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POLYURETHANE CEMENT REINFORCEMENT FOR SEISMIC TESTING OF CURVED BEAM BRIDGES PIERS

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ABSTRACT

The "bending and torsion coupling" effect of curved bridges increases the likelihood of shear fracture and bending collapse of curved girder bridge piers and columns under earthquake action, leading to serious consequences such as overall collapse or overturning of the bridge structure. Polyurethane cement is commonly used as a reinforcement material for structural seismic reinforcement due to its excellent performance. In this study, a three-way shaking table test was conducted on a curved girder bridge, and an OpenSees finite element software was utilized to establish a fiber unit model of the abutment specimen. The model was then used to conduct parameter sensitivity analysis in order to investigate the influence of abutment height and polyurethane reinforcement on the seismic performance of polyurethane cement-reinforced abutment specimens. The results indicate that higher abutments lead to decreased reinforcing effects of polyurethane cement, while greater thicknesses of polyurethane cement result in improved reinforcing performance. Specifically, it was found that higher abutments diminish the reinforcing effect of polyurethane cement, whereas thicker layers of polyurethane cement reinforcement yield more pronounced effects. Based on data from parameter sensitivity analysis, parameters were optimized and the most economical parameters were derived. These findings provide a sufficient theoretical basis for utilizing polyurethane cement for reinforced curved beam bridge piers.

KEYWORDS

Curved beam Bridge piers, Polyurethane cement, Seismic Strengthening, OpenSees, Parameter optimization

INTRODUCTION

Curved beam bridges are widely utilized in various interchanges and ramps due to their unique advantages. However, these bridges experience complex forces under seismic conditions, owing to the characteristics of pier-beam connection and continuous curvature. The bridge pier plays a crucial role in bearing the load of the bridge and providing resistance against lateral forces. Seismic data shows that damage to bridge piers is a common phenomenon, which can lead to severe structural damage and even collapse of the bridge. Despite the maturity of many current bridge pier reinforcement technologies, there is a relatively limited amount of comparative research on seismic performance. Rational reinforcement methods can not only bring economic viability but also achieve better reinforcement effects. Therefore, enhancing the seismic performance of bridge piers is crucial for addressing the insufficient seismic capacity of beam bridges. Improving the seismic performance of bridge piers has become a hot topic in academic research.

In the presence of seismic loads, bridge piers on curved beam bridges are prone to serious damage. Many scholars have conducted research on methods for strengthening bridge piers against seismic forces [1-6]. Haoyang Zhang et al. [7] utilized polyurethane cement as a reinforcing material for treating the curved beam bridge piers. They conducted scaled-down model tests using a three-way shaking table to analyze and evaluate the effectiveness of the reinforcement treatment. The test results and data analysis indicate that the use of polyurethane cement can improve the seismic performance of reinforced curved beam bridge piers. He et al. [8] employed externally bonded fiber-reinforced polymer (FRP) materials to repair severely damaged reinforced concrete (RC) piers and columns, and then subjected them to seismic performance testing using a proposed static test system. The results demonstrate that whether or not steel reinforcement is broken affects the effectiveness of fiber composites in reinforcing severely damaged RC piers and columns.

When the seismic intensity is high and the duration is prolonged, the overall integrity of the plastic hinge region of bridge piers is severely weakened, ultimately leading to its crushing and causing the pier to lose its bearing capacity. This type of failure, known as flexural crushing, poses a significant risk of collapse, and the pier becomes challenging to repair after an earthquake. Polyurethane is a block copolymer formed by polycondensation reaction with isocyanate as hard segment and polyol as soft segment. It is used as cementing material in bridge projects. Polyurethane composite materials with different engineering characteristics are prepared by mixing cement, fly ash, coarse aggregate, rubber particles, steel fibers, etc., to meet technical requirements. These include polyurethane cement composite, polyurethane fly ash composite, polyurethane emery, polyurethane concrete, elastic polyurethane concrete and steel fiber reinforced polyurethane concrete [9] ~ [11]. In recent years, polyurethanecement has gradually been applied in the reinforcement of structures due to its excellent axial compression, flexural, and shear properties. It shows broad prospects in seismic-prone areas. There have been some studies on the performance of polyurethane cement indicating its numerous advantages [12] ~ [14].

Letizia Verdolotti's team [15] conducted a study in which they blended polyurethane material with silicate cement to form polyurethane cement. They investigated the mechanical properties of this composite material and demonstrated the mutual continuity between hydrated cement and polyurethane phases. In a separate study, Wang Jianlin et al. [16] utilized polyurethane cement composite materials to reinforce hollow slab beam bridges. The results of their research indicated that this method could effectively enhance the load-bearing capacity of the bridge, and the reinforcement process could be carried out without interrupting vehicular traffic. Furthermore, Haleem K. Hussain's team [17] conducted experiments to measure material parameters. They found that the compactness of polyurethane cement composite materials had a significant impact on material strength. Additionally, compared to conventional concrete, polyurethane cement materials exhibited substantial improvements in flexural and compressive strength.

This paper focuses on the seismic retrofitting of curved beam bridge piers using polyurethane cement. The research adopts a combined approach of experimental studies and numerical simulations to investigate the advantages of polyurethane cement in enhancing the seismic performance of curved beam bridge piers. The findings aim to provide theoretical support for the seismic retrofitting of curved beam bridge piers using polyurethane cement.

EXPERIMENTAL STUDY ON MECHANICAL PROPERTIES OF POLYURETHANE CEMENT

Materials

Polyurethane is a composite material synthesized through the polymerization of polyols and polyisocyanates, belonging to the category of synthetic resins. Its primary raw materials include oligomeric polyols and polyisocyanates. Polyurethane cement is a novel resin concrete composed mainly of polyurethane as the base and cement as the filling material. It possesses characteristics such as fast curing, high early strength, and good viscosity. This material is suitable for rapid concrete repair and structural reinforcement in building structures, making it a new type of high-strength, high-toughness organic-inorganic composite material.

The primary raw materials used in this study for the preparation of polyurethane cement are a two-component polyurethane (consisting of isocyanate and combined polyether) and ordinary Portland cement with a strength rating of 42.5. The key additives include catalysts, water-reducing agents, and mold release agents. The intended ratio for the preparation of polyurethane cement is as follows: black material (isocyanate): white material (combined polyether): cement = 1:1:2.

Polyurethane Cement Cubic Compression Test

At a temperature of 20℃, uniaxial compressive strength tests were conducted on polyurethane cement using cubic specimens with dimensions of 70.7mm × 70.7mm × 70.7mm. Both the upper and lower compression surfaces were coated with Vaseline to reduce friction-induced confinement forces resulting from the free deformation of the contact surfaces. Horizontal and vertical strain gauges were affixed to the free surfaces for measuring the material's Poisson's ratio. The tests were performed on a universal testing machine at a loading rate of 0.5mm/min. Figure 1 presents the results of the uniaxial compressive strength test for polyurethane cement, while Figure 2 displays photographs of its compressive failure.

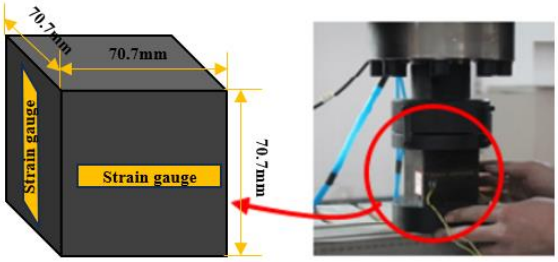

Fig. 1 - Polyurethane Cement Uniaxial Compression Test Graph

Fig. 2 - Polyurethane Cement Uniaxial Compression Failure Diagram

From Figure 2, it is evident that the compressive failure of polyurethane cement exhibits a typical plastic behavior, characterized by the formation of cracks penetrating to create a failure surface. Based on the experimental findings, the stress-strain relationship curve for uniaxial compression of polyurethane cement can be depicted, as illustrated in Figure 3.

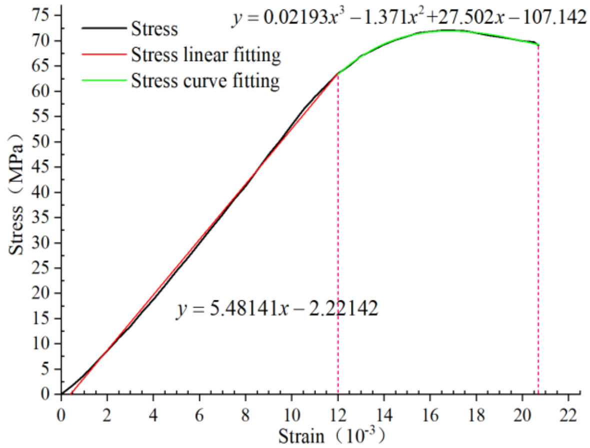

Fig. 3 - Polyurethane Cement Uniaxial Compression Stress-Strain Curve

From Figure 3, it is evident that the uniaxial compression behavior of polyurethane cement can be categorized into two distinct stages. The first stage demonstrates linear elastic behavior, with a stress-strain relationship characterized by an elastic modulus of approximately 5481.3 MPa and an elastic limit of around 63.4 MPa, corresponding to a strain of 12.1 mε. The second stage exhibits nonlinear behavior, following a higher-order curve with an ultimate compressive stress of about 72.05 MPa at a strain of 16.6 mε, and a failure strain of approximately 20.6 mε. The stress-strain fitting equations for these two stages are as follows:

$$\sigma=5481.41\varepsilon-2.22142, \quad \varepsilon<12\times10^{-3} \tag{1}$$

$$\sigma=2.193\times10^{7}\varepsilon^{3}-1.371\times10^{6}\varepsilon^{2}+27502\varepsilon-107.142, \quad 12\times10^{-3}<\varepsilon<20.6\times10^{-3} \tag{2}$$

Polyurethane Cement Tensile Test

Polyurethane Cement Direct Tensile Test [18] was conducted using dumbbell-shaped thin specimens with a thickness of 12.7mm, a central width of 30mm, and side widths of 60mm. The axial tensile test was performed on a small-scale universal testing machine with a loading speed of 50N/s and a head spacing of 85mm between the upper and lower fixture heads, as illustrated in Figure 4.

Strain gauges were strategically positioned along the direction of tension at the center of the specimen to measure strain variations during the tensile process. Based on the experimental results, the uniaxial tensile curve for polyurethane cement composite material can be plotted as shown in Figure 5.

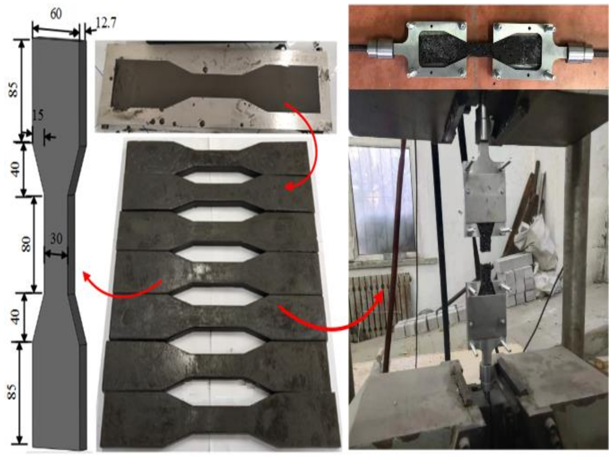

Fig. 4 - Polyurethane Cement Tensile Performance Test Graph (Unit: mm)

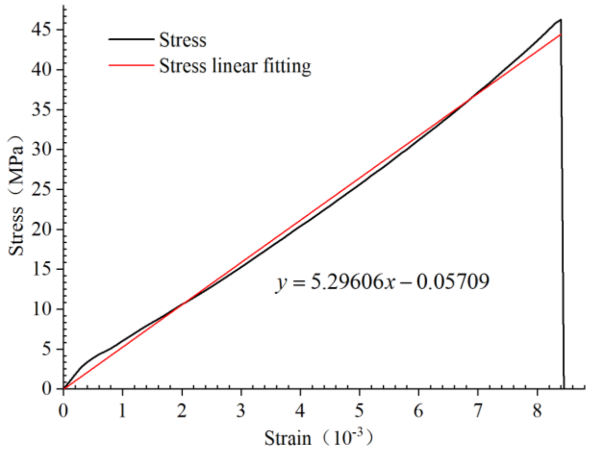

Fig. 5 - Polyurethane Cement Uniaxial Tensile Stress-Strain Curve

From Figure 5, it is evident that the uniaxial tensile curve of polyurethane cement demonstrates linear elastic behavior in the stress-strain relationship. The elastic modulus measures approximately 5296.1 MPa, which is consistent with the elastic modulus under axial compression. The ultimate tensile strength is approximately 46.25 MPa, corresponding to a strain of 8.45 mε. The fitting equation for the tensile curve is:

$$\sigma = 5296.06\varepsilon - 0.05709 , \ \varepsilon < 8.45\times10^{-3} \tag{3}$$

ESTABLISHMENT OF FINITE ELEMENT MODEL FOR POLYURETHANE CEMENT STRENGTHENING CURVES OF BRIDGE PIERS

Polyurethane Cement Reinforcement Curves Vibration Table Test of Bridge Pier

This paper presents a study on the vibration table test conducted by Haoyang Zhang et al. [7] on bridge piers reinforced with polyurethane cement as the research background. A corresponding finite element model is established using the finite element analysis software OpenSees, and the experimental data are compared with the finite element results to verify the effectiveness of the model and the correctness of the modeling approach. Based on this, a sensitivity analysis of reinforcement effects is conducted by varying various parameters of polyurethane cement material used for strengthening the bridge piers, aiming to obtain a more reasonable form of reinforcement. This study aims to provide a rational basis and reference for applying polyurethane cement reinforcement in strengthening curved girder bridge piers.

The experimental model is a continuous two-span curved bridge with unequal heights, featuring a radius of 4250 mm. The height of pier 1 is 730 mm, pier 2 is 880 mm, and pier 3 is 1030 mm. Four polytetrafluoroethylene (PTFE) laminated rubber bearings with a diameter of 150 mm and a thickness of 50 mm are utilized to connect the upper part of pier 1 and pier 3 to the main girder. For pier 2, a cast-in-place pier-beam integral form is employed. The longitudinal reinforcement for the piers consists of Φ8 steel bars, totaling ten in number, with spiral ties using12# galvanized iron wire at a spacing of45mm. The cross-section of the bridge deck is rectangular. The concrete for the piers is C15 concrete, while for the bridge deck it's C30 concrete [7]. Figure6 shows construction photos of the experimental bridge.

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Fig. 6 - The experimental bridge construction site photos [7]

Introduction to the OpenSees Program

Since its formal inception in 1999, the OpenSees program has been widely adopted in research projects at advanced universities and higher research institutions in developed countries. It has successfully simulated numerous real-world engineering projects and shake table experiments, validating its excellent accuracy in the field of nonlinear numerical simulations.

The core code of OpenSees can be categorized into three major modules:1. Model Builder: This module involves defining the model by specifying node coordinates, constraints, loads, material constitutive laws, section properties, element types, and coordinate transformations. It completes the process of model creation. 2. Analysis: This module controls numerical analysis by specifying the analysis solver type, load increment steps, iteration algorithms, and convergence tolerance. It is responsible for the overall control of numerical analysis. 3. Recorder: This module defines data and oversees the output of simulation results. It plays a crucial role in managing the output of running results. These three modules collectively form the basic structure of OpenSees, allowing for effective structural analysis and control over nonlinear numerical simulations.

Components and Material Parameters

The selection of a suitable material constitutive model is essential for ensuring the accuracy of structural elastoplastic analysis. Conventional curved girder bridge piers are typically composed of ordinary concrete and reinforcing steel as constituent materials. In addition to these, the material properties of polyurethane cement also need to be taken into consideration for finite element analysis. The mechanical characteristics of these three materials play a significant role in determining the performance of the bridge pier, particularly during the nonlinear stage where various nonlinear features manifest to different extents in the hysteresis response of the pier columns.

The OpenSees program offers a variety of uniaxial and multiaxial material models. The use of fiber beam-column element models simplifies the selection of material constitutive models, requiring only the adoption of uniaxial constitutive models under uniaxial loading conditions.

The following presents the constitutive relationship model for polyurethane cement material used in modeling:

Based on the aforementioned experimental analyses, a constitutive relationship for the stress-strain behavior of polyurethane cement has been proposed. The complete stress-strain curve for polyurethane cement is depicted in Figure 7, and the specific parameters for the constitutive model are as follows:

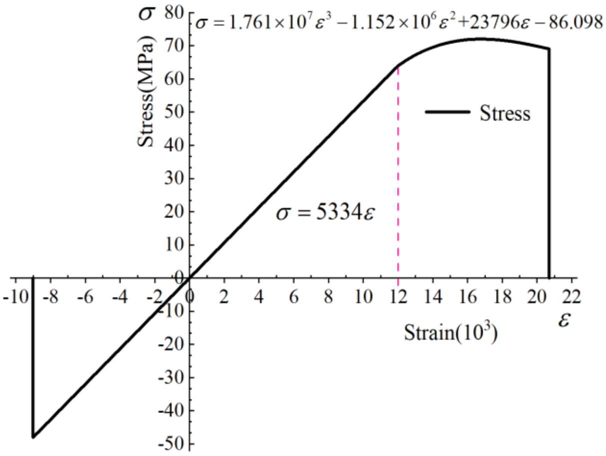


Fig. 7 - Polyurethane Cement Stress-Strain Full Curve (compression as positive)

The elastic modulus of polyurethane cement is 5334 MPa, the Poisson's ratio is 0.27, and the density is in the range of 1.51 to 1.53g/cm³. Here, a density of 1520kg/m³ is used.

Establishing Finite Element Model

Seismic loads are applied based on the seismic wave data obtained during experiments. The El-Centro seismic wave data are configured for north-south, east-west, and vertical directions, representing longitudinal, transverse, and vertical seismic excitations respectively. Two loading conditions are established: one for a seismic condition with a severity level corresponding to seismic intensity VI and another with a severity level corresponding to seismic intensity VII. These intensity levels are determined by scaling the model and converting to equivalent seismic input intensities.

Using the flexibility method, nonlinear beam-column elements are employed to simulate the experimental bridge pier components. Each component is modeled with a single element, and five Gauss integration points are set. Based on the material composition of the pier and the different constrained states experienced by concrete, the section is divided into four types of fibers: protective layer concrete, hoop-restrained concrete, restrained steel bars, and polyurethane cement. Each steel bar is treated as a fiber.

For a circular section, the core concrete is divided into at least thirty sections radially and ten fiber grids circumferentially. The protective layer concrete is divided into ten sections circumferentially and ten fiber grids radially. In total, the section is divided into 412 fibers.

The material constitutive parameters for each fiber are input based on actual material performance tests or recommended values from relevant studies.

The base nodes of the beam-column elements are fully constrained, with the constraint handling method set to "Plain". Masses, moments, and torques are applied at the top nodes of the elements to simulate the connection between the pier and the beam in the original bridge model. The solution to the nonlinear equation system will be achieved through a combination of various iterative algorithms, with a convergence tolerance criterion based on the energy method and an accuracy control of 10^5. Finally, a Recorder is utilized to output results such as displacement of the top nodes for post-processing.

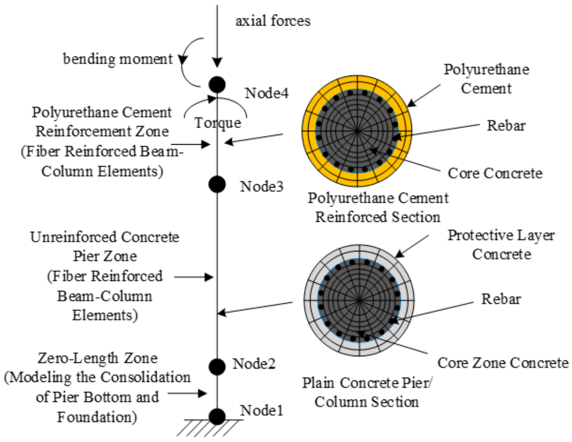
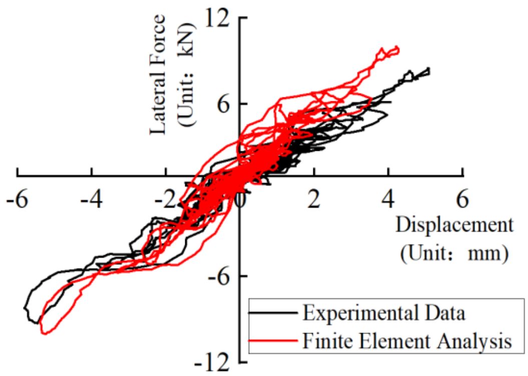


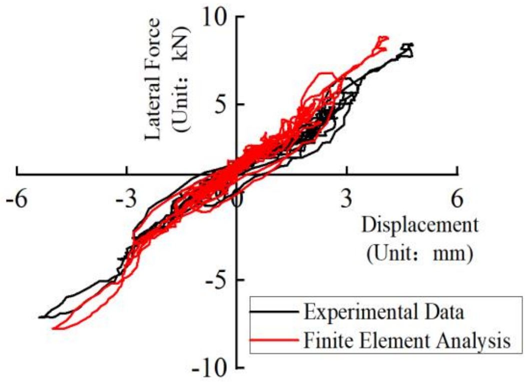
Fig. 8 - Finite Element Modeling Schematic

Analysis Results Verification

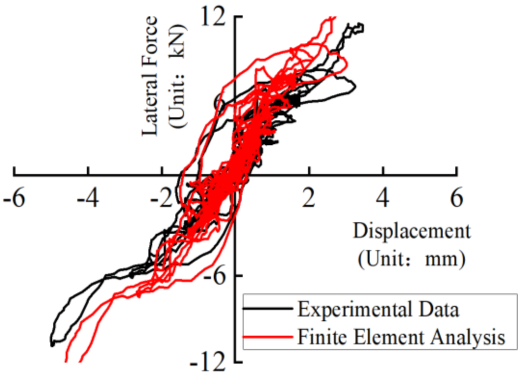
After conducting finite element simulation and obtaining the results, a comparison was made between the measured hysteresis curves of each bridge pier specimen in the shake table test. This paper presents a comparison of the experimental values and finite element data hysteresis curves, as well as the pier top displacement under intensity level VI, as shown in Figure 9. The hysteresis curves generated by the finite element numerical simulation generally coincide well with those obtained from the experimental results. The finite element simulation effectively reflects the behavior of the bridge pier during the loading process: as seismic response changes, the pier top displacement varies. Over time, significant displacement occurs in the pier, resulting in substantial lateral forces. Subsequently, due to elastic-plastic properties of materials, situations arise where seismic load is zero while displacement and lateral forces are not zero.



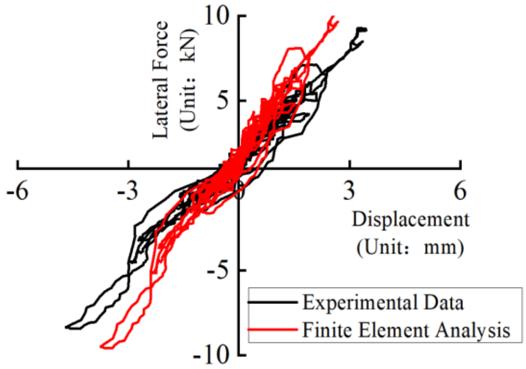
（a）Unreinforced Pier Top Longitudinal Hysteresis Curve under Intensity Level VI



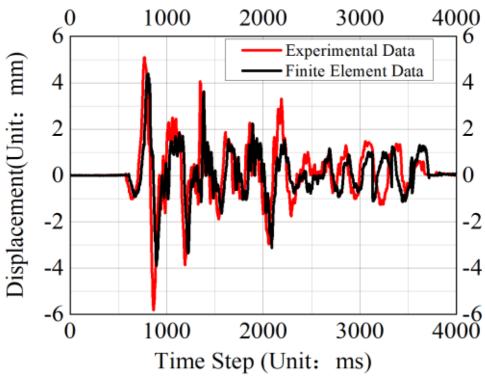
（b）Unreinforced Pier Top Transverse Hysteresis Curve under Intensity Level VI



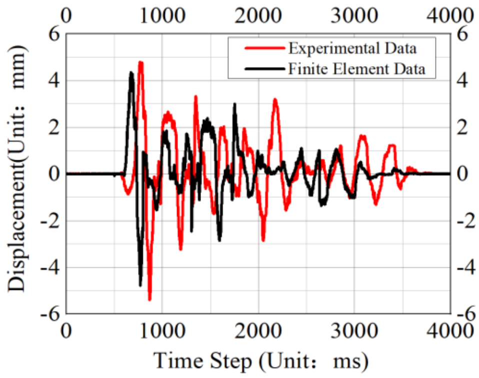
(c) Reinforced Pier Top Longitudinal Hysteresis Curve under Intensity Level VI



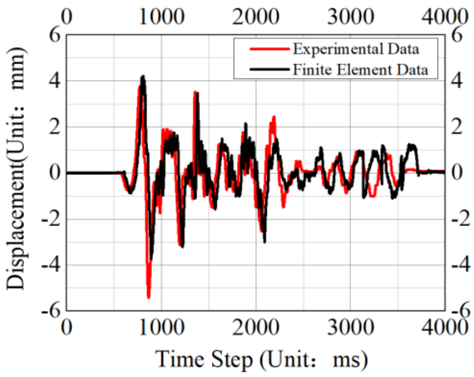
(d) Reinforced Pier Top Transverse Hysteresis Curve under Intensity Level VI



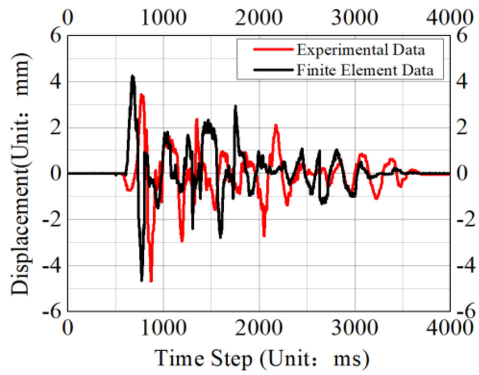
(e) Unreinforced Pier Top Longitudinal Displacement under Intensity Level VI



(f) Unreinforced Pier Top Transverse Displacement under Intensity Level VI



(g) Reinforced Pier Top Longitudinal Displacement under Intensity Level VI



(h) Reinforced Pier Top Transverse Displacement under Intensity Level VI

Fig. 9 - Comparison Chart of Measured Values and Finite Element Data for Pier Top Hysteresis Curves

The measured transverse and longitudinal displacements under different intensities and conditions consistently exceed the results obtained through finite element simulation. Specifically, at intensity level VI, the unreinforced pier top transverse and longitudinal displacement responses from the finite element model are approximately 0.78 to 0.92 times the experimentally measured data. After reinforcement at intensity level VI, the transverse and longitudinal displacement responses of the pier top from the finite element model are approximately 0.75 to 1.12 times the experimentally measured data. At intensity level VII, the unreinforced pier top transverse and longitudinal displacement responses from the finite element model are approximately 0.65 to 0.91 times the experimentally measured data. Additionally, after reinforcement at intensity level VII, the transverse and longitudinal displacement responses of the pier top from the finite element model are approximately 0.68 to 0.97 times that of experimental measurements. The discrepancies may be attributed to: 1) deviations in control parameters of concrete and steel constitutive models during reverse loading; 2) a certain degree of discrepancy between simulating polyurethane cement material according to concrete constitutive type and actual polyurethane cement material; 3) changes in various loads acting on pier tops due to seismic load effects; 4) some error between input seismic waves and those used in experiments.

Comparison between shake table test results and OpenSees finite element simulation data under similar conditions indicates that hysteresis curves and displacement time history curves for pier tops fall within a reasonable range for both seismic intensities, suggesting that OpenSees modeling method has sufficient accuracy and reliability for this study.

PARAMETER SENSITIVITY ANALYSIS

The Influence of Pier Height

The height of bridge piers has a significant impact on the various natural frequencies of the overall bridge structure. As the height of bridge piers increases, the overall stiffness of the structure decreases, leading to larger overall natural periods and smaller seismic design acceleration response spectrum values. Consequently, the horizontal shear forces experienced by the piers decrease. However, taller piers result in larger moments at the base of the piers for the same shear force, leading to greater horizontal displacement at the top of the piers. Therefore, pier height has a complex influence on the seismic performance of bridges. It is necessary to analyze how polyurethane cement affects seismic performance at different pier heights.

In this study, we will consider piers with heights of 640mm, 760mm, 880mm, 1000mm, and 1120mm. Figure 10 illustrates a schematic diagram showing polyurethane cement reinforcement with only changes in pier height while keeping other parameters constant. The study aims to investigate how polyurethane cement reinforces piers of different heights under conditions where other parameters remain unchanged.

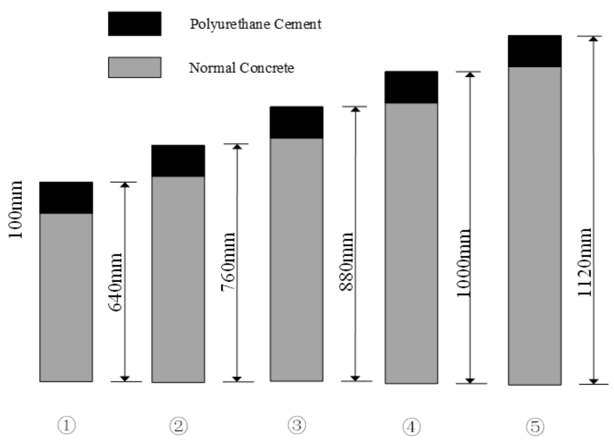


Fig. 10 - Schematic Diagram of Reinforcement by Changing Pier Height

The aforementioned models will undergo finite element analysis using the validated method. The decrease in maximum transverse and longitudinal bridge displacements at the pier top under intensity levels VI and VII will be utilized to assess the seismic effectiveness of polyurethane-reinforced piers. The collected data will be organized into Table 1.

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Tab. 1 - Finite Element Model Maximum Displacements at Different Pier Heights (Unit: mm)

Model	Reinforcement Status	Intensity Level VI Transverse Maximum Displacement	Intensity Level VI Longitudinal Maximum Displacement	Intensity Level VII Transverse Maximum Displacement	Intensity Level VII Longitudinal Maximum Displacement
①	Not Reinforced	4.271	3.494	8.154	6.648
	Reinforced	4.139	3.277	4.770	3.703
	Reinforcement Effect	0.031	0.062	0.415	**0.443**
②	Not Reinforced	4.834	3.994	8.427	7.349
	Reinforced	4.704	3.802	5.262	4.319
	Reinforcement Effect	0.027	0.048	0.376	**0.412**
③	Not Reinforced	5.391	4.583	10.256	8.721
	Reinforced	5.261	4.396	6.979	5.656
	Reinforcement Effect	0.024	0.041	0.32	**0.352**
④	Not Reinforced	6.224	5.214	11.606	9.842
	Reinforced	6.087	4.976	8.613	7.12
	Reinforcement Effect	0.022	0.046	0.258	**0.277**
⑤	Not Reinforced	6.845	6.782	13.054	11.867
	Reinforced	6.715	6.572	10.208	9.090
	Reinforcement Effect	0.019	0.031	0.218	**0.234**

When all other parameters are held constant, an increase in pier height leads to a gradual increase in peak displacements in both transverse and longitudinal directions. This suggests that as the pier height increases, the stiffness of the specimen decreases, resulting in a reduced capacity to resist seismic loads. When comparing the reinforcement effects of five different height pier models at various intensity levels (the difference in displacement between reinforced and unreinforced conditions, normalized by the unreinforced displacement), it is found that the maximum reinforcement effects for the five models are 0.443, 0.412, 0.352, 0.277, and 0.234 respectively.

Therefore, within a certain range, taller piers exhibit poorer reinforcement effects with polyurethane cement. This may be attributed to increased pier height leading to decreased bridge stiffness, increased flexibility, and larger response under seismic loads. Consequently, the seismic effects on the material at the top of the pier become more pronounced, resulting in a smaller seismic resistance effect for the same polyurethane cement material. Overall, these findings suggest that taller piers may have a detrimental impact on their ability to withstand seismic forces when using polyurethane cement as a reinforcing material.

Impact of Retrofitting Height

Polyurethane cement demonstrates high tensile strength and good tensile deformation capacity, making it a suitable material for reinforcement. Therefore, conducting a sensitivity analysis on the retrofitting height parameter for polyurethane cement is essential to understand its impact on the seismic performance of curved bridge piers. In this study, five different retrofitting schemes with polyurethane cement heights of 50mm, 100mm, 150mm, 200mm, and 250mm are proposed.

Figure 11 depicts a schematic representation of the proposed schemes where only the retrofitting height of polyurethane cement is varied while keeping other parameters constant. This analysis aims to explore the sensitivity of the seismic retrofitting effect on bridge piers concerning different polyurethane cement retrofitting heights.

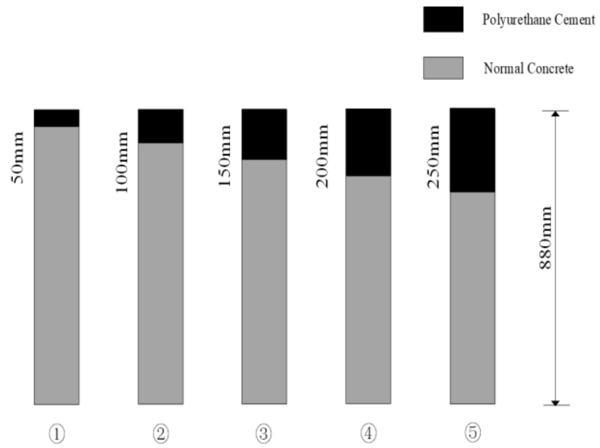

Fig. 11 - Altering Retrofitting Height Schematic

Conduct finite element analysis on the aforementioned models using the validated method. Assess the seismic resistance of the bridge piers retrofitted with polyurethane by examining the reduction in maximum horizontal and vertical bridge displacements under seismic intensities VI and VII. Present the collected data in Table 2.

Tab. 2 - Finite element model maximum displacement at different widths of polyurethane cement (Unit: mm)

Model	Reinforcement Status	Intensity Level VI Transverse Maximum Displacement	Intensity Level VI Longitudinal Maximum Displacement	Intensity Level VII Transverse Maximum Displacement	Intensity Level VII Longitudinal Maximum Displacement
	Not Reinforced	5.391	4.583	10.256	8.721
①	Reinforced	5.301	4.487	8.338	7.062
	Reinforcement Effect	0.017	0.021	0.187	**0.190**
	Not Reinforced	5.391	4.583	10.256	8.721
②	Reinforced	5.261	4.396	6.979	5.656
	Reinforcement Effect	0.024	0.041	0.32	**0.352**
	Not Reinforced	5.391	4.583	10.256	8.721
③	Reinforced	5.232	4.358	6.659	4.841
	Reinforcement Effect	0.03	0.049	0.351	**0.445**
	Not Reinforced	5.391	4.583	10.256	8.721
④	Reinforced	5.179	4.294	6.15	4.787
	Reinforcement Effect	0.039	0.063	0.4	**0.451**
⑤	Not Reinforced	5.391	4.583	10.256	8.721

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Reinforced	5.172	4.281	6.107	4.714
Reinforcement Effect	0.041	0.066	0.405	**0.459**

Maintaining other parameters constant, an increase in the height of polyurethane cement reinforcement leads to a gradual decrease in peak displacements at the top of the pier in both horizontal and vertical directions. This suggests that a greater height of polyurethane cement reinforcement results in increased stiffness for the specimen. When comparing the reinforcement effects at different intensities (difference in displacement between reinforced and unreinforced states, as well as the ratio of unreinforced displacement), it is observed that the maximum values for the five models are 0.190, 0.352, 0.445, 0.451, and 0.459 respectively. Therefore, within a certain range, a higher height of polyurethane cement reinforcement leads to improved reinforcement effects on curved bridge piers. This can be attributed to the enhanced stiffness and ductility provided by polyurethane cement reinforcement, resulting in reduced response under seismic loads, particularly at the top of the pier.

However, due to its limited flexibility, high stiffness, susceptibility to plastic deformation and relatively high cost; selecting an appropriate width is crucial for optimizing economic benefits and reinforcing effects when strengthening piers.

Parameter Optimization Analysis

Based on the sensitivity analysis of the parameters for polyurethane cement reinforced bridge piers, it is evident that the effectiveness of polyurethane cement reinforcement decreases with increasing pier height. Conversely, a thicker layer of polyurethane cement reinforcement leads to a more pronounced effect. Therefore, by optimizing the parameters of polyurethane cement reinforcement height and pier height, we can identify the most cost-effective parameter range to optimize the economic efficiency of constructing polyurethane cement reinforced bridge piers.

The ratio of polyurethane cement reinforcement height to pier height, referred to as the reinforcement ratio, is a crucial control indicator in practical engineering. By using the maximum displacement in the vertical bridge direction under Level VII intensity as a reference value for reinforcement effectiveness, we can determine an optimal reinforcement ratio based on its growth rate. The data from the finite element model is summarized in Table 3 and illustrated in Figure 12.

Tab. 3 - Parameter Optimization Analysis

Reinforcement Ratio	0.057	0.089	0.100	0.114	0.132	0.156	0.171	0.227	0.284
Reinforcement Effect	0.19	0.234	0.277	0.352	0.412	0.443	0.445	0.451	0.459

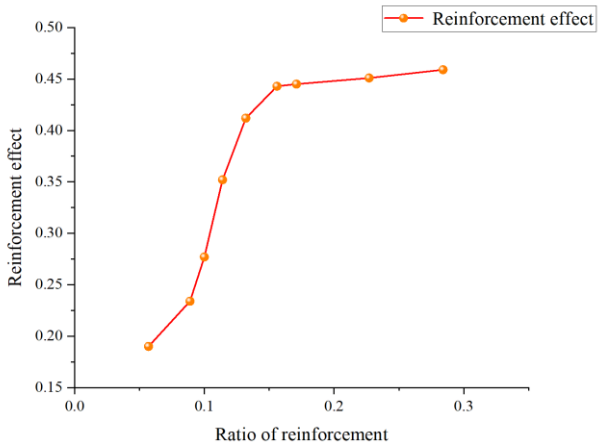

Fig. 12 - Parameter Optimization Analysis Chart

The results from finite element simulation indicate that when the reinforcement ratio is approximately 0.132, there is a greater growth rate in reinforcement effect compared to when it is around 0.156. As the reinforcement ratio exceeds 0.156, there is a gradual decrease in growth rate towards zero, potentially resulting in material waste. Thus, it can be concluded that optimal economic efficiency of reinforcement occurs at a ratio around 0.132 which provides scientific support for reinforcing bridge piers with polyurethane cement.

CONCLUSIONS

This dissertation focuses on the reinforcement of curved bridge piers with polyurethane cement [7] and utilizes OpenSees for numerical simulation of experimental results. The numerical simulation results are compared with shake table test data, confirming a good fit between the finite element modeling and experimental results. Through finite element parameter sensitivity analysis, with bridge pier height, material thickness, and bridge pier type as variables, sensitivity patterns of corresponding reinforcement parameters are determined. Additionally, parameter optimization leads to the following conclusions:

1. Polyurethane cement has an isotropic elastic model with basic properties such as tensile strength, compressive strength, flexural strength all around 5334 MPa, and a Poisson's ratio of approximately 0.27. The ultimate tensile strain (ε_t) is 9×10-3, and the ultimate tensile stress (σ_t) is 48 MPa. In the nonlinear phase, the ultimate compressive strain (ε_c) is 16.7×10-3, and the ultimate compressive stress (σ_t) is 72.04 MPa. Polyurethane cement exhibits high compressive strength, strong toughness, elevated tensile strength, and good ductility, making it a suitable material for reinforcement.

2. Utilizing the OpenSees platform for simulations of pier specimens from a three-axis shake table experiment involving polyurethane cement-reinforced curved beam bridge piers resulted in displacement time-history curves that closely aligned with experimentally measured displacement time-history curves. This provides evidence supporting the rationality of the adopted material constitutive model and related parameter settings.

3. Sensitivity analysis of polyurethane cement-reinforced curved beam bridge pier parameters revealed that within a certain range under identical conditions, taller piers exhibit diminished effects from polyurethane cement reinforcement; similarly, thicker polyurethane cement reinforcement within a certain range yields more pronounced reinforcement effects.

4. Based on data from sensitivity analysis,the parameters of polyurethane cement reinforcement height and pier height were optimized. It was found that when the ratio of polyurethane cement reinforcement height to pier height is around 0.132, the growth rate of reinforcement effect is maximized, suggesting optimal economic efficiency for reinforcement.

The findings from this study serve as valuable reference for seismic reinforcement strategies pertaining to curved beam bridge piers, enabling practical engineering schemes to be guided towards improved economic viability.

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