

Experimental and numerical investigation on the seismic resilience of PUC-strengthened curved bridge piers under flexural-torsional coupling

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Abstract

To enhance the seismic performance and seismic resilience enhancement of curved beam bridge piers, polyurethane cement (PUC) is adopted for pier retrofitting. Material mechanical tests on PUC specimens and shaking table model tests with a geometric scale of 1:10 under earthquake loading levels ranging from 0.2g to 0.6g on unreinforced and reinforced piers are performed to reveal their seismic response characteristics, and a refined numerical model of curved piers is built on the OpenSees platform for mutual validation of experimental and numerical results. Test results indicate PUC has a compressive strength of 72.0 MPa, which is approximately 1.8 times the standard value (40 MPa) of the commonly used C40 concrete cube in engineering. Compared with superior deformation coordination and interfacial adhesion over conventional repair materials. PUC retrofitting effectively restrains the coupled flexural-torsional deformation of curved piers; under the 0.6g major-earthquake condition, the lateral displacement is reduced by 46.28% and the torsion angle by 51.76%, presenting a more prominent suppression effect on torsion, markedly inhibiting residual plastic deformation accumulation. The hysteretic energy dissipation capacity of the reinforced rear pier is significantly enhanced; stress concentration at the pier base is alleviated; plastic damage is distributed more diffusely from the pier base to the rest of the pier structure; and the damage mode is optimized. Furthermore, finite element analysis error is controlled within 5%, verifying reliable calculation accuracy. This research proves PUC can significantly upgrade the seismic performance of curved beam bridge piers and provides technical references for seismic retrofitting of analogous curved bridges.

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1. Overview

Curved beam bridges are widely applied in urban interchanges, mountain highways, and riverfront bridge engineering because they have flexible alignment, strong adaptability, and can fit complex terrains and transportation hubs [1-2]. At the present stage, many in-service curved beam bridges globally generally face problems such as long construction periods, low design seismic standards, and structural aging damage. Under the threat of frequent earthquake disasters, the demand for seismic retrofitting and performance enhancement of these bridges becomes increasingly urgent [3]. Traditional bridge retrofitting methods include concrete jacket retrofitting, bonding steel plate retrofitting, and carbon fiber reinforced polymer retrofitting. These methods have defects such as long construction periods, large dead weight increments, poor durability, and vulnerability to

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environmental corrosion. Therefore, traditional methods are difficult to adapt to the construction needs of the irregular curved surfaces of curved bridge piers [4-5]. Polyurethane Cement (PUC) represents a new type of organic-inorganic hybrid retrofitting material. PUC has the characteristics of high strength, high toughness, excellent bonding performance, light dead weight, fast curing speed, and excellent high-low temperature resistance and fatigue resistance. PUC shows broad application prospects in the field of bridge seismic retrofitting [6-7]. Open System for Earthquake Engineering Simulation (OpenSees), as an open-source finite element simulation platform, possesses powerful structural nonlinear dynamic analysis capability. The OpenSees code can efficiently model the damage evolution process, plastic behavior, and dynamic responses of concrete structures and composite materials reinforced by concrete. OpenSees code has been extensively used in numerical simulations regarding seismic behavior of bridge structures [8].

Previous studies carried out many investigations around the application of polyurethane materials in engineering structures. Qader D N et al. systematically reviewed the progress in seismic resilience enhancement technology for concrete infrastructure. These scholars pointed out that new composite materials represent an important development direction in the field of structural seismic retrofitting in the future [9]. Wu Y et al. used the application of polyurethane elastomers for seamless bridge expansion joints. The research proved the superior properties of deformation compatibility and service stability of this material [10]. Mortazavi S J et al. created a new polyurethane elastomers material. The authors conducted the material constitutive modeling and structure mechanics simulation using the OpenSees platform. The research proved the effectiveness of polyurethane materials usage for structural simulation [11]. Regarding the inherent bending-torsion coupling seismic damage problem of curved beam bridges, relevant studies have shown that the offset of the mass-center will cause the bridge piers to bear complex bending-torsion combined internal forces, significantly amplifying the seismic damage requirements at the pier bottom [12]; under multi-dimensional seismic excitation, the torsional effect of the curved bridge will further aggravate the non-uniform damage of the bridge piers, and traditional retrofitting methods are difficult to achieve the coordinated improvement effect of resisting bending and torsion [13].

However, most of the available researches were mainly concerned with conducting basic properties tests of polyurethane materials and studying the behavior of conventional straight bridge piers. Relevant studies focusing on the flexural-torsional coupling damage mechanism of curved beam bridge piers are rather scarce, because conventional retrofitting materials possess single stiffness characteristics and poor adaptability to irregular curved surfaces, which fail to coordinate the complex coupled deformation of curved piers and cannot effectively alleviate torsion-induced seismic damage. The available literature does not contain any systematic investigations on the response regularity and damage characteristic of PUC retrofitting systems. Therefore, further investigation on the seismic behavior of PUC retrofitting systems is still needed. To address this issue, this study combines mechanical tests, shaking table model tests, and OpenSees numerical simulation to reveal the seismic enhancement mechanism of curved beam bridge piers reinforced with PUC. The core innovation of this study is clarifying the stress regulation mechanism of PUC retrofitting: the superior hyper-elastic and ductile characteristics of PUC material effectively redistribute the complex flexural-torsional coupling stress of curved bridge piers and disperse the concentrated plastic damage at pier bottoms. Meanwhile, a refined fiber-section numerical model matching the mechanical properties of the PUC composite retrofitting system is established on the OpenSees platform, which realizes accurate simulation of the nonlinear deformation and damage evolution of curved piers under multi-dimensional seismic excitation. This study quantitatively analyzes the evolution regularities of dynamic responses, damage distribution, and energy dissipation characteristics of the structure before and after retrofitting. This study provides theoretical support for the engineering application of new composite materials in the field of curved bridge seismic retrofitting.

2. Materials and Methods

2.1 Preparation of PUC Material

2.1.1 Raw Material Ratio and Selection

PUC composite material is compounded by polyurethane prepolymer, P·O 42.5 ordinary Portland cement, ultra-fine fly ash, quartz sand, and categorical functional additives including defoamer and organometallic catalyst. The optimal mix proportion is determined through preliminary proportioning tests. The mass ratio of polyether component, isocyanate component, and cement is 1:1:2, which means the ratio of polyurethane black and white materials to cement also adopts 1:1:2. The adopted polyurethane prepolymer possesses an NCO content of $16 \pm 1\%$ and a rotational viscosity of 320-380 mPa·s (25 °C). Low-viscosity and high-activity industrial raw materials are selected for the polyurethane prepolymer to enhance the penetration capability of the slurry and the interface bonding effect. P·O 42.5 ordinary Portland cement serves as the main binding agent to guarantee the basic mechanical strength of the matrix. Ultra-fine fly ash with a median particle size (d_{50}) of 5-10 μm and quartz sand with a median particle size (d_{50}) of 80-120 μm serve as filling aggregates to optimize the internal particle grading, improve material density, suppress shrinkage deformation, and ensure excellent interface bonding performance with concrete substrates.

2.1.2 Preparation Process and Specimen Fabrication

The PUC material is prepared using a combination of dry and wet mixing processes. First, cement and ultra-fine quartz powder dry powder are uniformly dry-mixed for 2 min to achieve full mixing of the powders. Then, the pre-mixed polyurethane emulsion and water reducer aqueous solution are slowly added, and continuous low-speed stirring is maintained for 5 min until the slurry is uniform without particles and the fluidity is stable. The specially formulated defoamer incorporated in the PUC system can effectively suppress the chemical reaction between isocyanate groups and free water, avoiding CO_2 foaming and pore defects induced by aqueous solution. Meanwhile, low-speed mixing reduces entrained air, and subsequent full vibration further eliminates micro-pores, ensuring the compactness of the cured material. Standard specimens are cast according to the standard dimensions of mechanical tests. Standard specimens for compression, tension, bending, and interface shearing are fabricated respectively. After casting, full vibration is conducted to eliminate internal air bubbles and avoid pore defects. After the specimens stand at room temperature for initial setting, they are covered with film for moisture retention, and mechanical property tests are carried out after standard curing for 28 d. Meanwhile, the retrofitting construction of the curved bridge piers is completed using this preparation process. After the base layer of the pier body is polished and cleaned, the PUC slurry is applied uniformly in layers. The nominal thickness of the PUC retrofitting layer is controlled at 10 mm for the 1:10 scaled model. The uniformity of the retrofitting layer thickness is strictly controlled to ensure that the retrofitting layer bonds tightly with the concrete matrix without hollowing or cracking.

2.2 Retrofitting Shaking Table Test Method

To clarify the differences in structural dynamic response and damage evolution before and after retrofitting, a 1:10 scaled model dynamic loading test is carried out using an earthquake simulation shaking table in this test. Strict seismic similitude design is implemented to guarantee the equivalence between the scaled model and the prototype bridge. The detailed geometric, physical, and dynamic similitude coefficients adopted in this study are listed in Table 1. The overall equipment composition and architecture of the earthquake simulation shaking table used in the test are shown in Figure 1.

According to Figure 1, El-Centro earthquake wave, Taft earthquake wave, and site-simulated artificial earthquake wave are selected as excitation loads. The selection of these three seismic waves follows structural dynamic matching and site spectral compatibility principles: the dominant periods of the selected waves cover the natural vibration period range of the curved beam bridge pier, which can effectively arouse the typical flexural-torsional coupled dynamic

response. Meanwhile, natural waves with different frequency characteristics and site-matched artificial waves are adopted to enrich the spectral input diversity.

Table 1. Seismic similitude scaling coefficients for the 1:10 curved bridge pier model

Physical Parameter	Similitude Symbol	Scaling Ratio (Model/Prototype)
Geometric dimension	S	1/10
Elastic modulus	S	1
Density	S	1
Mass	S	1/1000
Time / Period	S	$1/\sqrt{10} \approx 0.316$
Acceleration	S	1
Stress	S	1
Strain	S	1
Stiffness	S	1/10

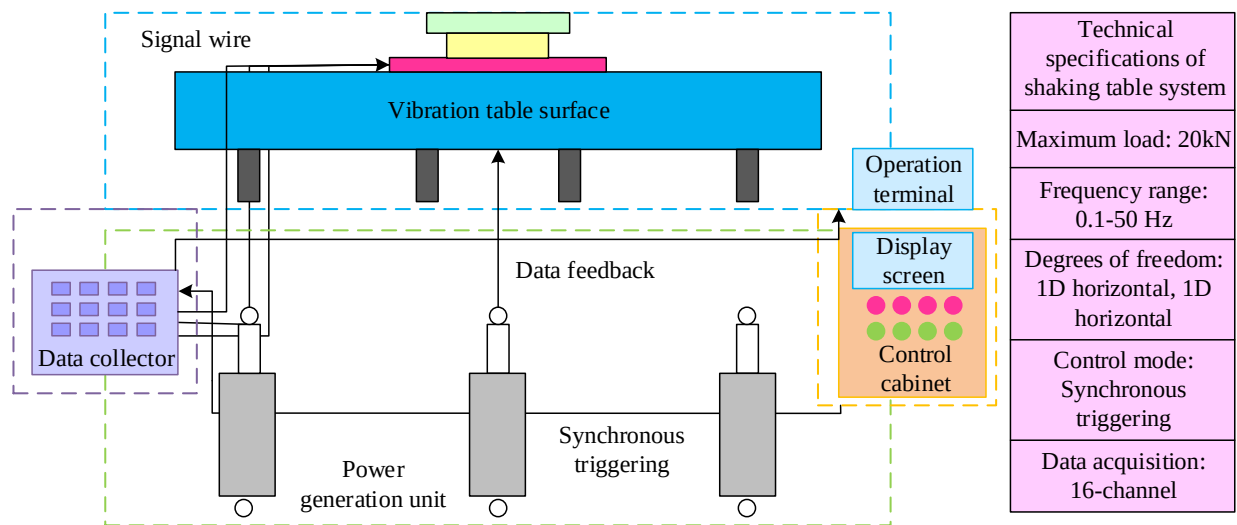


Fig. 1. Equipment composition and architecture

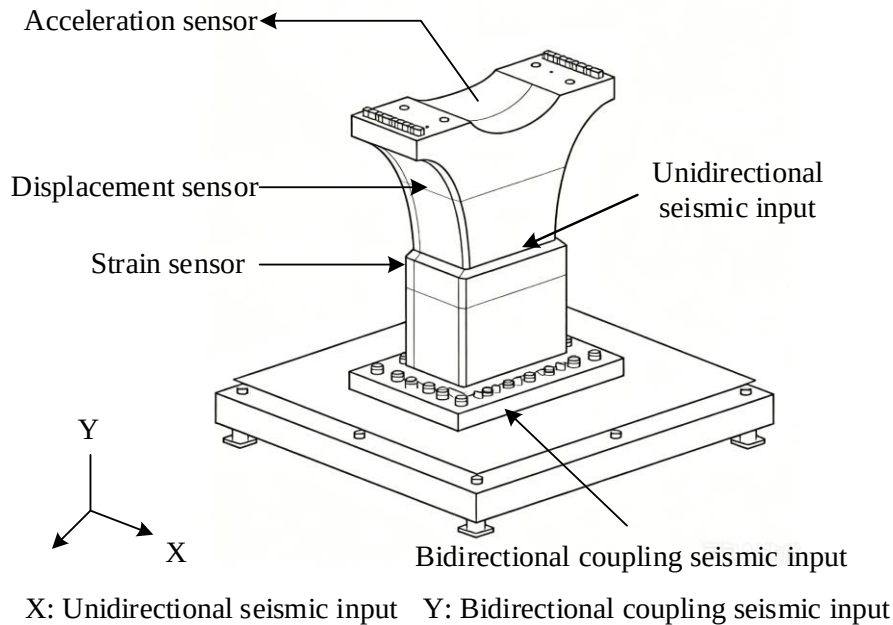


Fig. 2. Arrangement of measurement points in shaking table test

Three levels of peak acceleration, namely 0.2g, 0.4g, and 0.6g, are inputted respectively, corresponding to minor, moderate, and major earthquake conditions. During the test, the control

system imports earthquake wave instructions with different frequency spectrum characteristics and peak accelerations. The hydraulic power system receives electrical signals and converts them into mechanical actions, which drives the shaking table surface to achieve reciprocating motion according to the preset waveform. The data acquisition system collects the dynamic response data such as acceleration and displacement of the table surface and the specimen in real time, and feeds them back to the control system to guarantee the loading accuracy and stability under various earthquake conditions [14-15]. The measurement point arrangement for the shaking table test of curved beam bridge piers is shown in Figure 2.

According to Figure 2, unidirectional and bidirectional coupled earthquake input modes are adopted in the test to fully restore the torsional coupled stress characteristics of curved bridge piers under actual earthquake actions. An X-Y coordinate system is defined, where the X-axis corresponds to unidirectional seismic excitation and the Y-axis corresponds to the additional horizontal component for bidirectional coupled excitation. Acceleration sensors, displacement sensors, and strain sensors are arranged at the pier top, the middle-upper part of the pier body, and the cap position to monitor the structural acceleration response, lateral displacement, torsional displacement, and strain changes of steel bars, concrete, and the retrofitting layer respectively [16]. Specifically, a pair of opposing displacement sensors are mounted on two opposite sides at the pier top; the torsion angle is calculated from the relative displacement readings obtained by this sensor pair. In addition, the test process is recorded in high-definition throughout the entire period to record the crack development, deformation progress, and damage failure modes of the bridge piers under different earthquake conditions, systematically obtaining the dynamic response regularities and seismic damage characteristics of the curved beam bridge piers before and after retrofitting.

2.3 Selection of Finite Element Software and Model Parameters

2.3.1 OpenSees Principle and Element Selection

OpenSees finite element software possesses a complete structural nonlinear dynamic analysis module, which can accurately simulate the plastic damage of concrete structures, yielding of steel bars, and cooperative stress characteristics of composite materials. OpenSees is suitable for refined numerical analysis of bridge structure seismic responses [17-18]. This study carries out numerical modeling of curved beam bridge piers based on the OpenSees platform. Combined with the spatial stress characteristics of curved bridge piers and the mechanical properties of retrofitting structures, reasonable element selection is conducted. The element framework and modeling process of the OpenSees platform are shown in Figure 3.

According to Figure 3, the model adopts displacement-based beam-column elements (dispBeamColumn) to simulate the pier body. The composite fiber section is discretized with 36 fibers to balance calculation efficiency and numerical precision. Compared with force-based beam-column elements, the displacement-based formulation is selected in this study because it provides superior numerical convergence performance under complex flexural-torsional coupling deformation and multi-stage cyclic seismic loading. It can effectively avoid calculation divergence in strong nonlinear analysis and stably simulate the full-range dynamic nonlinear response of curved beam piers. The concrete matrix adopts the Concrete02 model, and the steel bars adopt the Steel02 model. The PUC retrofitting layer is realized through a composite fiber section, and its constitutive parameters are calibrated by the results of uniaxial compression and tension tests. As derived from the mechanical test results in Figure 4, the ultimate compressive strength is set to 72.0 MPa, the elastic modulus is set to 5.48 GPa, and the Poisson's ratio is set to 0.27. Boundary conditions are set according to the test conditions. The bottom cap is fixed, and an equivalent mass load is applied at the pier top, with a mass ratio of 1:1 to the test model. The earthquake motion input adopts the El-Centro wave, which is consistent with the shaking table test, and the peak accelerations of loading are 0.2g, 0.4g, and 0.6g respectively.

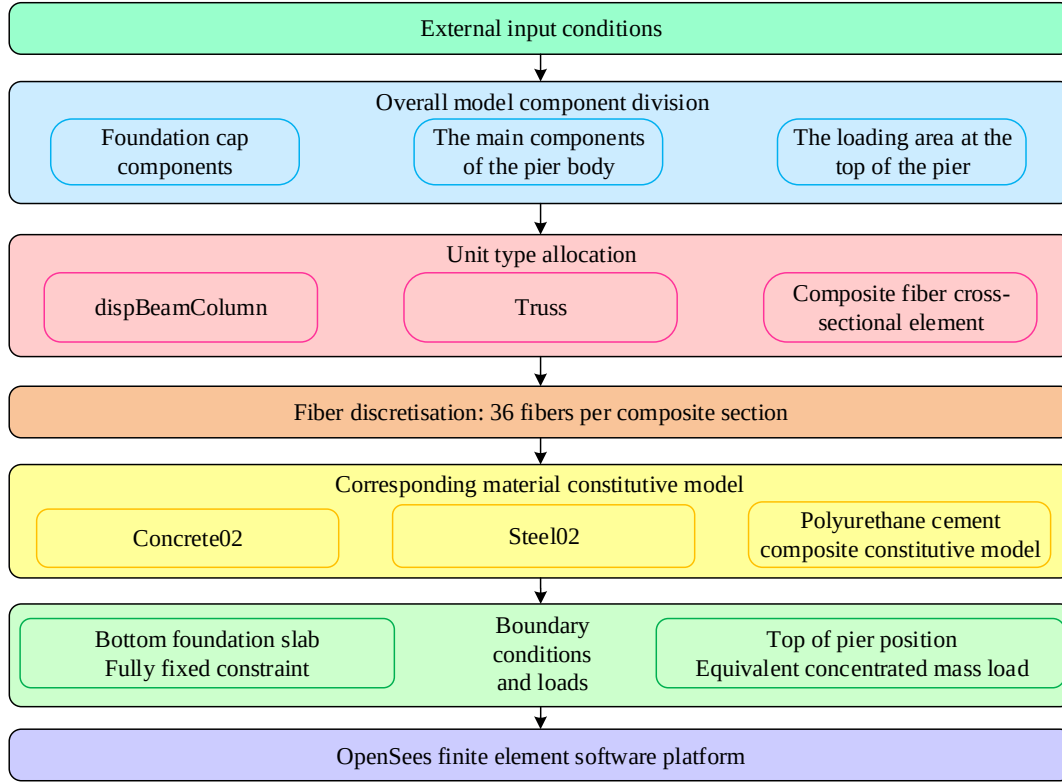


Fig. 3. Element framework and modeling process of OpenSees platform

2.3.2 Model Establishment and Parameter Calibration

According to the actual dimensions and material parameters of the test model, a refined finite element model of the curved beam bridge pier corresponding 1:1 to the test model is established. A fixed constraint is set at the bottom of the model to simulate the fixed state of the cap and the foundation. A mass load corresponding to the test condition is applied at the pier top to match the actual mass distribution characteristics of the structure. Based on the mechanical property test results of PUC and the code parameters of concrete and steel bars, the assignment and calibration of each material constitutive parameter in the model are completed. The numerical loading system is completely unified with the shaking table test. The earthquake wave type, peak acceleration level (0.2g, 0.4g, 0.6g), and loading mode remain consistent with the test conditions, and nonlinear dynamic time-history analysis is carried out. By comparing the simulation and test data of dynamic response indicators such as pier top lateral displacement and torsion angle, key numerical parameters were quantitatively calibrated to minimize errors: the structural damping ratio was adjusted from the initial empirical 5% to 2.5% for curved pier nonlinear vibration; the concrete ultimate compressive strain was finely tuned to match the plastic development trend; and the interface shear stiffness between the PUC layer and concrete matrix was corrected to reflect the composite cooperative working performance. After systematic calibration, the numerical prediction error is controlled within 5%, finally obtaining a refined finite element model with reliable accuracy.

3. Experimental Results

3.1 Analysis of Mechanical Property Test Results Of PUC

To investigate the basic mechanical characteristics, deformation regularities, and interface bonding performance of PUC, this study performed mechanical property tests. The mechanical response curves of PUC under the full process of uniaxial compression are shown in Figure 4.

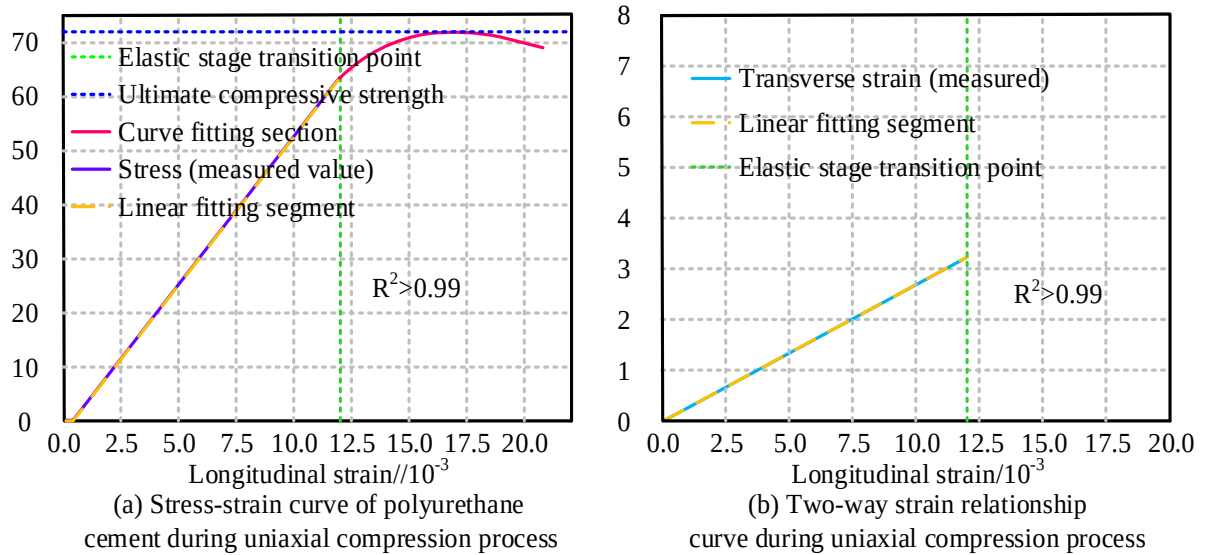


Fig. 4. Mechanical response curves of PUC under uniaxial compression

According to Figure 4(a), during the early stage of loading, stress and longitudinal strain increased linearly. The elastic modulus of 5.48 GPa adopted in the numerical model is the secant modulus derived from this linear fitting segment ($R^2 > 0.99$). Due to its lower modulus compared to concrete, the strengthening layer can deform alongside the concrete without causing a stiffness jump. This match avoided stress concentration caused by modulus differences between the retrofitting layer and the matrix. When the longitudinal strain reached approximately 12.0×10^{-3} , the material entered the plastic retrofitting stage. The curve slope decreased gradually, showing obvious ductility characteristics. The material reached its ultimate compressive strength of 72.0 MPa when the longitudinal strain reached approximately 17.5×10^{-3} . Afterwards, the graph decreased slowly without any brittle fracture behavior, which suggested that this material has excellent load-carrying capability and deformability while failing under compression. In Figure 4(b), during the elastic region, there was a linear relationship between the transverse and longitudinal strains.

The curves of uniaxial tension and bending tests of PUC are shown in Figure 5.

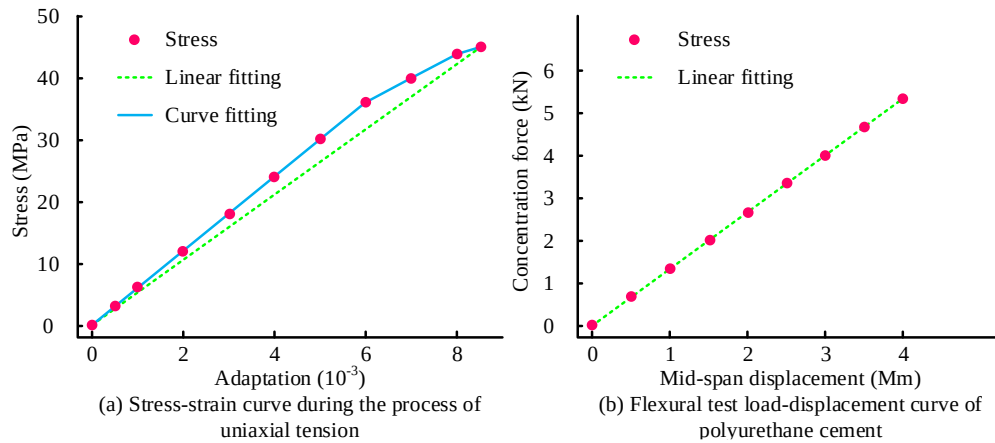


Fig. 5. Test curves of PUC under uniaxial tension and bending

Figure 5(a) presents the stress-strain relationship curve of PUC under uniaxial tension. According to Figure 5(a), when the tensile strain reached approximately 8.45×10^{-3} , the specimen reached the ultimate tensile strength of 46.25 MPa, and then fracture occurred. This relatively high ultimate tensile strength is attributed to the high polyurethane fraction within the PUC cementitious composite. Such excellent tensile bearing capacity is particularly valuable for curved bridge piers, which are prone to severe tensile stress induced by torsional coupling effects under seismic loading. The full process lacked obvious plastic deformation and yielding platforms, indicating that the material had excellent stiffness stability under tensile conditions, but its plastic deformation capacity was limited. The overall process exhibited linear elastic brittle fracture characteristics.

Figure 5(b) illustrates the load-midspan displacement relationship curve of the PUC bending test. According to Figure 5(b), when the midspan displacement reached 4.0 mm, the ultimate load on the specimen was approximately 5.33 kN. There was no apparent non-linear deformation on the material during the loading test, indicating that the material exhibited a linear elastic failure form under bending state. The result showed that the PUC material had excellent deformation compatibility and force stability under bending, which would meet the complex force and deformation demands.

The interface bonding performance between the retrofitting material and the concrete matrix represents the core indicator determining the overall cooperative working capacity of the retrofitting system. To analyze and compare the interface bonding advantages and disadvantages of PUC and traditional repair materials, this study carried out concrete interface shear comparison tests of three types of materials. The failure modes are shown in Figure 6.

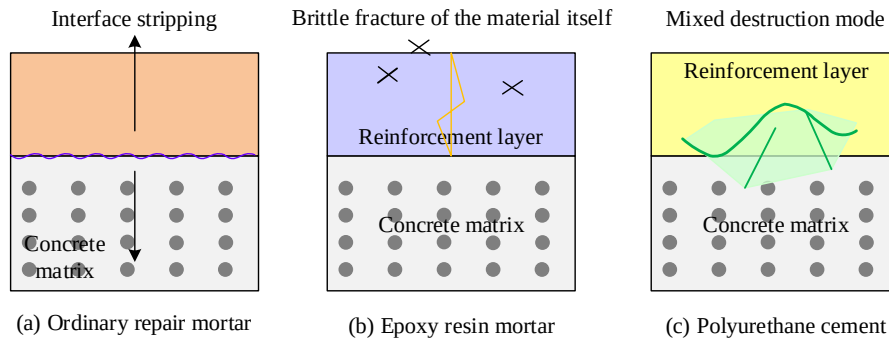


Fig. 6. Failure modes of concrete interface shear tests with different materials

Figure 6(a) displays the interface shear failure mode between ordinary repair mortar and concrete. Under the action of shear load, the mortar layer separated from the concrete matrix directly. The low interface bonding strength failed to guarantee the cooperative force between the retrofitting layer and the original structure, making it prone to detachment failure under cyclic earthquake loads. Figure 6(b) shows the interface shear failure mode between epoxy resin mortar and concrete. Brittle fracture of the material body occurred in the epoxy resin mortar, while the interface remained intact. This behavior indicated that the interface bonding strength between the epoxy resin mortar and concrete was higher than the material strength itself. However, the fracture mode of the material was brittle fracture without obvious signs of plastic deformation, which easily led to sudden cracking under repeated earthquake loads. Figure 6(c) illustrates the interface shear failure mode between PUC and concrete. Rather than adhesive failure along the bonding plane, a typical cohesive-mixed failure is observed. The failure zone penetrated both the PUC retrofitting layer and the concrete surface layer simultaneously, and no overall interface separation occurred. This phenomenon indicated that the interface bonding strength between PUC and the concrete substrate was higher than that of ordinary repair mortar, and the material itself possessed a certain toughness.

3.2 Analysis of Retrofitting Shaking Table Test Results

In order to measure the variations of dynamic behaviors of the bridge piers due to different earthquake intensities and the effects of improvements in the capacity of deformation control and energy dissipation due to the retrofitting using the PUC method, the maximum lateral displacement and maximum torsion angle of the piers were listed for different intensities of Peak Ground Acceleration (PGA) as presented in Table 2.

The data in Table 2 indicated that the curved beam bridge piers experienced a significant flexural-torsional coupled vibration effect. Under earthquake actions, the piers generated lateral deformation and torsional deformation simultaneously, and the responses grew nonlinearly as the PGA increased. Under the same level of earthquake load, both the lateral displacement and the torsion angle of the PUC-retrofitted bridge pier were significantly smaller than those of the unreinforced bridge pier. It is observed that under 0.6g seismic loading, lateral displacement dropped from 12.68 mm to 6.81 mm (a 46.28% reduction) and the torsion angle decreased from

0.0085 rad to 0.0041 rad (a 51.76% reduction) thanks to PUC strengthening. The reduction magnitude of the torsion angle exceeded that of lateral-displacement mitigation, representing the most remarkable performance improvement of PUC retrofitting for curved-beam piers. The outcomes proved that the PUC retrofitting successfully controlled the spatial coupled deformation of curved bridge piers, and exerted more prominent suppression on the adverse torsional vibration response, and enhanced their seismic vulnerability, which was characterized by force unbalance and large deformation.

Table 2. Maximum response results of pier top displacement and torsion angle

PGA condition	Test specimen type	Maximum lateral displacement at the pier top (mm)	The maximum torsional angle at the top of the pier (10^{-3} rad)	Displacement Reduction Rate (%)	Torsion Angle Reduction Rate (%)
0.2g (minor tremor)	Not reinforced	2.86	2.10		
	Reinforced	1.62	1.00	43.36	52.38
0.4g (moderate tremor)	Not reinforced	6.93	4.80		
	Reinforced	3.75	2.20	45.89	54.17
0.6g (major earthquake)	Not reinforced	12.68	8.50		
	Reinforced	6.81	4.10	46.28	51.76

To visually compare the displacement response regularities of the bridge piers before and after retrofitting during the full process of earthquake loading, this study took the 0.4g moderate earthquake condition as an example and plotted the comparison curves of the pier top displacement time-history and displacement envelopes, as shown in Figure 7.

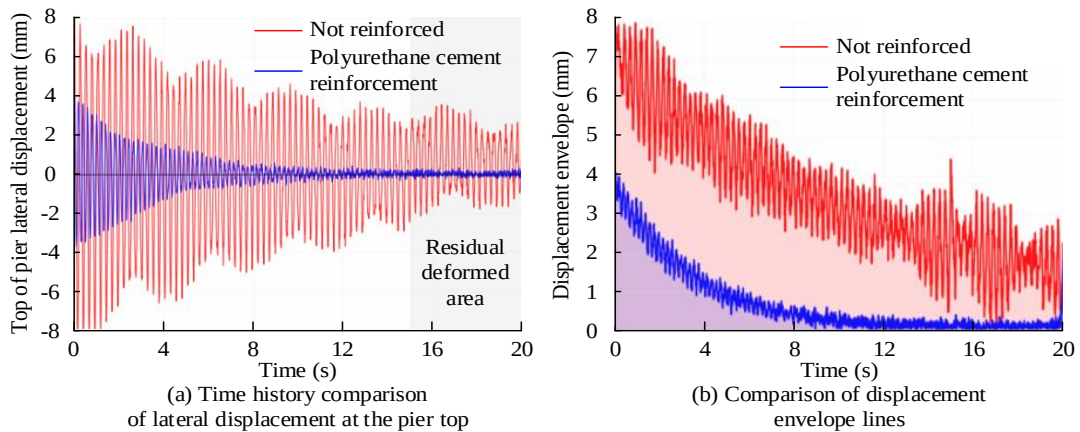


Fig. 7. Comparison of pier top displacement responses under 0.4g earthquake condition

In Figure 7(a), the maximum displacement of the unreinforced bridge pier under the earthquake action was approximately 7.75 mm. The displacement fluctuations had a relatively high amplitude, while the rate of damping was relatively low, and there appeared to be a definite zone of residual deformation during the later stages of loading (15–20 s). This suggested that the system had sustained irreversible plastic damage due to cyclic loading. According to Figure 7(b), the displacement envelope of the unreinforced bridge pier covered a wide range and attenuated slowly, reflecting its low efficiency in dissipating vibration energy. Conversely, the displacement envelope of the PUC-reinforced bridge pier decreased significantly overall and attenuated rapidly. This trend showed that the retrofitting effectively controlled and dissipated the vibration energy of the structure, and the overall stability of the structure increased substantially.

In order to quantitatively study the effect of improvement of PUC reinforcing performance in controlling residual deformation and energy dissipation capability, the comparison results of the accumulation of residual displacement at pier top and vibration attenuation capability under 0.4g earthquake excitation are illustrated in Figure 8.

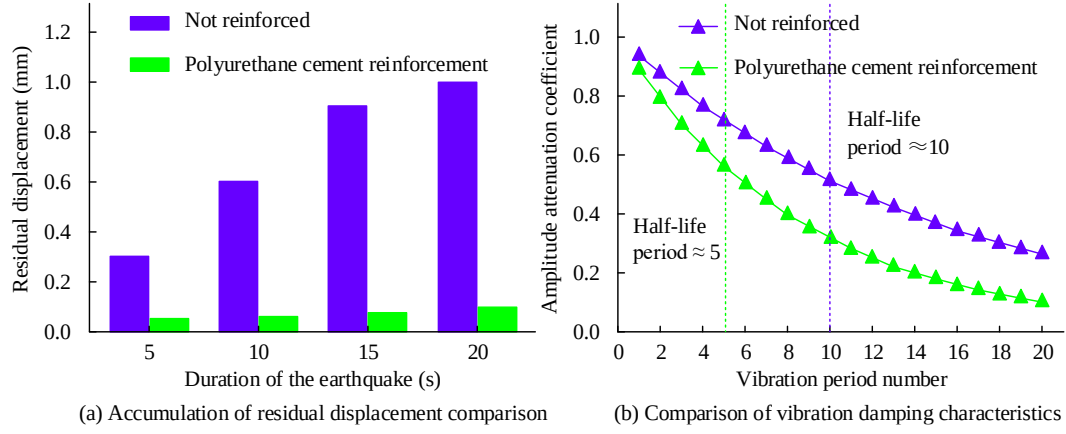


Fig. 8. Comparison of residual displacement accumulation and vibration attenuation

Figure 8(a) presents the comparison of residual displacement accumulation at the pier top under different earthquake durations. According to Figure 8(a), the residual displacement of the unreinforced bridge pier increased continuously with the extension of the earthquake duration, growing from 0.3 mm at 5 s to 1.0 mm at 20 s. This growth indicated that plastic damage accumulated constantly. However, the residual displacement of the PUC-reinforced bridge pier stayed at an extremely low level throughout, slight increase from 0.05 mm at 5 s to 0.10 mm at 20 s. This result demonstrated that the retrofitting layer constrained the opening and propagation of concrete plastic cracks effectively, avoiding the accumulation of unrecoverable deformation. Figure 8(b) shows the comparison curves of the amplitude attenuation coefficient based on damping ratio characteristics. As shown in Figure 8(b), it is known that the half-life period of amplitude attenuation of the non-reinforced curved bridge pier is around 10 vibration periods, whereas the half-life period of the PUC-reinforced curved bridge pier is only about 5 vibration periods. The rate of attenuation became much faster. This superior damping performance benefits from the inherent viscoelastic characteristics of the PUC composite material. The viscoelastic deformation of polyurethane components provides stable additional structural damping and continuously dissipates vibration energy, thereby rapidly suppressing structural oscillation. In summary, the PUC retrofitting method could enhance the seismic capacity of curved beam bridge piers in many aspects, such as amplitude control, residual deformation reduction, vibration energy dissipation, and torsional coupled effect minimization.

3.3 Analysis of Retrofitting Seismic Performance

Taking into account the geometrical dimension, retrofitting details of the test bridge pier and the constitutive model of PUC material calibrated earlier, the present study developed a sophisticated non-linear dynamic analysis model of the curved beam bridge pier both prior to and after retrofitting using the OpenSees platform. To verify the reliability of the model, this study compared the numerical simulation results with the shaking table test data. The verification results of key dynamic response indicators are shown in Table 3.

In Table 3, the pier top displacement and torsion angle calculated by the OpenSees model agreed well with the measured test values. The relative errors stayed within 5%, indicating that the established refined model could accurately reflect the nonlinear dynamic response characteristics of curved beam bridge piers before and after retrofitting. For the interface simulation between the PUC retrofitting layer and concrete substrate, the numerical model adopts a perfect bond assumption with calibrated interface shear stiffness based on experimental shear test data, without configuring additional independent interface elements. The selection of model parameters was reasonable, providing reliable support for subsequent seismic performance analysis. The hysteretic curve is a critical indicator reflecting the energy dissipation capacity and ductility of a structure under cyclic loads. The comparison of hysteretic curves of the curved beam bridge pier before and after retrofitting under the 0.6g condition is shown in Figure 9.

Table 3. Verification of key dynamic response indicators between simulation and test results

PGA condition	Specimen status	Indicators	Test value	Simulation value	Relative error/%
0.2g	Unreinforced	Maximum lateral displacement at pier top/mm	2.86	2.74	-4.20
		Maximum torsional angle at pier top/ 10^{-3} rad	2.10	2.02	-3.81
	PUC-retrofitted	Maximum lateral displacement at pier top/mm	1.62	1.56	-3.70
		Maximum torsional angle at pier top/ 10^{-3} rad	1.00	0.96	-4.00
0.4g	Unreinforced	Maximum lateral displacement at pier top/mm	6.93	6.64	-4.18
		Maximum torsional angle at pier top/ 10^{-3} rad	4.80	4.59	-4.38
	PUC-retrofitted	Maximum lateral displacement at pier top/mm	3.75	3.61	-3.73
		Maximum torsional angle at pier top/ 10^{-3} rad	2.20	2.10	-4.55
0.6g	Unreinforced	Maximum lateral displacement at pier top/mm	12.68	12.12	-4.42
		Maximum torsional angle at pier top/ 10^{-3} rad	8.50	8.08	-4.94
	PUC-retrofitted	Maximum lateral displacement at pier top/mm	6.81	6.59	-3.23
		Maximum torsional angle at pier top/ 10^{-3} rad	4.10	3.90	-4.88

Note: Relative error = (Simulation value - Test value) / Test value $\times$ 100%. A negative error indicates that the numerical result is smaller than the experimental result.

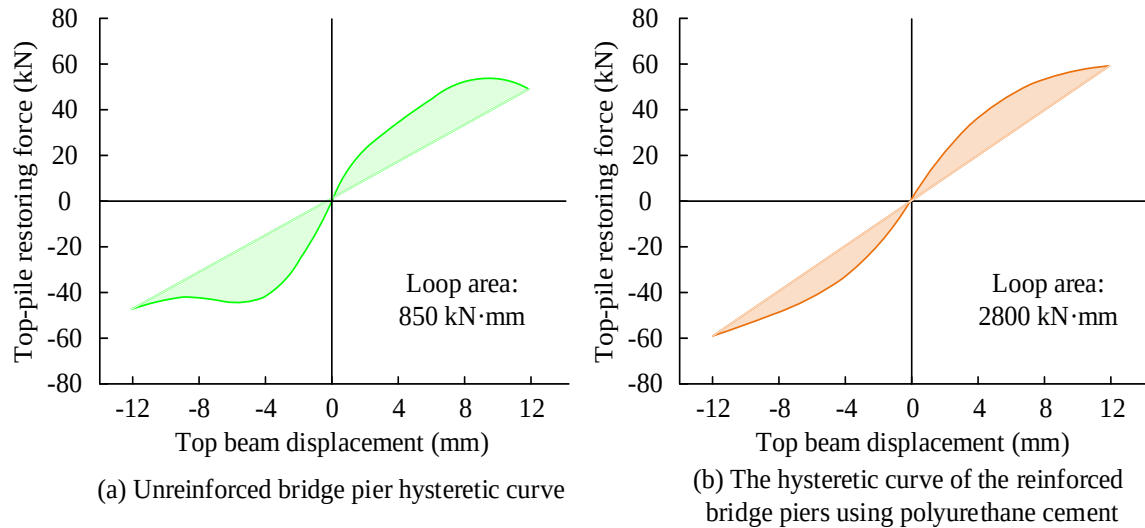


Fig. 9. Comparison of pier hysteretic curves under 0.6g earthquake condition

Figure 9(a) shows the hysteretic curve of the unreinforced bridge pier. According to Figure 9(a), the curve exhibited an obvious pinching feature, and the hysteretic loop area was small, measuring approximately 850 kN·mm. The stiffness degraded significantly in the late stage of loading, and the residual deformation was large after unloading. These observations indicated that the unreinforced bridge pier had limited energy dissipation capacity under cyclic earthquake loads and easily generated irreversible plastic damage. Figure 9(b) displays the hysteretic curve of the PUC-reinforced bridge pier. In Figure 9(b), her hysteretic loops were full and symmetric, and the area

increased substantially to approximately 2800 kN·mm. Physically, for curved beam bridge piers, the unreinforced specimen suffers uneven damage induced by flexural-torsional coupling; asymmetric torsional displacement offsets the positive-negative loading paths and produces severe pinching. After PUC retrofitting, the PUC retrofitting layer simultaneously improves the flexural stiffness and torsional stiffness of the pier section, suppresses the asymmetric torsional drift caused by coupled bending-torsion effects, mitigates the differential plastic damage on two sides of the pier cross-section, and therefore yields full, symmetric hysteretic loops. This tremendous improvement is not only derived from the superior toughness and viscoelastic energy-dissipating characteristics of PUC materials, but more critically, benefits from the effective enhancement of structural torsional rigidity. The PUC layer restrains the unique flexural-torsional coupling effect of curved piers, eliminates asymmetric torsional deformation and premature stiffness degradation, stabilizes the cyclic loading response, and ultimately achieves a substantial enhancement in structural energy dissipation capacity. No obvious pinching phenomenon occurred, and the loading-unloading paths remained symmetric and stable.

To further explore the influence of PUC retrofitting on the plastic damage distribution of the bridge pier, the proposed model outputted the plastic hinge distribution and curvature response of the key section of the bridge pier under the 0.6g major earthquake condition via OpenSees, as shown in Figure 10.

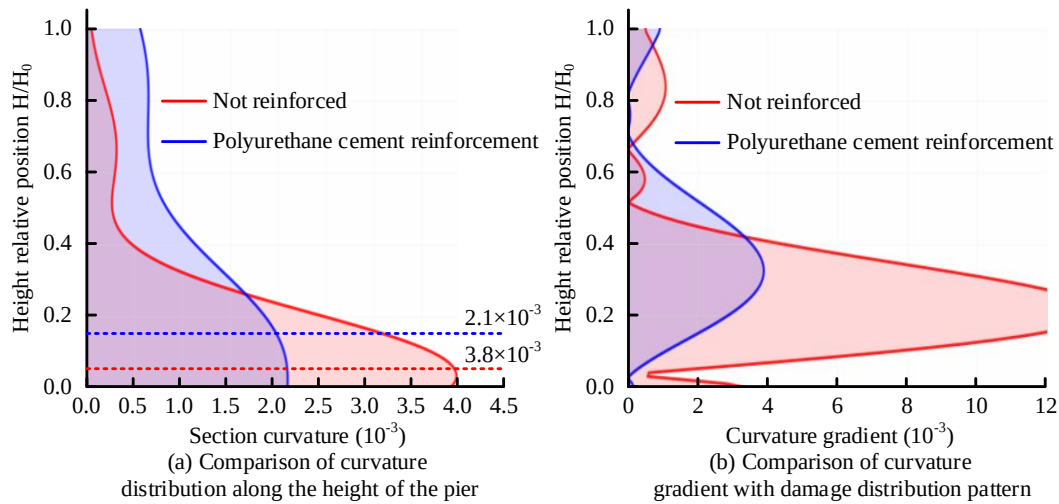


Fig. 10. Comparison of curvature distribution and damage modes

Figure 10(a) presents the comparison of curvature distribution along the pier height. According to Figure 10(a), the curvature of the unreinforced bridge pier concentrated at the bottom section of the pier. The maximum curvature reached 3.8×10^{-3} , and an obvious plastic hinge zone formed in the pier bottom region ($H/H_0 < 0.2$), where the stress concentration phenomenon was prominent. In contrast, the curvature distribution of the PUC-reinforced bridge pier was gentler. The maximum curvature dropped to 2.1×10^{-3} , representing a reduction of 44.7%. This phenomenon reflects the favorable effect of relocation of plastic hinges from the pier base to the pier body. The plastic hinge distribution zone scattered uniformly from the pier bottom toward the middle and upper parts of the pier, effectively avoiding concentrated damage at key sections. Figure 10(b) illustrates the comparison of curvature gradients and damage distribution modes. Curvature gradient denotes the spatial change rate of sectional curvature over pier height; a high local curvature gradient indicates sharp variation of plastic deformation over a short vertical distance, which is an important indicator for identifying potential brittle-shear risk at the pier bottom. According to Figure 10(b), the curvature gradient at the bottom of the unreinforced bridge pier changed drastically, indicating that the force concentrated at the pier bottom section, which easily induced brittle shear failure. However, the curvature gradient of the reinforced bridge pier decreased significantly overall, and the distribution curve became flat. It also visually demonstrates that severe plastic damage no longer accumulates merely at the pier base; instead, damage spreads and disperses upward into the pier body after PUC retrofitting. Through this modification, it became clear that the PUC reinforcing layer modified the load transfer characteristics of the bridge pier,

changing the previously concentrated plastic deformations to micro-plastic deformations in the reinforcing layer. Thus, this technique solved the problem of stress concentration at the critical section of the pier base and enhanced the resistance reserve of the structure against failure.

4. Discussion and Implications

The combination of results of material test, shaking table test, and numerical simulations revealed a clear flexure-twist coupling effect produced by the curved beam bridge piers when subjected to earthquake. Under the 0.6g earthquake action, the lateral deflection of the unbraced pier top was 12.68 mm, while the twist angle was 0.0085 rad. The reason behind such result is the curved shape of the structure because of which the earthquake inertial force produces torsional-flexural interaction arising from the eccentricity between the center of mass and the center of stiffness, thereby keeping the structure in a flexure-twist stress state for quite some time. High stress was induced at the bottom part of the pier, which created micro-cracks within the concrete. Ordinary concrete was unable to resist tension stresses, leading to development of cracks. When the loading reached 20 s, the residual displacement accumulated to 1.0 mm, causing irreversible plastic damage to the structure. Similarly, stress concentration and accumulation of plastic strains under cyclic loading have been identified by Zheng Y et al. as the major causes behind the deterioration of seismic behavior in concrete structures [19]. The conclusion made by Zheng et al. is similar to the damage progression pattern found during the test studies.

PUC retrofitting reduced the lateral displacement and torsion angle of the pier top under the 0.6g condition by 46.28% and 51.76%, respectively. This outcome primarily benefited from the good mechanical compatibility between the material and the concrete. The low elastic modulus of PUC (5.48 GPa) allowed it to act as a 'ductile shell' capable of dissipating energy without causing excessive stiffness accumulation on the concrete matrix. Its ultimate compressive strength is 72.0 MPa, and it sustained loads stably even when the compressive strain reached 17.5×10^{-3} , showing excellent ductility. Interface shear tests indicated that PUC and concrete formed a mixed failure mode, which is different from the interface peeling of ordinary mortar and the body brittle fracture of epoxy resin mortar. This behavior proved that its interface bonding strength was sufficient, which guaranteed the cooperative deformation of the retrofitting layer and the matrix. This reliable interface bonding integrity serves as the fundamental prerequisite for excellent seismic energy-dissipating performance. Without interface debonding and premature separation, the PUC composite can fully exert its viscoelastic damping effect, which directly contributes to the full and stable hysteretic loops and the greatly improved energy dissipation capacity (2800 kN·mm) of the retrofitted curved bridge pier. Oh S et al. pointed out in their research on the seismic performance of reinforced concrete components that the mechanical compatibility between the retrofitting material and the original structure, the reliability of the interface connection, and the material's own ductility level further confirm the application advantages of polyurethane cement materials [20].

From the perspective of dynamic response, the vibration attenuation half-life period of the reinforced structure shortened from 10 cycles to 5 cycles, while its residual displacement increased slightly from 0.05 mm at 5 s to 0.10 mm at 20 s. This reduction occurred because the external PUC retrofitting layer produces a prominent torsional-flexural shielding effect. This unique mechanical behavior comprehensively enhances the global bending stiffness and torsional rigidity of the curved bridge pier, effectively weakening the adverse flexural-torsional coupled vibration effect under seismic excitation. Numerical simulations showed that the maximum curvature at the pier bottom after retrofitting decreased from 3.8×10^{-3} to 2.1×10^{-3} . The reason is that the retrofitting layer achieved cross-sectional stress redistribution after participating in bearing the force. In accordance with the structural fuse mechanism proposed in existing studies, the flexible PUC layer serves as an effective protective structural fuse for curved bridge piers. Through this working mechanism, severe and concentrated plastic damage originally localized at the vulnerable pier base is rationally transferred and transformed into uniform micro-damage widely distributed along the pier body, which significantly reduces the risk of sudden structural collapse and optimizes the seismic failure mode of curved piers. This behavior is in line with findings reported by researchers Foyouzzati A and Khaloo A that through optimization of the damage distribution pattern and

improving the structural energy dissipation capability, the seismic resistance of concrete structures could be improved in medium-high seismicity regions [21]. It is noted that all simulated responses are slightly lower than the test results with negative errors within 5%. This systematic bias mainly originates from the ideal fully-bonded interface assumption and slightly overestimated structural damping in the numerical model, which renders the model marginally stiffer than the real specimen. Such minor systematic deviation is acceptable and does not affect the reliability of the analysis results.

5. Conclusion and Future Work

The current study was able to finish the property test of PUC and the retrofitting test of curved beam bridge pier by material test, the shaking table test with a scale of 1:10, and OpenSees simulation. From the material test, it was found that the ultimate compressive strength was 72.0 MPa and the ultimate tensile strength was 46.25 MPa. Rather than relying on elastic-modulus compatibility with concrete, the material exhibits excellent high ductility, which compensates for the inherent brittleness of concrete substrate. PUC reinforcement reduced the lateral displacement and torsion angle by up to 46.28% and 51.76%, respectively. Verification proved that the relative errors of all indicators of the established finite element model stayed below 5%, indicating reliable calculation accuracy. The simulation results confirmed that the hysteretic loop area of the structure after retrofitting increased from 850 kN·mm to 2800 kN·mm. The peak curvature at the pier bottom dropped significantly, and the structural energy dissipation capacity and damage resistance increased substantially. Such prominent enhancement in energy-dissipation performance is critical for the seismic safety of curved beam bridges, as it helps minimize permanent structural damage and reduces the collapse risk under severe earthquake events. Therefore, PUC represents a bridge seismic retrofitting material with excellent comprehensive performance. It can effectively improve the seismic weakness of curved beam bridge piers under flexural-torsional coupled stress, showing good engineering application value. However, this study only set unidirectional and bidirectional coupled earthquake input conditions, failing to restore the action effects of actual multi-dimensional complex earthquake motions. In addition, vertical seismic acceleration, which is critical for curved bridges and may induce additional torsional structural instability, was not considered in current tests and simulations. Subsequent studies can carry out multi-dimensional earthquake motion and cyclic fatigue load tests to investigate the mechanical response and durability of the retrofitting system under long-term service conditions. Moreover, further attention should be paid to the environmental ageing behaviour, ultraviolet resistance of PUC, as well as the long-term interface stability between PUC and concrete under complex service environments.

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