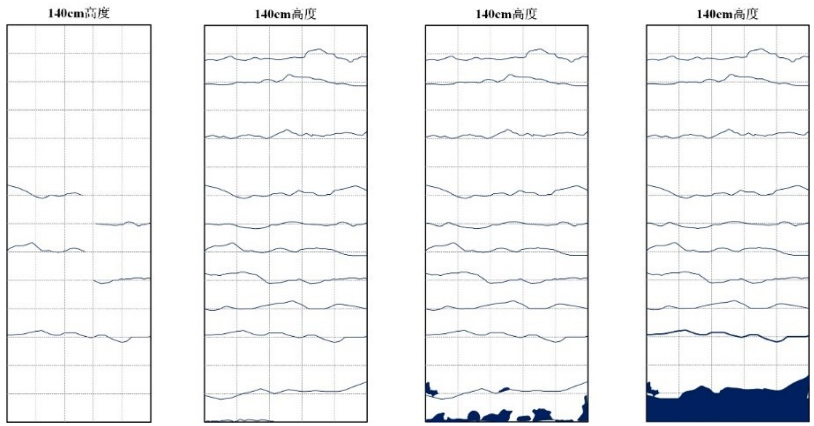


Fig. 6. Cyclic loading protocol.

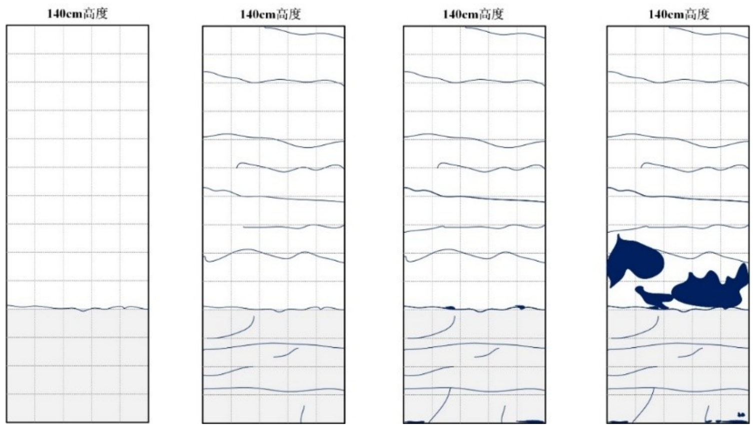
4 Seismic performance of precast piers with UHPC connections

✓ Observed damage

- High pier(The pier height is 3000 mm) -–The comparison of the observed damage of high pier for Cast-in-place GCIP and UHPC connection G12D-0.8



（a） 10mm （b） 60mm （c） 120mm （d） 180mm



（a） 10mm （b） 60mm （c） 120mm （d） 180mm

Cast-in-place high pier GCIP

UHPC connection pier G12D-0.8

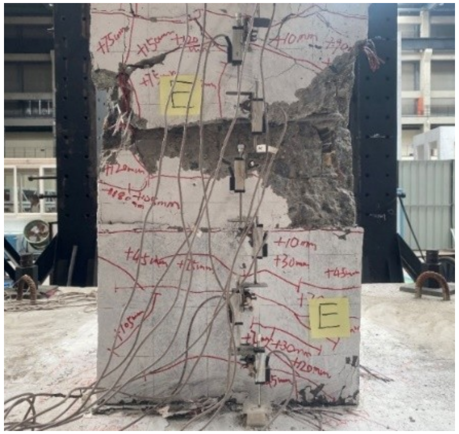
4 Seismic performance of precast piers with UHPC connections

- High pier – the comparison of the observed damage of UHPC connection piers with different connection length

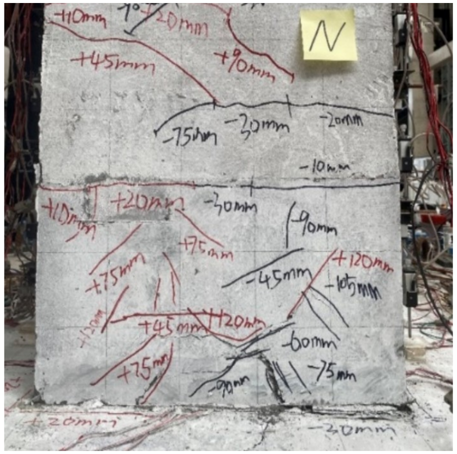
G12D-0.8

G12D-0.4

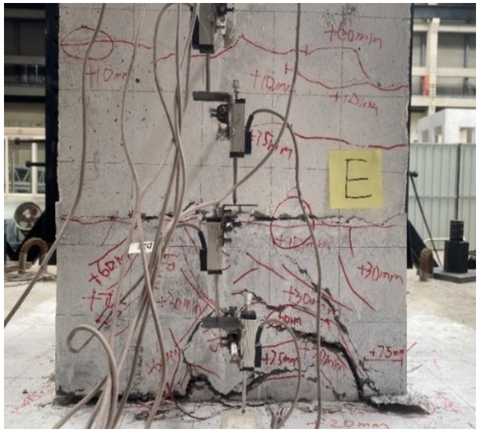
G12D-0



G10D-0.8



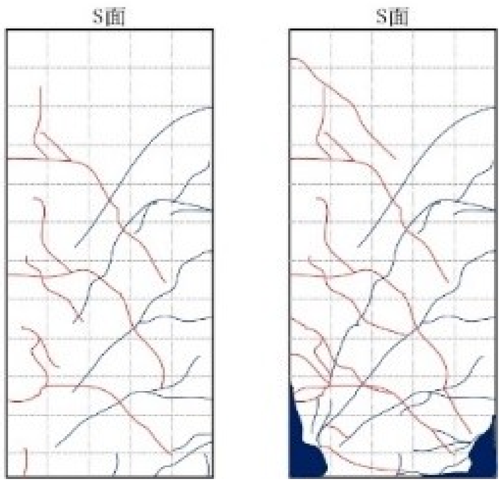
G8D-0.8



G6D-0.8

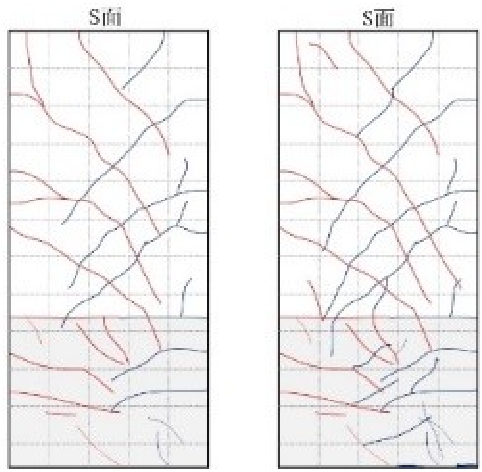
4 Seismic performance of precast piers with UHPC connections

- Short pier (pier height is 1160 mm)– damage for the short pier

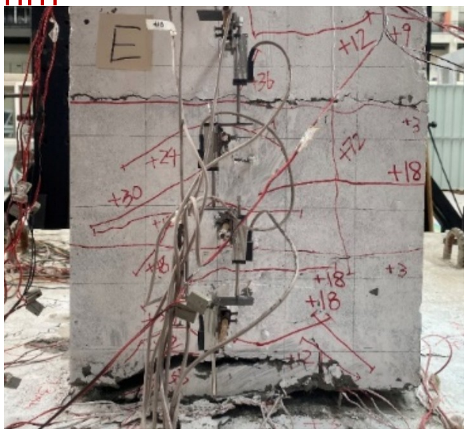


（a） 24mm （b） 60mm

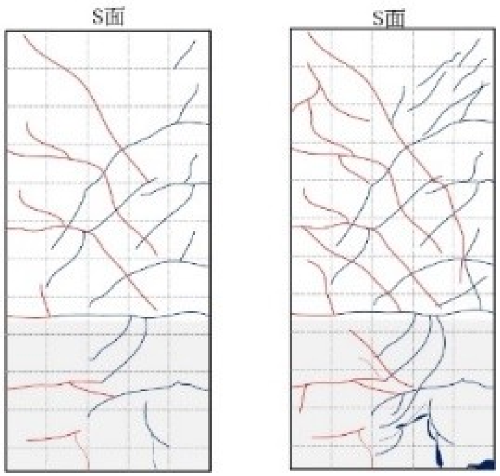
LCIP



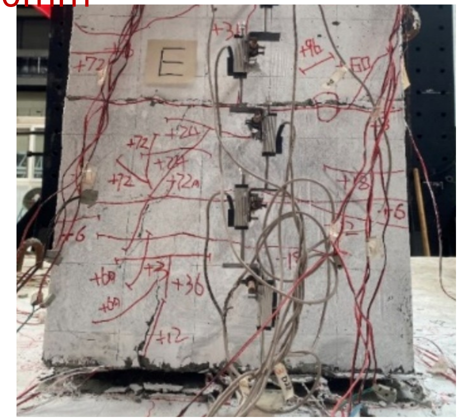
（a） 24mm （b） 60mm



L12D-0.8



（a） 24mm （b） 60mm

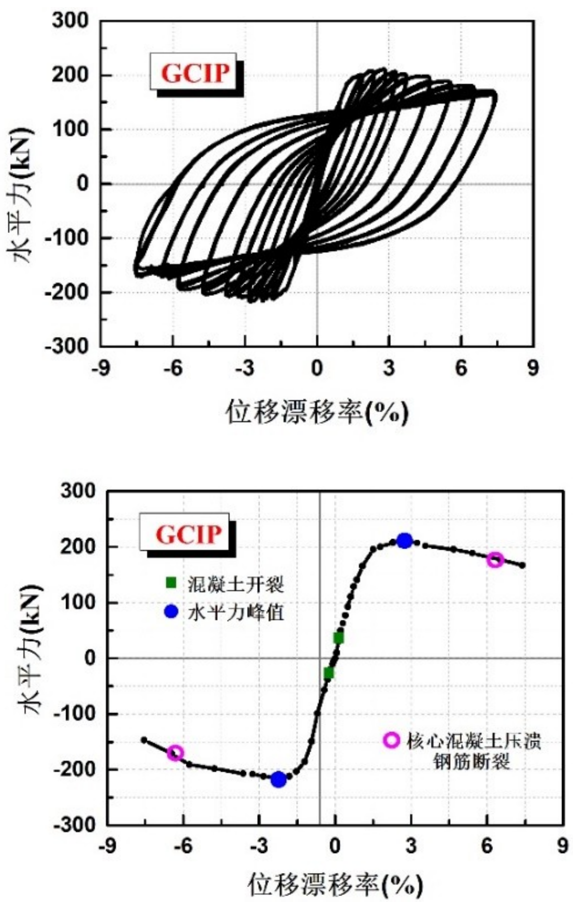


L12D-0.4

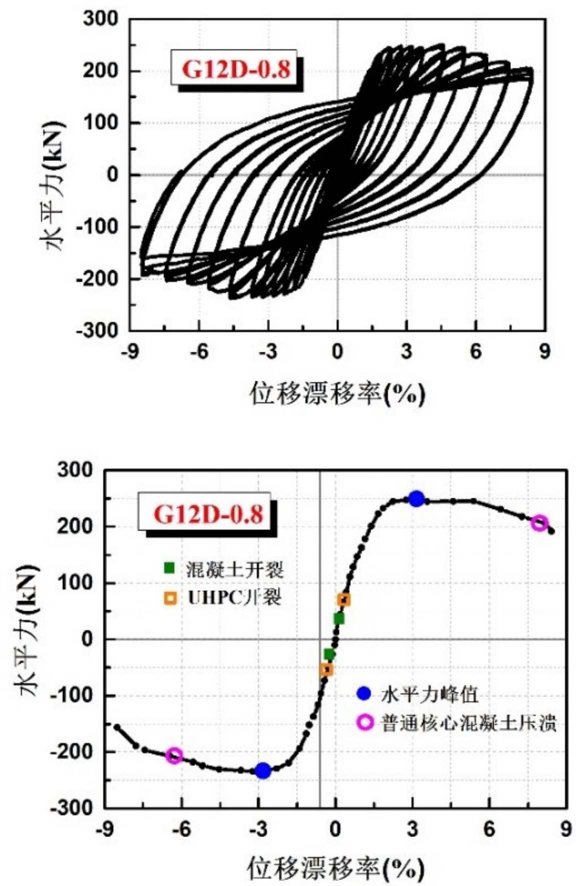
4 Seismic performance of precast piers with UHPC connections

✓Experimental Results Analysis

- Performance Comparison between Cast-in-Place and UHPC-Connected Precast high Piers—Comparison of Hysteretic loops



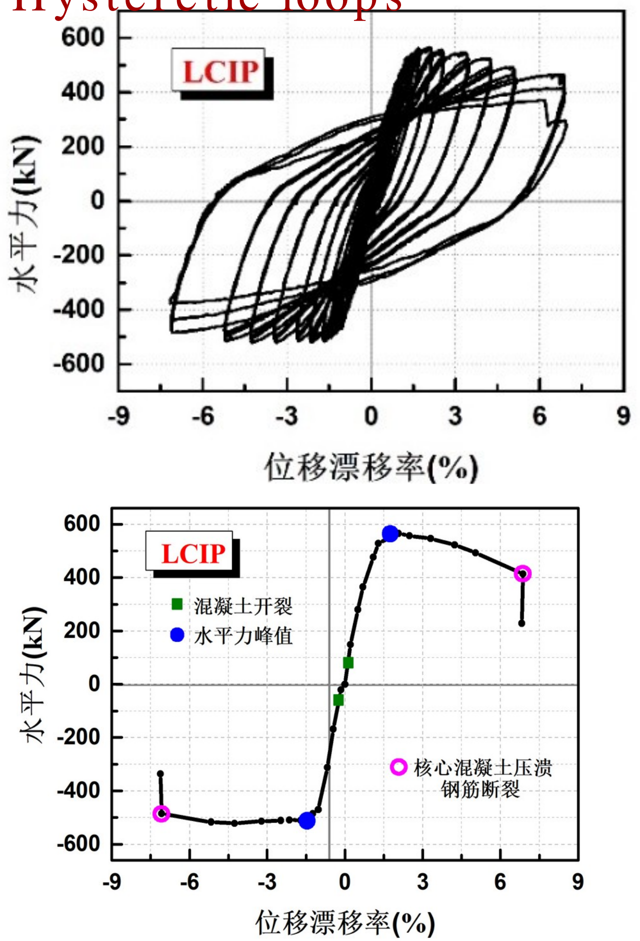
Cast-in-place GCIP



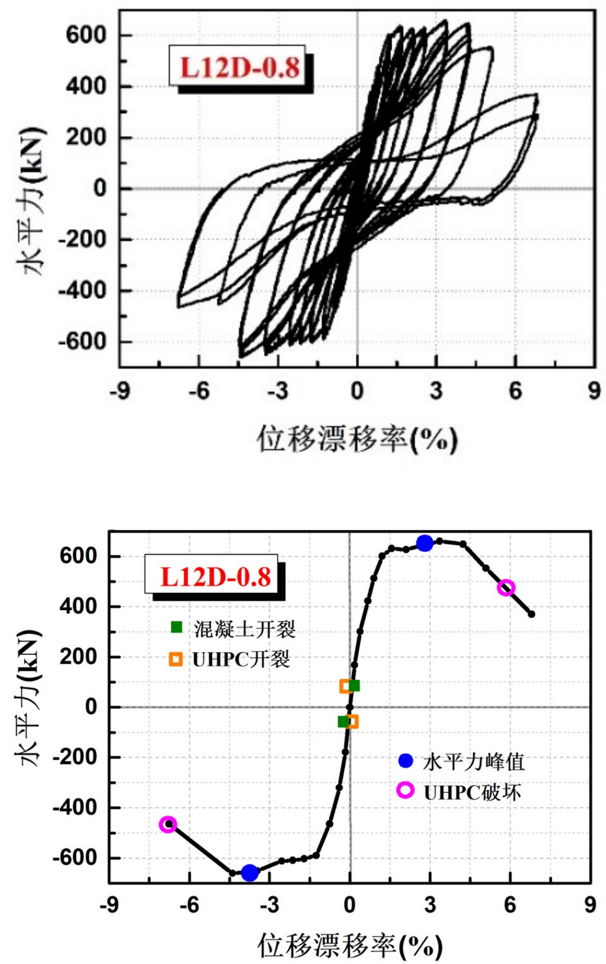
UHPC-connected bridge pierG12D-0.8

4 Seismic performance of precast piers with UHPC connections

- Performance Comparison between Cast-in-Place and UHPC-Connected Precast short Piers—Comparison of Hysteretic loops



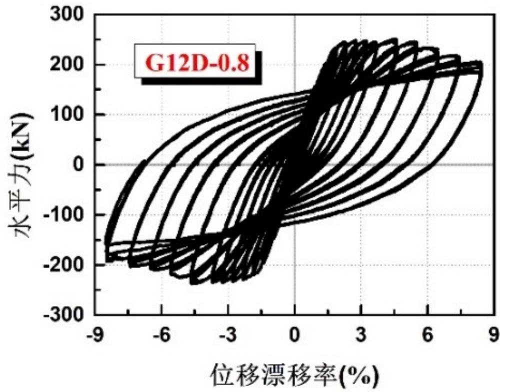
Cast-in-place LCIP

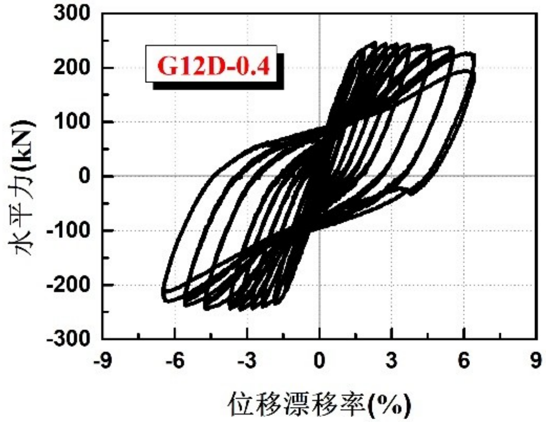


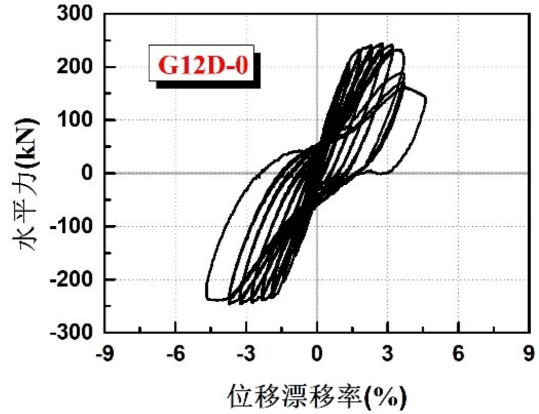
UHPC-connected bridge L12D-0.8

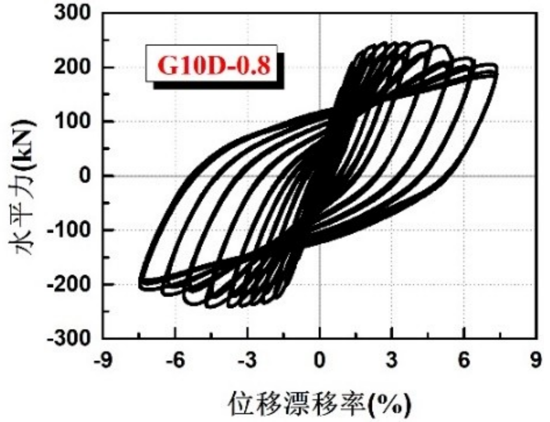
4 Seismic performance of precast piers with UHPC connections

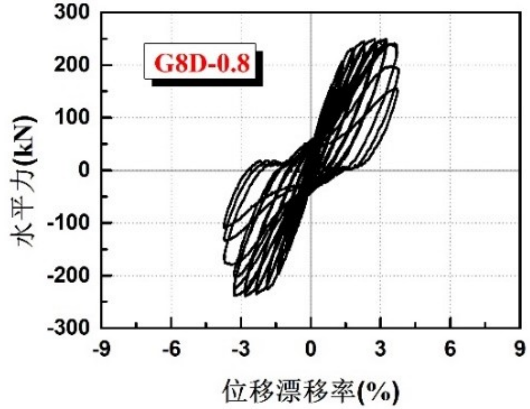
- Performance Comparison of UHPC-Connected high Piers with Different Connection length and Stirrup Ratios — Comparison of Hysteretic loops

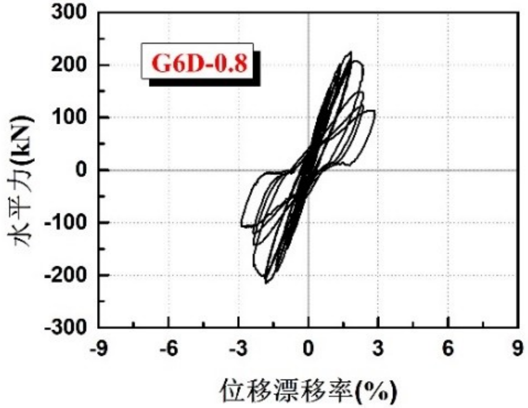












4 Seismic performance of precast piers with UHPC connections

- Summary of Hysteretic Performance and Failure Modes of the piers

Specimen type	No	Name	Yield displacement	Peak load force	Ultimate drift ratio	Damage mode
High pier	1	GCIP	45.9mm	216 kN	6.7%	The core concrete at the pier bottom was crushed
	2	G12D-0	45.6mm	244 kN	3.7%	UHPC tearing
	3	G12D-0.4	45.8mm	247 kN	6.4%	The core concrete above the connection segment was crushed
	4	G12D-0.8	52.8mm	250 kN	7.8%	The core concrete above the connection segment was crushed
	5	G10D-0.8	50.1mm	250 kN	7.1%	The core concrete above the connection segment was crushed
	6	G8D-0.8	48.4mm	249 kN	3.7%	UHPC tearing
	7	G6D-0.8	41.9mm	225 kN	2.3%	UHPC tearing
Short pier	8	LCIP	16.4mm	571 kN	6.8%	Core concrete crushing at pier base, rebar fracture
	9	L12D-0.8	17.2mm	669 kN	5.8%	UHPC tearing
	10	L12D-0.4	16.7mm	625 kN	5.1%	Pier column uplifting; UHPC cracking

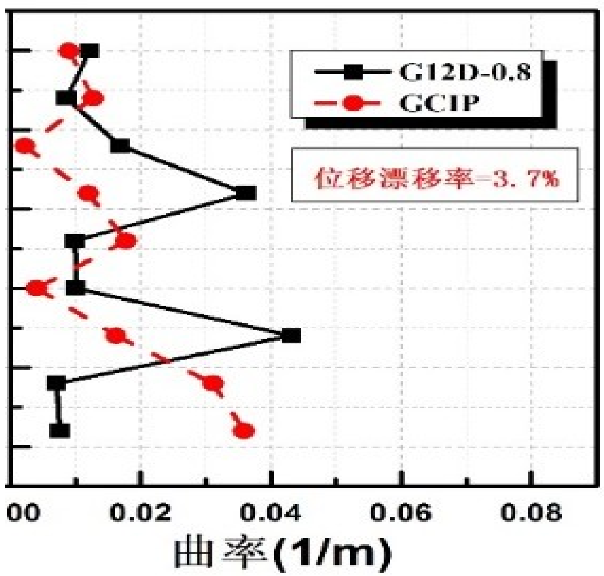
4 Seismic performance of precast piers with UHPC connections

- The failure mode of high piers is primarily flexural failure in the pier standard segments; However, if the rebar anchorage length or stirrup ratio is insufficient, bond-slip failure between UHPC and rebar occurs. For short piers, however, failure modes are significantly affected by shear force, are bond-slip failure between UHPC and rebar at the pier base.

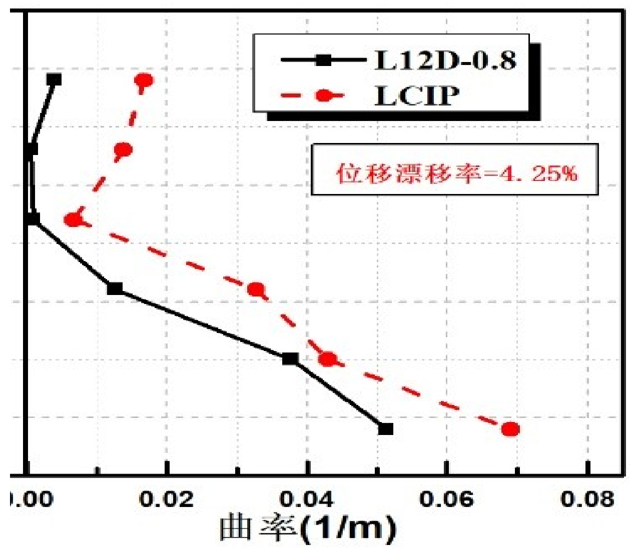
- For a stirrup ratio of 0.8%, the recommended anchorage length is greater than or equal to 10d; for a stirrup ratio of 0.4%, the recommended anchorage length is greater than or equal to 12d.

4 Seismic performance of precast piers with UHPC connections

- Performance Comparison between Cast-in-Place and UHPC-Connected Precast high Piers — Comparison of Curvature Distribution



Comparison of Pier Body Curvature between GCIP Pier and G12D-0.8 Pier



Comparison of Pier Body Curvature between LCIP Pier and L12D-0.8 Pie

For the G12D-0.8 pier, the curvature at the pier base is much smaller than that of the cast-in-place pier.

4 Seismic performance of precast piers with UHPC connections

4.2 Design method

✓ A connection detailing design method for ring UHPC connection between precast bridge piers and pile caps (or bent caps) is developed to satisfy the dual requirements of bond performance and capacity protection

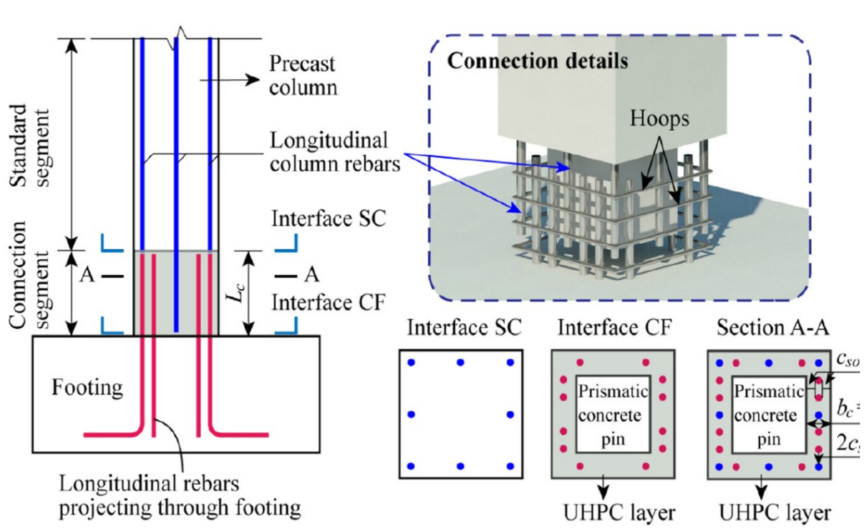
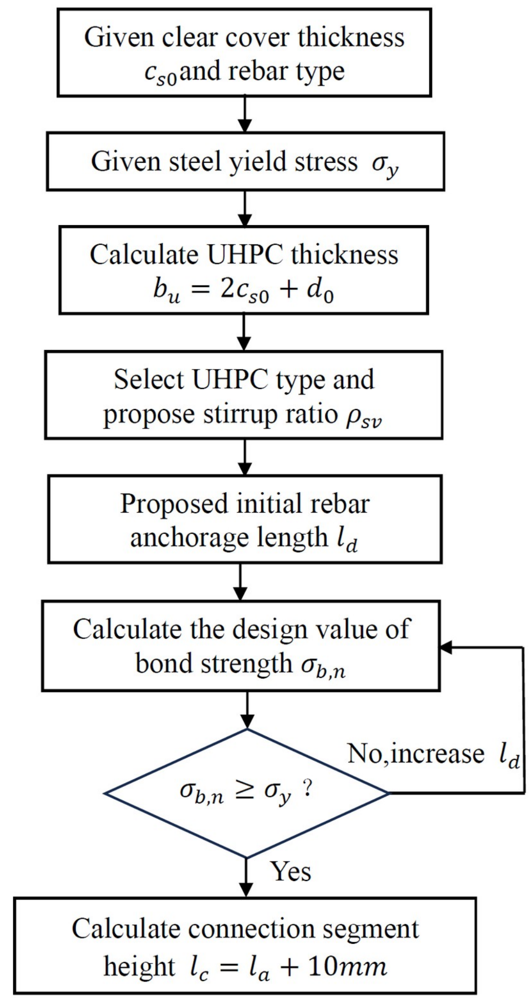


Fig. 5. Configuration details of the novel lap splice connection by UHPC.



Design of rebar anchorage detailing in the connection zone

4 Seismic performance of precast piers with UHPC connections

✓ Reinforcement design for the bottom joint of the connection zone are based on the capacity protection principle to avoid strain concentration in the longitudinal rebar at the pier bottom

$$M_{CF} \geq \lambda_0 M_{SC}(1 + L_c/H)$$

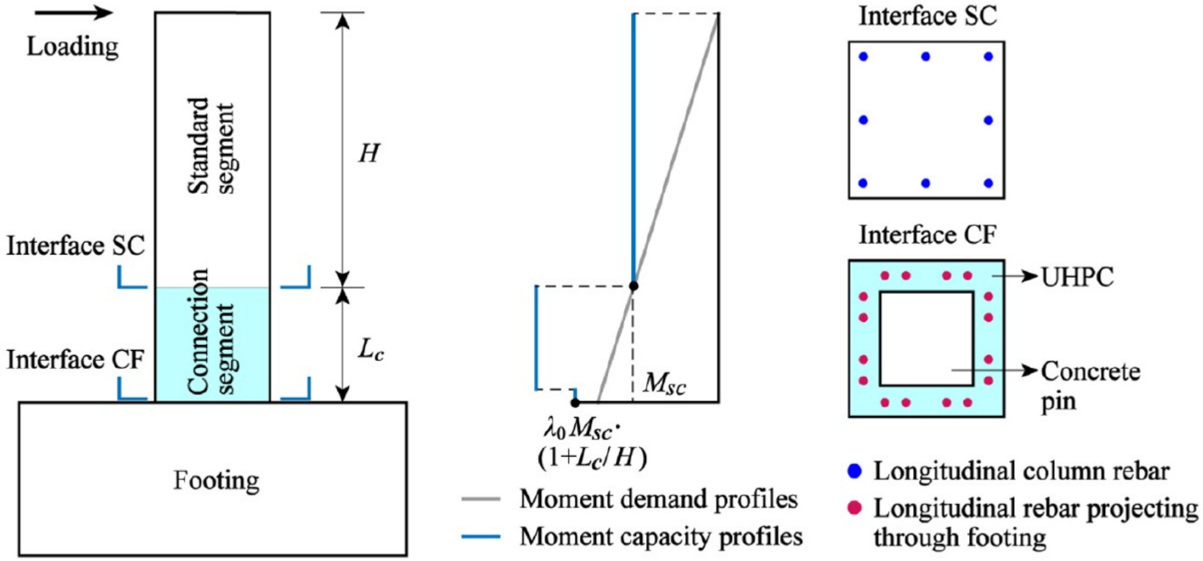


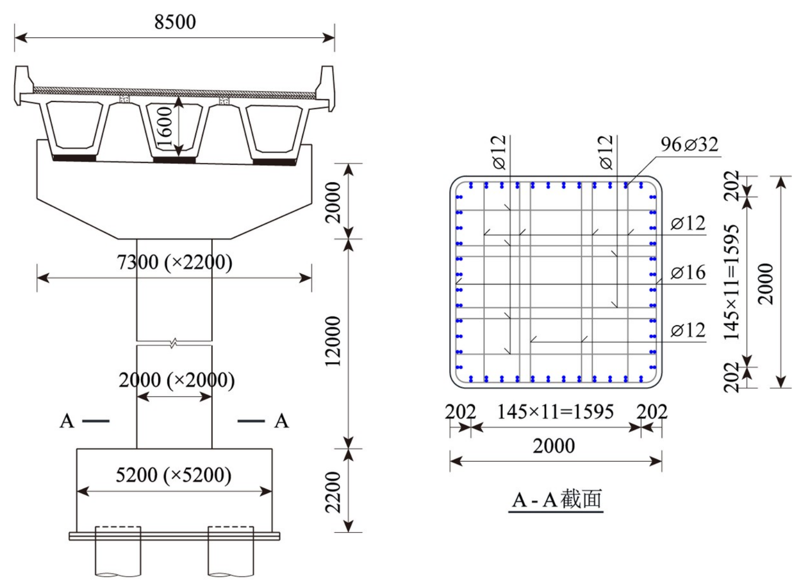
Fig. 6. Capacity-protected principle of interface CF.

4 Seismic performance of precast piers with UHPC connections

4.3 Shaking table test validation

✓ To further verify the effectiveness of the UHPC-connected precast pier, a 1/3.5 scale bridge model with UHPC-connected precast piers was designed and fabricated for shaking table testing.

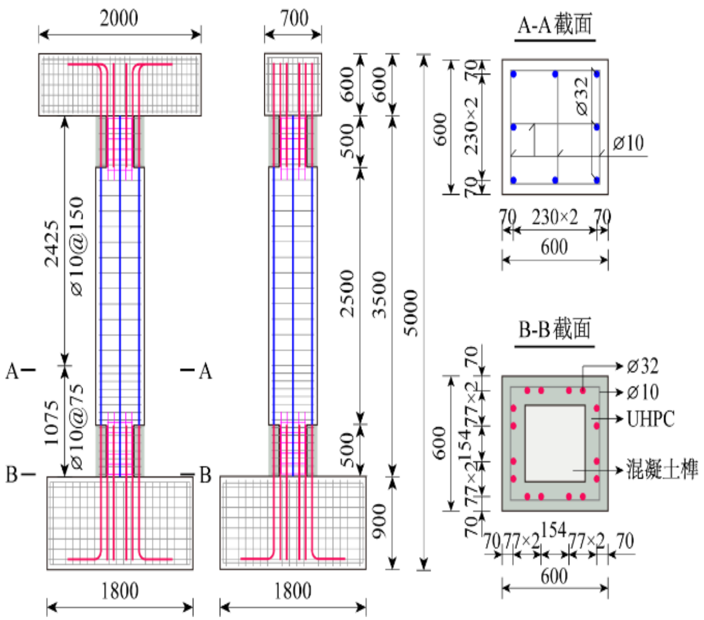
- The prototype bridge is simply supported beam bridge with span of 30m. The pier height is 12 m with cross-sectional dimensions 2 m × 2 m. The total weight of the prototype bridge is 527tons.
- Rebar consists of HRB400 steel bars with a diameter of 32 mm, and the sectional reinforcement ratio is ρs = 1.9%.

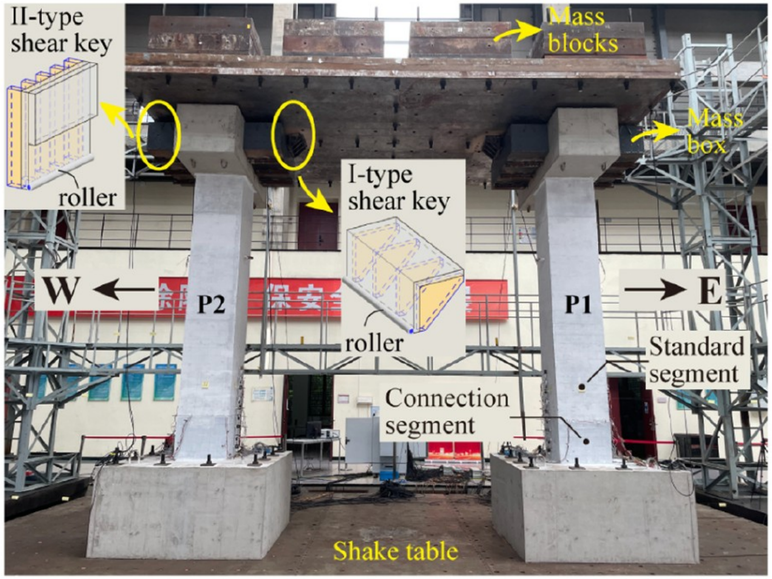


The prototype bridge （mm）

4 Seismic performance of precast piers with UHPC connections

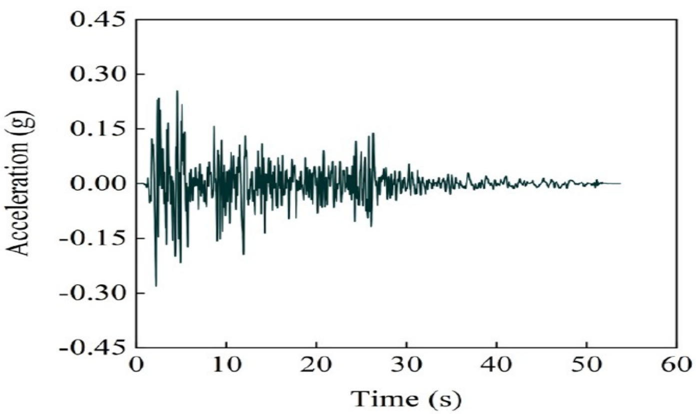
- Connection segment detailing: UHPC thickness of 140 mm; stirrup ratio of 0.8%; rebar anchorage length of 490 mm (=15.3db); connection segment length of 500 mm; 16 HRB400 steel bars with a diameter of 32 mm arranged longitudinally at the bottom joint of the connection zone, serving as pile cap lap splices for longitudinal reinforcement; total model weight of 86.1 t.





4 Seismic performance of precast piers with UHPC connections

- The El Centro ground motion recorded at the Imperial Valley-02 event in 1940 was chosen for shake table tests.



Loading protocol.

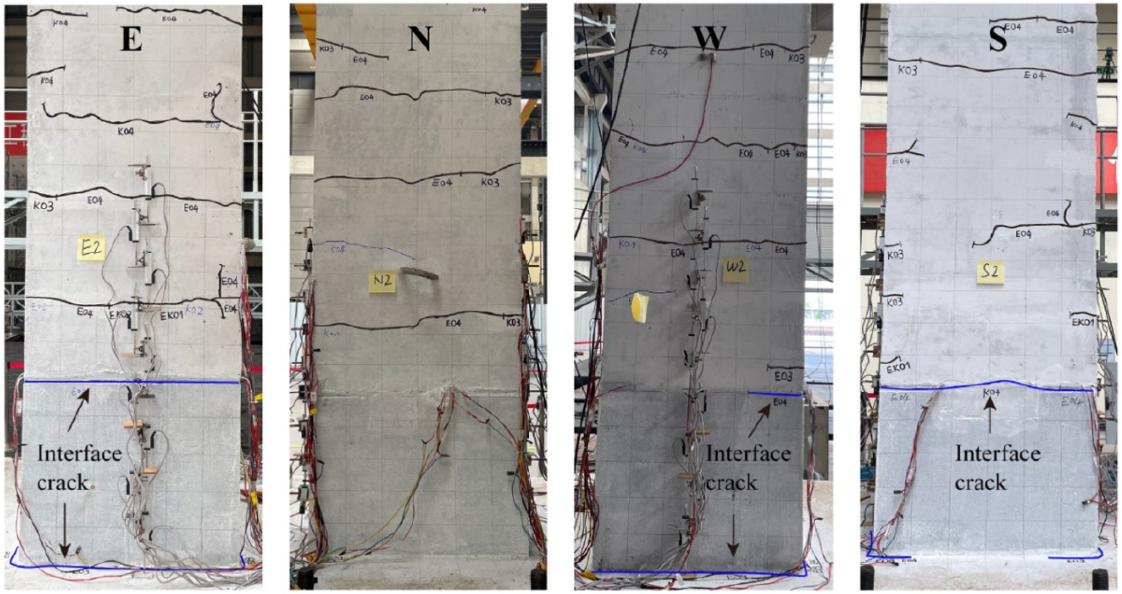
Run	Ground motion	PGA (g)	Run	Ground motion	PGA (g)
1	El Centro	0.1	6	El Centro	0.8
2	El Centro	0.2	7	El Centro	1.0
3	El Centro	0.3	8	El Centro	1.2
4	El Centro	0.4	9	El Centro	1.4
5	El Centro	0.6			

4 Seismic performance of precast piers with UHPC connections

✓ Observed damage

PGA=0.4g

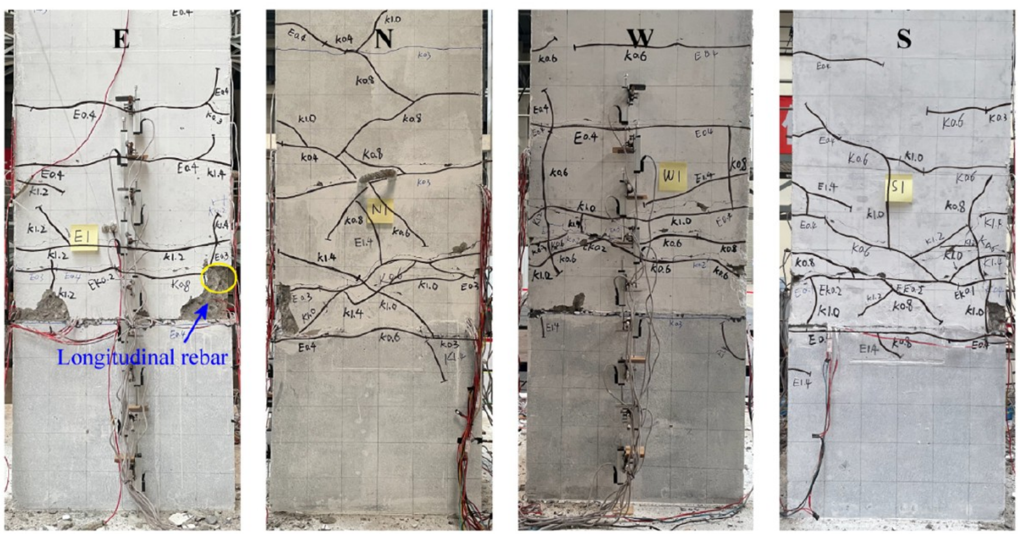
- Most flexural cracks appeared in the lower part of the standard segment, and no cracks were observed in the connection segment.
- The records from strain gauges indicated the yielding of a few longitudinal rebars in the lower part of the standard segment



4 Seismic performance of precast piers with UHPC connections

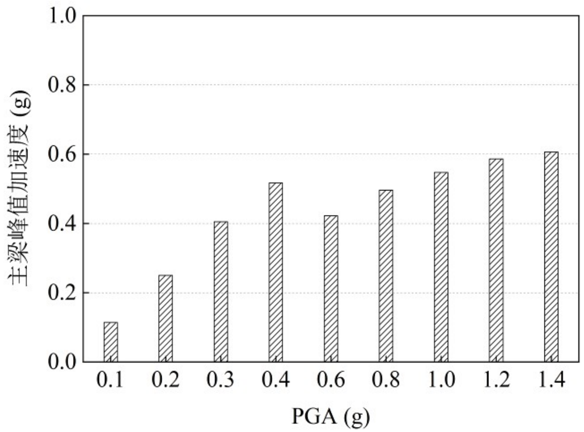
PGA=1.4g

- When the PGA increased to 1.4 g, the damage state of the column was illustrated in Fig. As seen, the cover concrete spalled off moderately in the lower part of the standard segment, and a longitudinal rebar was exposed at the corner. However, only one hairline crack was observed in the connection segment.
- Experimental results show that the precast column is damaged in a flexural pattern, with its plastic region shifted to the lower part of the standard segment. The minimal damage in the connection segment indicates excellent bond behavior between UHPC and rebar.

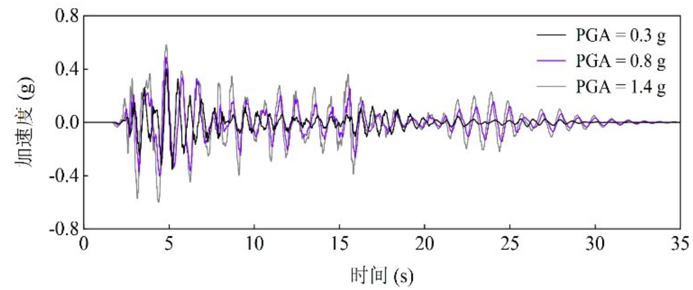


4 Seismic performance of precast piers with UHPC connections

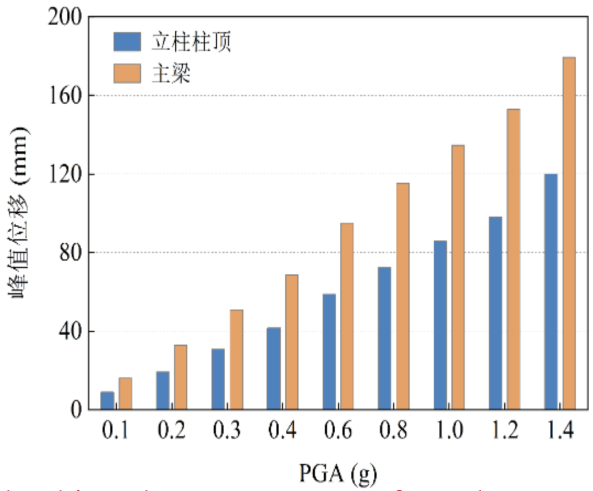
✓ Acceleration response of the main girder and displacement response at the pier top



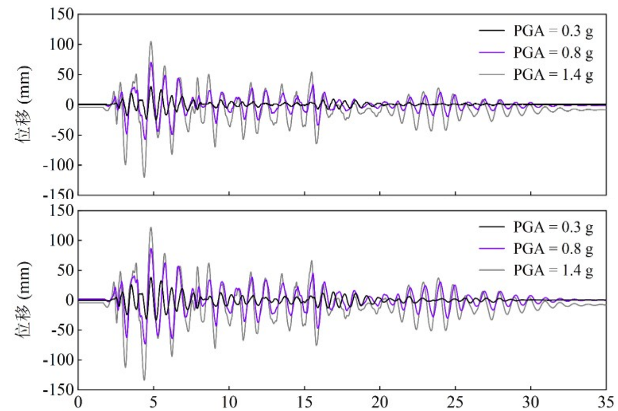
Peak acceleration of the main girder



Acceleration time history of the main girder



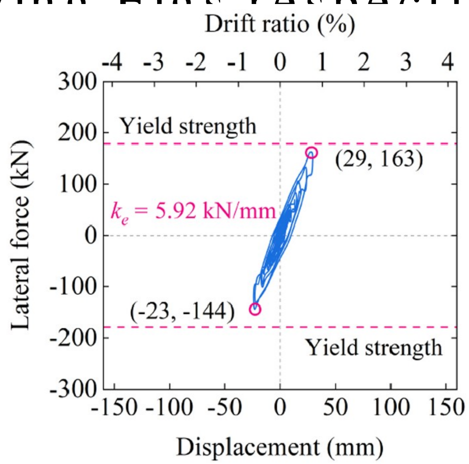
Peak displacement of columns and main girder



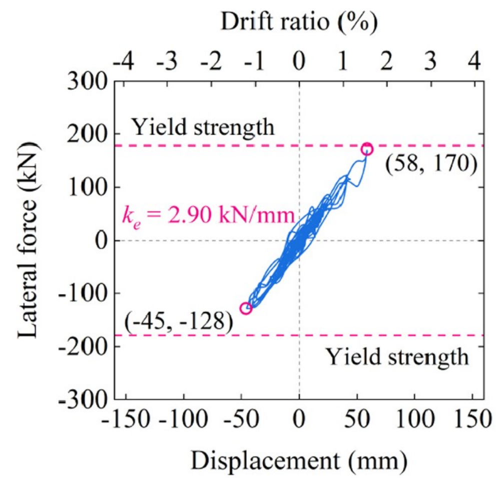
Displacement time history of column top and main girder

4 Seismic performance of precast piers with UHPC connections

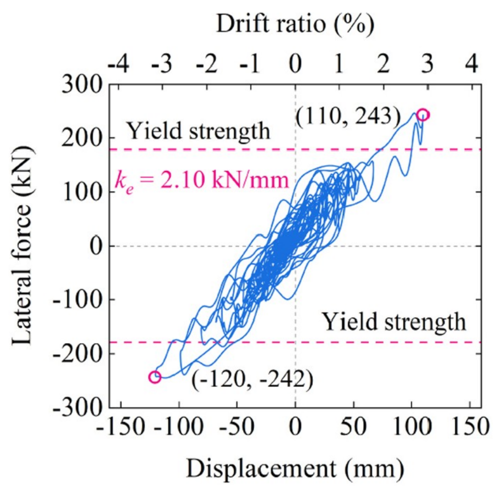
✓ The lateral force - displacement hysteretic loops of column P1 at PGAs = 0.3 g, 0.6 g and 1.4 g were shown in the following Figs respectively.



(a) PGA = 0.3 g



(b) PGA = 0.6 g



(c) PGA = 1.4 g

- It can be found that the hysteretic loops become wider as the PGA increases, and the lateral stiffness (secant stiffness) computed at the peak displacement degrades successively

4 Seismic performance of precast piers with UHPC connections

- ✓ The curvature of column P1 was shown in following
- As seen from Fig, inelastic curvature is mainly concentrated in the lower part of the standard segment when the PGA exceeds 0.3 g. In contrast, the curvature in the connection segment remains lower than the yield curvature. Such observation suggests that the plastic region shifts upward

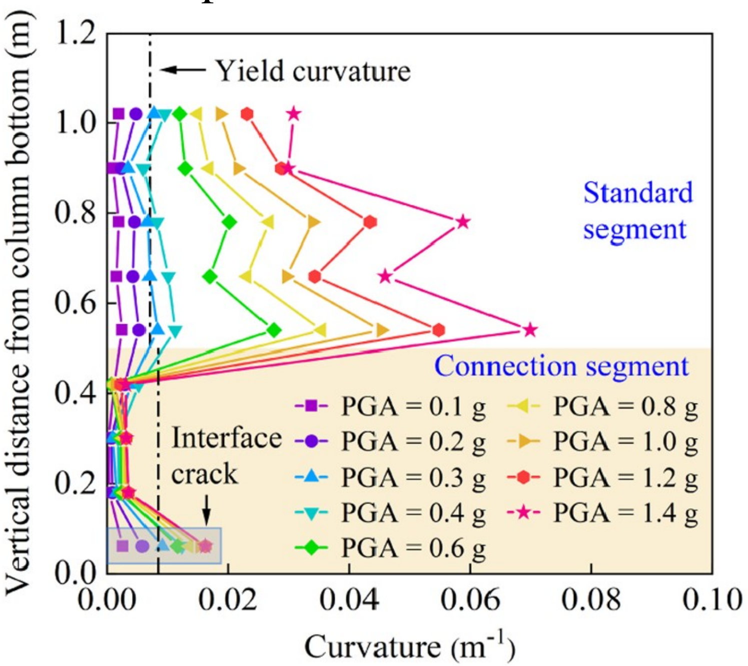


Fig. 16. Curvature distribution along the height of column P1.

4 Seismic performance of precast piers with UHPC connections

✓ Numerical modeling

- The FE modelling for the shaking table test model was also developed based on the OpenSees platform .As shown in

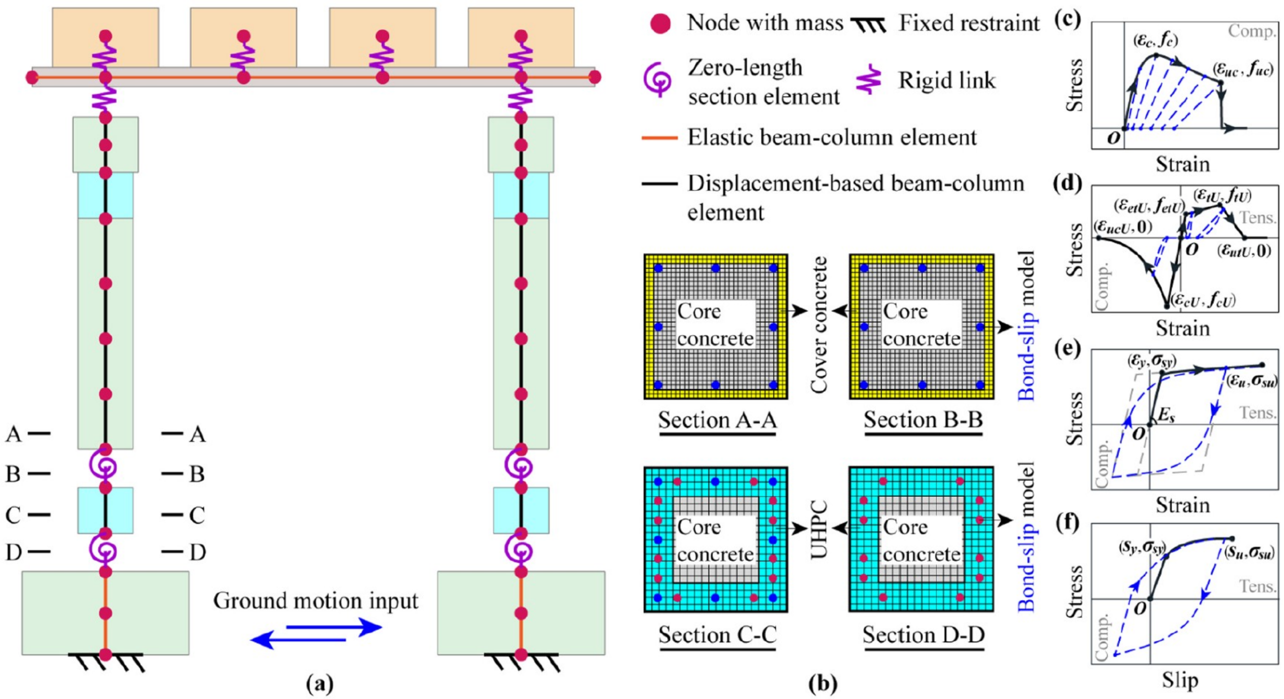
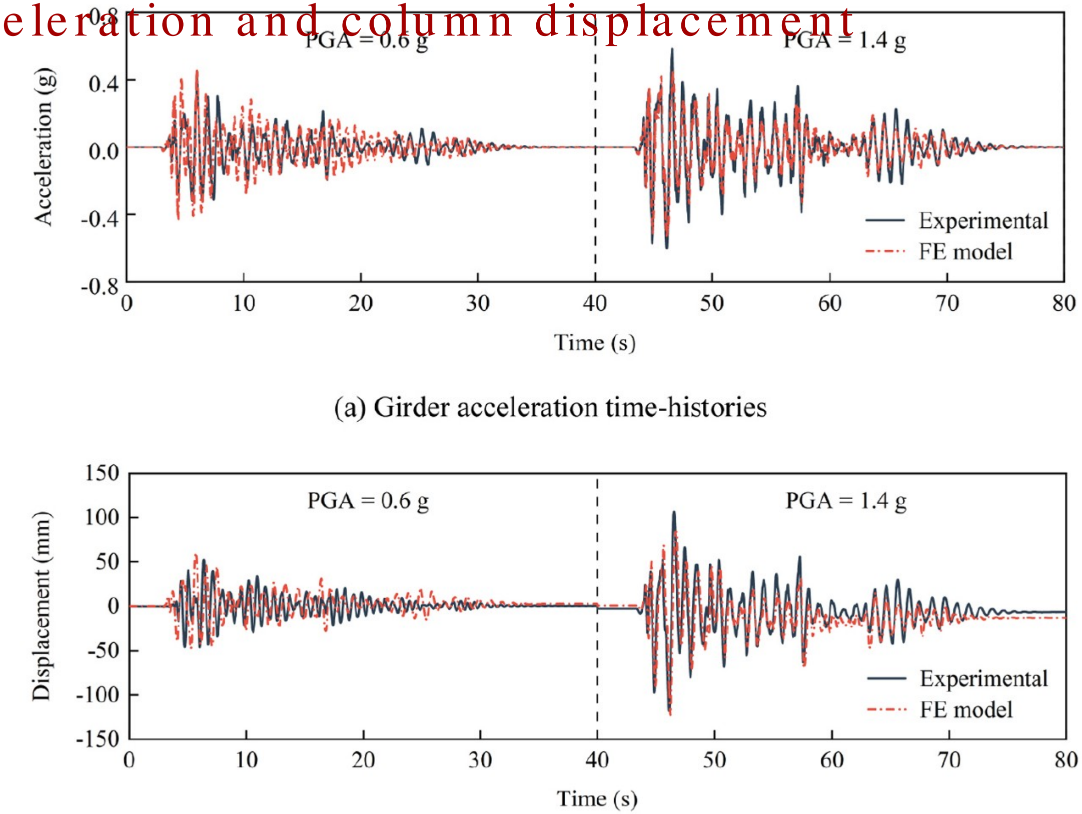


Fig. 18. OpenSees model.

OpenSees model.

4 Seismic performance of precast piers with UHPC connections

- These Figs compared response time histories for the girder acceleration and column-tip displacement at PGAs = 0.6 g and 1.4 g between shake table tests and the FE model. It can be seen that there is consistency in the shape of response time-histories for both girder acceleration and column displacement



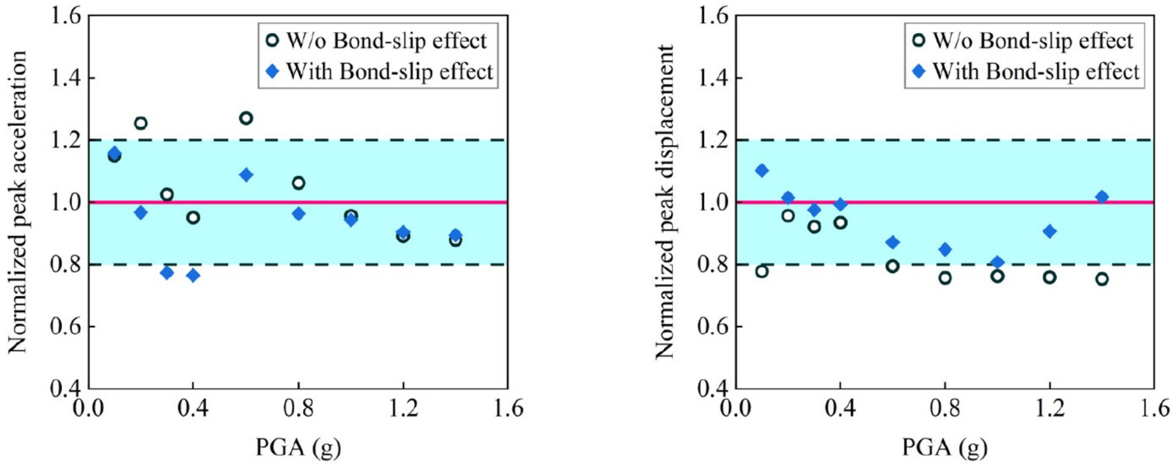
(a) Girder acceleration time-histories

(b) Column-tip displacement time-histories

Fig. 19. Comparison of response time-histories obtained by shake table tests and the FE model considering the bond-slip effect.

4 Seismic performance of precast piers with UHPC connections

- It can be found from Fig that the FE model has 12.0 % and 18.5 % relative errors on average in predicting the girder peak acceleration and peak column-tip displacement, respectively, if the bond-slip effect is neglected. However, the averaged relative errors mentioned above are reduced to 11.5 % and 8.1 %, respectively, when the bond-slip effect is considered.



(a) Peak girder acceleration

(b) Peak column-tip displacement

Fig. 20. Effect of bond-slip on peak responses of the scaled model.

4 Seismic performance of precast piers with UHPC connections

4.4 Application

No.	Project Name	Connection Type	Year
1	Shanghai Jiamin Elevated Road	with enlarged base UHPC connection	2016
2	South Extension of Ningbo Airport Road	with enlarged base UHPC connection	2017
3	Shanghai S2 Haigang Avenue Interchange	with enlarged base UHPC connection	2019
4	Shanghai Riverside Passage River-Crossing Tunnel	with ring UHPC connection	2020
5	Xinjiang Chengbei Main Road	with enlarged base UHPC connection	2021
6	Ningbo Xihong Bridge (Approach Bridge and Interchange)	with ring UHPC connection	2021
7	Shanghai Daye Highway	with ring UHPC connection	2021
8	Xinjiang East Approach Expressway	with ring UHPC connection	2021~

4 Seismic performance of precast piers with UHPC connections

✓ Shanghai Jiamin Elevated Road

Pile Cap and Rebar Arrangement

Precast Column and Cap Beam

Precast Cap Beam Hoisting

UHPC Mixing

Grouting of Column-Pile Cap Joint Completed

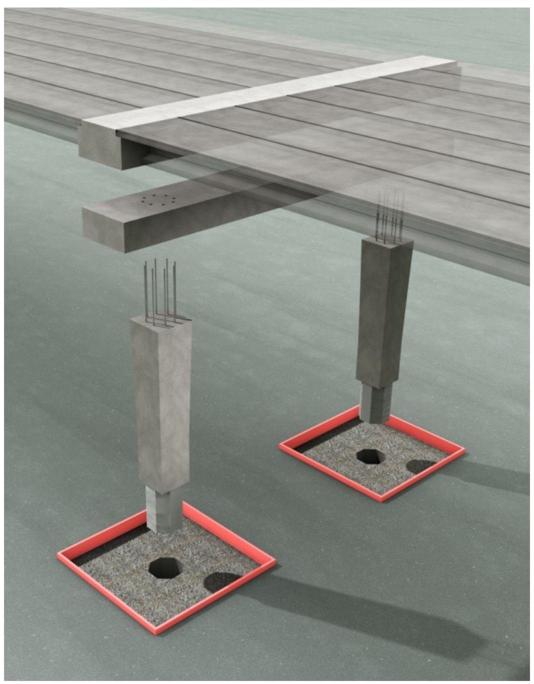
Grouting of Column-Cap Beam Joint Completed

5 Conclusions

- ✓ The two types of UHPC connection details for precast bridge piers introduced in this paper are feasible, and their connection methods provide seismic performance equivalent to that of cast-in-place piers.
- ✓ The UHPC connection details for precast bridge piers have been applied in many actual bridge projects in China, achieving good economic and social benefits.
- ✓ The research on UHPC-connected precast bridge piers provides new opportunities for the application of new materials and the innovation of new structural systems

5 Conclusions

- ✓New bridge structures should be economical.
- ✓ New structures are durable and environmentally friendly, with minimal impact on the public



Thank you