Fiber finite element analysis on seismic performance of segment-assembled CFST bridge

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Abstract. In recent years, the segmental self-centering bridge structure has emerged as a prominent research area in the field of bridge engineering due to its exceptional seismic performance and recoverability. This study establishes a fiber finite element model based on vibration table tests conducted on a segmental self-centerting concrete-filled steel tube (CFST) bridge. Then, the accuracy of the finite element model is verified by comparing the superstructure response and peak seismic acceleration obtained from finite element model simulation and vibration table test. Furthermore, enabling an analysis of its seismic behavior and response under large intense ground motion. The findings demonstrate that even when subjected to 60% amplitude ground motion, the segment-assembled self-resetting concrete-filled steel tube bridge maintains excellent seismic performance and recoverability with a minimal residual displacement ratio of only 0.67%.The lateral force-displacement hysteretic curve of the segmental self-centering CFST bridge shows a spindle shape, which can reflect its strong plastic deformation and energy consumption capacity in the high seismic fortification-resistant area.

Keywords: Self-centering bridge, Fiber finite element, Seismic performance.

1 Introduction

Self-centering piers have good restorability. The magnitude of residual displacement after earthquake plays an important role in effectively evaluating the restorability ability of bridges. By relaxing the constraint with the foundation, the rocking behavior of precast pier can reduce the residual displacement caused by the plastic deformation of the structure and reduce the structural damage. Nowadays, scholars have conducted

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a lot of theoretical and experimental studies on segmentally assembled reinforced concrete self-centering piers, among which, non-bonding post-tensioned prestressing system is widely used in self-centering piers[1]. Under the action of strong earthquake, the prestressed tendons and the surrounding concrete remain unbonded, and the prestressed steel strand avoids yielding and provides enough restorability for the bridge pier to return to the initial position after the earthquake. Hewes[2] conducted pseudo-static test research on self-centering piers connected by post-tension-prestressed steel strands, and studied the influences of prestressed level, aspect ratio of piers and other parameters on force-deformation characteristics, energy consumption, damage degree and failure mode of piers. It is pointed out that the piers' hysteretic curve is S-shaped and the residual displacement after unloading is very small, but the energy consumption capacity is very low.

The concrete filled steel tube piers are composed of concrete filled inside the steel tube. The existence of steel tube not only improves the compressive strength and ultimate strain of the bearing concrete, but also improves the bending strength of the pier. Segmental concrete-filled steel tubular (CFST) piers can solve the problem of serious damage at the bottom of reinforced concrete segmental piers after earthquakes, and improve the seismic performance and self-restorability performance of piers [3]. Palermo et al. [4] conducted a pseudo-static test study of prestressed segmental preassembled piers, and the results showed that, compared with bonded prestressed tendones, unbonded prestressed can reduce the damage of piers, improve the stiffness after yielding, reduce the residual displacement, and have a more significant self-restorability effect. Shen et al. [5] proposed a new self-centering pier. Through numerical simulation analysis, its hysteretic curve is fuller, its residual displacement is reduced, and its self-restorability performance is better. Dawood et al. [6] used the finite element method to conduct numerical simulation of segally-assembled self-centering piers, and studied the influence of relevant design parameters on their seismic performance. The results pointed out that when the total axial compression ratio generated by prestress and gravity is around 0.2.

The segmental self-centering structure has the characteristic of "rocking", and the plastic deformation of the structure is very small under the action of earthquake. Compared with the traditional ductile seismic structure, this system does not consume energy through the plastic deformation of materials, so its energy-consumption capacity is relatively poor. Therefore, it is necessary to add some energy-consumption devices to form a mixed structure, so as to enhance the energy-consumption capacity and effectively control the damage of the structure [7]. Some researchers have investigated ways to improve the energy consumption capacity of segmental piers by introducing additional energy consumption (ED) devices, which can be divided into internal and external ED devices. Studies have shown that the energy consumption performance of prefabricated segment piers can be improved by inserting internal energy-consumption steel bars [8]. If the internal ED equipment is damaged, it is difficult to replace it. External ED devices are usually in the form of rebar or angle steel [9][10], which exhibit strong energy consumption capacity and can be replaced following seismic events. Ou et al. [11] conducted an experimental study on four large-scale segment assembled post-tensioned prestressed piers, and the energy-consumption reinforcement bars (ED) were installed at the joint of the segments. The results showed that the hysteresis curve was fuller and the energy-consumption performance was better. Han et al. [12] used the self-centering structure of external energy-consumption parts to study and verify that it has good replaceable ability.

Static and quasi-static test methods are generally used to analyze the seismic performance of precast segment piers. Some researchers have also carried out vibration table test on bridge piers. Moustafa et al. [13] conducted vibration table tests on three damage-resistant segmental hollow section piers to evaluate their seismic performance. Additionally, various studies have investigated the seismic performance of unbonded prestressed hollow concrete piers. Test results demonstrate that models utilizing innovative materials are well-suited for high-seismic-risk areas due to their high energy dissipation capabilities and minimal damage in the plastic hinge region. [14]. An underwater vibration table test was conducted on a single-span bridge with Prestressed Concrete Filled Steel Tubular (PCFST) piers by Zhang et al. [1] to investigate the impact of dynamic water pressure on the seismic performance of the bridge under varying water depths. The results indicate that the well-designed PCFST bridge demonstrates excellent seismic performance.

Due to the influence of the test site and equipment, it is difficult to carry out the damage test in the vibration table test. In order to more accurately understand the seismic performance of segmental self-centering CFST bridges, this research establishes a fiber finite element model through Opensees and verifies it through the vibration table test. After that, the data obtained from the large-amplitude ground motion is analyzed. The seismic performance and response of segmental self-centering CFST bridges are analyzed.

2 Establishment and verification of the FFE model

2.1 Overview of vibration table test

The experiment was conducted at the Key Laboratory of Coastal Civil Engineering Structures and Safety, Ministry of Education, Tianjin University. A total of 25 unidirectional acceleration sensors were installed at the superstructure, pier and support positions. The arrangement of the bridge model and experimental platform is shown in Fig.1. The bridge piers consists of an self-centering pier with external energy consumption bars. The superstructure adopts a steel box girder section and the piers are composed of three segments. The energy consumption device and self-centering device consist of energy consumption rebars (HRB400 grade rebars) and prestressed steel strands, respectively.

The section of the superstructure is made of steel box girder, the size is 13.04 m × 0.6 m × 0.5 m (length × width × height), the material is made of steel box girder with a thickness of 10 mm, and the elastic modulus is 2.016×105MPa. The pier is composed of three sections, loading end and cap. The size of the cap is 1.5m × 1.0m × 0.5m. Among them, the concrete form of three sections can ensure that the pier remains elastic and has a certain recovery under earthquake action. Each section is

0.6m high, and section cross-section is selected in the form of concrete-filled steel tube with a diameter of 0.4m. The steel tube material is Q235 steel, the thickness is 6mm, the elastic modulus is 2.026 × 105MPa, and the inner core concrete is C40 commercial concrete (28-day cubic compressive strength is 42.3 MPa). The energy-dissipating device and the self-centering device are composed of laying energy-dissipating steel bars (HRB400 steel bars) and prestressed steel bars respectively. The energy consumption steel bar has an unbonded section of 0.15m, and the lower part is anchored in the bearing. The prestressed reinforcement adopts seven wire steel strand with a diameter of 15.2mm, the ultimate tensile strength is 1860MPa, and the design tensile value is 300kN. Detailed information on vibration table tests can be found in reference [1].

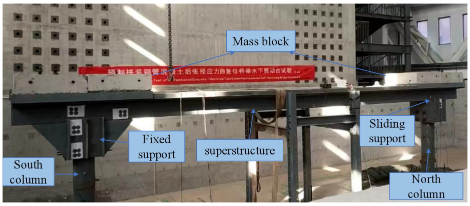


Fig. 1. The test setup of the vibration table test

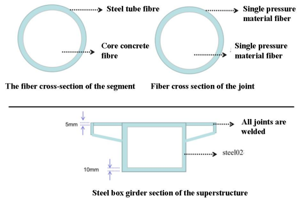


Fig. 2. Main sections of the bridge

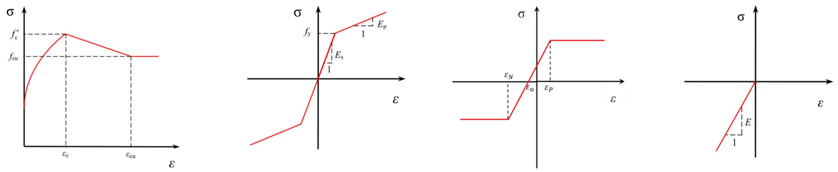
2.2 Build the model

The superstructure of the bridge is a steel box section, as shown in Fig. 2, which is simulated using the DispBeampier element in OpenSees based on the stiffness method and the Elastic Section section. The material model of the Steel02 uniaxial material used in the simulation is shown in Fig. 3. Es is the initial elastic modulus of the material, P is the tangent modulus of the material after yielding, and f_y is the yield strength of the steel. The south abutment is fixed at the location and can be achieved by constraining the horizontal and vertical degrees of freedom. The north abutment is a sliding support and can be achieved by constraining the horizontal degree of freedom.

DispBeamColumn units were used for concrete-filled steel tube sections at bridge piers, and fiber section was selected as section, as shown in Fig. 2. The elastoplastic properties of concrete-filled steel tube can be simulated by fiber cross section. The Concrete01 material model, derived from the Kent-Scott-Park principle, is employed for concrete modeling, with its constitutive relationships depicted in Fig. 3. In this model, ε_c denotes the peak strain, and ε_{cu} represents the ultimate compressive strain. The parameters $f_c^{'}$ and f_{cu} correspond to the peak compressive strength and ultimate compressive strength of the concrete, respectively, at ε_c and ε_{cu}. The Steel02 uniaxial material model in OpenSees is utilized to represent the steel pipe material, as illustrated in Fig. 3. This model effectively captures the isotropic strengthening and Bauschinger effects of the material.

The joints between steel tube concrete segments are modeled using ZeroLength and ZeroLengthSection elements, combined with an Elastic-No Tension material. Horizontal displacements at the joints are constrained, while the separation and rotation at the interface between the bottom segment and the abutment, as well as the upper segment, are represented by a single-pressure material with zero tensile strength. The zero tensile strength simulates the separation and rotation of the segment joints, as illustrated in Fig. 3. The stiffness of the Elastic-No Tension material represents the rotational capacity of the segments.

The Truss element is employed to model energy-absorbing steel bars, with its constitutive relationship defined by the Steel02 uniaxial material model. RigidLinkBeam elements and beam-pier elements are aligned at the same height to ensure coordinated deformation between the energy-absorbing steel bars and the bridge abutments. The self-recovery mechanism is implemented using unbonded prestressed steel bars, which are represented by the CorotTruss element using a separation modeling technique. The CorotTruss element, with its geometric nonlinear simulation capabilities, offers more accurate analysis compared to the Truss element. The constitutive behavior of the CorotTruss is represented by the Elastic-PP uniaxial material model, with the stress-strain curve shown in Fig. 3. The complete bridge fiber model is illustrated in Fig. 4.



(a) Concrete01 (b) Steel02 (c) Elastic PP (d) ENT

Fig.3. Constitute relationship for materials

2.3 Computational analysis

First, the gravity load on the structure is calculated, including the following components: the weight of the steel box girder at 110 kN, the weight of the abutment at 18.75 kN, the weight of the precast pier segment at 5.65 kN, and the loading end at 1.44 kN. Additionally, two concrete blocks, each weighing 29 kN, are placed at the ends of the superstructure, uniformly distributing the load across each element.

Subsequently, the structure undergoes dynamic analysis to simulate the seismic performance of a self-centering bridge in a high-intensity seismic zone with site classification II, as specified in JTG/T BO2-1-2010 "Specifications for Seismic Design of Highway Bridges". Earthquake records are selected from the PEER strong ground motion database (http://peer.berkeley.edu/ngawest2) and scaled to match the design response spectrum. The RSN292 earthquake motion is utilized with amplitudes of 10%, 20%, 30%, 40%, 50%, 60%, 70%, and 80% for dynamic analysis. This procedure yields the acceleration response of the superstructure nodes, thereby enabling the assessment of the structure's dynamic characteristics.

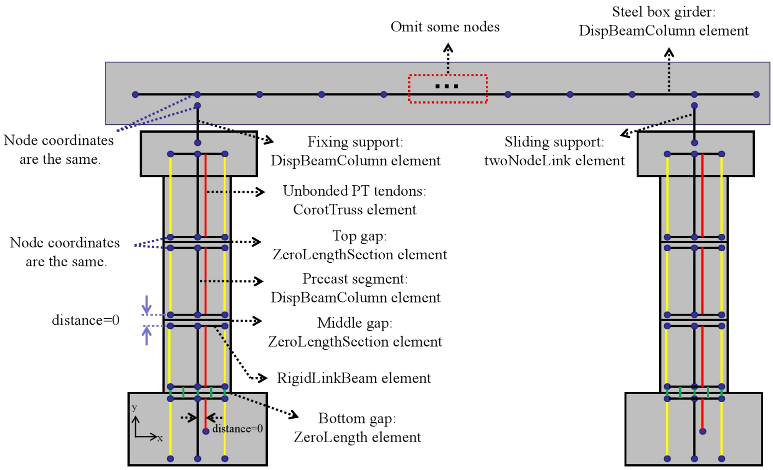


Fig.4. The whole bridge fiber model

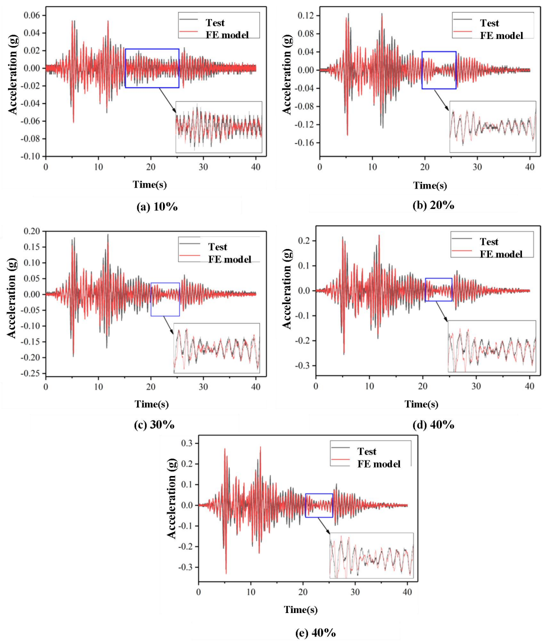


Fig.5. Acceleration time history of FE model under RSN292GM

2.4 Response parameter verification

The accuracy of the OpenSees fiber model is validated through a comparison with vibration table test results, specifically examining the acceleration response of the superstructure. Fig. 5 illustrates the comparison between the fiber model and experimental data. Table 1 presents the peak acceleration values extracted from the acceleration spectrum, with GM denoting ground motion and 10%~50% representing varying amplitudes of ground motion for RSN292. Both the figure and table demonstrate that the acceleration response time history of the mid-span node in the fiber model closely matches that of the test model. The peak acceleration values exhibit minor discrepancies, with relative errors within 10%, which is within an acceptable range. Overall, the fiber model's performance indicators are in strong agreement with the experimental results.

Table 1. Comparison of the peak acceleration between test and simulation

Peak acceleration (g)					
GM	10%	20%	30%	40%	50%
Test	0.061	0.142	0.197	0.256	0.310
FE model	0.062	0.144	0.187	0.249	0.332
Error	-1.4%	-1.6%	-5.3%	2.9%	-7.0%

3 Seismic performance analysis

3.1 Residual displacement and hysteresis analysis

Residual displacement [5] is a critical parameter for assessing the seismic performance of bridges, significantly impacting the evaluation of their restorability and repairability. The smaller the residual displacement ratio is, the stronger the self-centering ability and post-earthquake recovery ability of the bridge structure are. The residual displacement ratio is the ratio of the residual displacement to the maximum displacement generated by the structure. The Japanese code for seismic design of highway Bridges stipulates that the limit of residual displacement ratio is 1%. According to the finite element analysis, under the action of 10%-80% ground motion input of RSN292, the residual displacement corresponding to different ground motion amplitude is 0.005, 0.015, 0.025, 0.040, 0.065, 0.135, 0.230, 0.280mm, respectively. It can be found that the residual displacement generated by the structure is small, especially before 50%, the residual displacement is very small. Compared with the traditional concrete pier, the self-centering bridge shows better recovery performance. Fig.6 shows the residual displacement ratio of the structure under ground motion of 10%-80% amplitude RSN292. The residual displacement ratio corresponding to different amplitudes is 0.17%, 0.20%, 0.25%, 0.31%, 0.40%, 0.67%, 1.01% and 1.15%, respectively. With the increase of the amplitude, the residual displacement ratio shows an increasing trend. Before 60%, the increase trend of the residual displacement ratio is relatively moderate, and it is far lower than 1% required by the specification. The residual displacement of the self-centering bridge is relatively small, because the arrangement of the post-tensioning system without bonding greatly reduces the residual displacement ratio of the structure. However, after 60% amplitude, the residual displacement ratio has a large increase, and the residual displacement ratio corresponding to 70% and 80% amplitude is 1.01% and 1.15%. At this time, the ratio is already large, close to or even exceeding the 1% limit, because the ground motion amplitude at this time has far exceeded the seismic fortification level. The residual displacement rate corresponding to the 60% amplitude is 0.67%. According to the current research [57], the residual displacement rate of the traditional concrete pier at this time is 0.8-1.2%, which leads to problems of recovery and feasibility. The residual displacement ratio of the self-centering bridge is lower than that of the bridge using the traditional concrete pier. It can be seen that this structure has better self-recovery performance and repairability.

Fig.7 shows the lateral force-displacement hysteresis curves of the model under the action of 20%, 40%, 60% and 80% ground motion amplitudes. The lateral force is obtained by multiplying the mass of the steel box girder and the mass of the mass block by the output horizontal acceleration of the mid-span nodes (here assuming that the steel box girder of the superstructure is sufficiently rigid). The displacement of mid-span nodes is calculated using Opensees. As can be seen from the figure, hysteretic curves of the structure under different amplitude ground motions are similar in shape, all of which are fusiform. Hysteretic curves are approximately symmetric about the origin of coordinates, and results similar to those obtained in vibration table experiments are obtained here [1]. With the increase of ground motion amplitude of different RSN292 (10%-80%), the maximum displacement of the structure changes in the range of 3.19-24.3mm, and the maximum load increases from 6.67kN to 50.59kN, which accords with the law of input ground motion change. It can be seen that when the seismic response is small, the structure is subjected to small loads, and the time-delay curve with small force and displacement forms a dense black region, and the area of hysteresis curve is small, indicating that the energy consumption of the structure is small at this time, and it still has a large stiffness. The area of the hysteresis loop in the hysteresis curve gradually increases as the local seismic strain is large, and the overall characteristics of nonlinear growth are presented, and the energy consumption is increased. At the same time, with the increase of seismic amplitude, the maximum force and displacement of the structure increase, the lateral force-displacement curve of the structure is fuller, and the structure has strong plastic deformation ability.

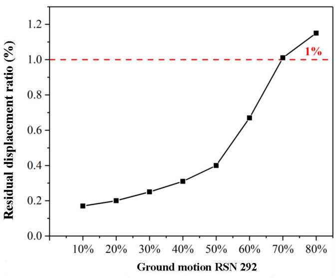


Fig.6. Residual drift ratios of the FE model

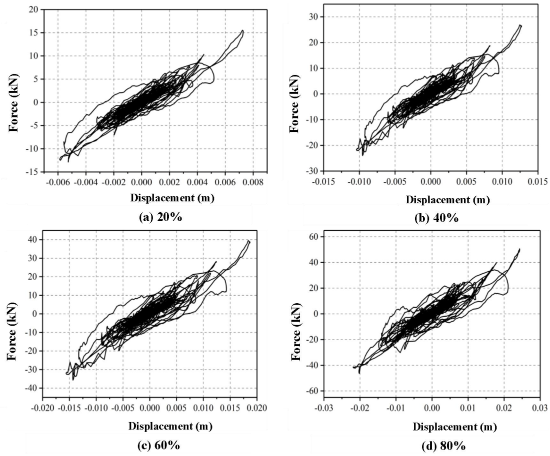


Fig.7. The force-displacement curve

3.2 Cumulative energy consumption and equivalent viscous damping ratio

The energy consumption is determined by integrating the lateral force-displacement hysteresis curve. For traditional precast reinforced concrete segment piers subjected to seismic loading, energy dissipation primarily occurs through the yielding of steel bars, the fracture of longitudinal bars connecting the bottom segment to the foundation, and concrete spalling. These mechanisms often result in structural damage that is challenging to repair. In contrast, the energy dissipation of the segmental self-centering piers designed in this study is predominantly achieved through the elastic rocking of the self-energy-dissipating structure, the contact friction between segments, and the energy-dissipating reinforcement.

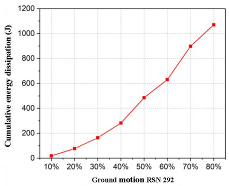


Fig.8. The cumulative dissipated energy

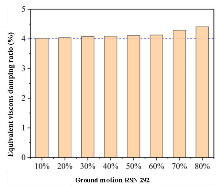


Fig.9. Equivalent viscous damping

Fig.8 shows the cumulative energy-consumption of the structure under different amplitude ground motion. When the amplitude is small, the cumulative energy-consumption of the structure corresponding to ground motion input with 10% amplitude is 18.61J, and then presents an increasing trend with the increase of the amplitude, and reaches the maximum energy consumption of 1168.80J when the maximum value reaches 80%. This is because with the increase of the amplitude of ground motion, the input energy of the system increases, while the residual displacement of the structure increases, and the energy consumption of the structure increases, indicating that the structure has good energy consumption performance.

To quantitatively assess the structural response to ground motions with varying amplitudes of RSN292, the equivalent viscous damping ratio is employed. The calculated equivalent viscous damping is illustrated in Fig. 9. The results indicate that while the equivalent viscous damping increases with the amplitude of ground motion, the change is relatively minor. Thus, it can be concluded that variations in ground motion amplitude have a limited impact on the equivalent viscous damping.

4 Conclusion

In this research, the overall dynamic response and seismic performance of a segmental self-centering CFST bridge are studied by numerical simulation. Firstly, the fiber finite element model model of the bridge is established by using Opensees finite element software and the vibration table test is simulated to study the seismic performance of the segmental self-centering CFST bridge and analyze the response of the superstructure. The conclusions are as follows:

(1) The accuracy of the finite element model is verified by comparing with the results of vibration table test. The error range of peak acceleration obtained by simulation model is 1.4%~7%.

(2) According to the FE analysis model, the residual displacement of segmental self-centering CFST bridge is 0.135mm under the action of 60% amplitude GM, and the residual displacement ratio is only 0.67%, which is less than 1% of the limit value. It can be obtained the bridge has good self-centerting performance and repairability. When the amplitude continues to increase to 70%, 80% (much higher than the fortification intensity), the residual displacement ratio exceeds the 1% limit value.

(3) The lateral force-displacement hysteretic curve of the segmental self-centering CFST bridge shows a spindle shape, which can reflect its strong plastic deformation and energy consumption capacity in the high seismic fortification-resistant area. With the increase of the input ground motion amplitude, the energy consumption increases, and the structure has a good energy consumption performance. While the equivalent viscous damping ratio does not change much.

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