

Numerical study of the self-centering prestressed concrete pier with external energy dissipators

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Abstract. A novel self-centering prestressed concrete (SCPC) pier with external energy dissipators (EDs) has been recently proposed to minimize the structural damage and residual deformations, and enhance the corrosion-resistant capability. In the SCPC pier with external EDs, internal post-tensioned basalt fiber-reinforced polymer (BFRP) tendons are used to provide the self-centering ability, and the energy dissipation is realized through the external aluminum bars. Previous cyclic load tests of 1/3-scaled specimens showed that the SCPC pier with external EDs had desirable self-centering and energy dissipation capacities. In this study, a three-dimensional finite element (FE) model is developed using the ANSYS software. The FE model can capture the complex behavior of the proposed pier, such as gap opening/closing at the pier-foundation interface, energy dissipation of EDs, and self-centering capacity. Good agreement is observed between the numerical and experimental results, demonstrating the accuracy of the developed FE model. This will enable the parametric studies on the seismic performance of the SCPC pier with external EDs in the future.

1 Introduction

For the conventional reinforced concrete (RC) bridge piers designed under the capacity design concepts, the columns are likely to yield and behave in a ductile manner to dissipate earthquake energy, so that the collapse of bridge could be avoided. However, these piers are anticipated to experience significant structural damage and residual deformations after severe earthquakes, which can result in substantial costs associated with operation disruption of the transportation network and repair of structural damage. The field surveys after recent seismic events showed that many seismically damaged RC bridge piers were demolished, even though the piers did not experience structural collapse [1].

To mitigate the residual deformations of the conventional RC bridge piers, precast concrete piers with unbonded post-tensioned (PT) elements have been developed and studied [2-3], in which rocking behavior is allowed at the pier-foundation interface and notable self-centering capacity can be obtained. Due to the inherent small energy dissipation capability, the maximum displacement demands of the unbonded PT piers may be excessively larger than acceptable. In order to control the lateral displacement demands under earthquakes, a certain level of energy dissipation is usually provided by the supplemental energy dissipators (EDs), such as internal unbonded mild steel bars [4-6] or externally attached yielding devices at the rocking pier-foundation joints [7-9].

In order to reduce the concrete damage at the pier-foundation interface, which are caused by the excessive compressive stress at the pier toes under cyclic loading, various damage control methods were provided in the region of the rocking joints. Hewes [10] confined the bottom segment of the precast segmental pier with a steel tube and found that the concrete damage at the pier-foundation interface was effectively reduced, while concrete spalling was observed above the steel tube. Chou and Chen [8] tested precast segmental piers fully encased in steel tubes and only minimum concrete damage was observed.

Recently, a new precast concrete pier, referred to herein as the self-centering prestressed concrete (SCPC) pier with external energy dissipators, has been developed and experimentally investigated by Guo et al. [11]. Superior corrosion resistance and easy replacement of the energy dissipators are expected for the proposed pier, in which the self-centering capability is obtained using the post-tensioned basalt fiber-reinforced polymer (BFRP) tendons, and the energy dissipation capacity is obtained through the external aluminum bars. In addition, glass fiber-reinforced polymer (GFRP) tube is installed at the pier ends to prevent the concrete in the vicinity of the rocking joints from damage when the pier rotates against the foundation.

In this study, a three-dimensional (3D) numerical model is developed using the ANSYS general purpose finite element analysis software to capture the hysteretic behavior of the SCPC pier with external energy dissipators. The 3D numerical model is validated against

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the experimental data of the cyclic load testing study conducted by Guo et al. [11].

2 Self-centering prestressed concrete pier with external energy dissipators

The configuration of the SCPC pier with external energy dissipators (EDs) is shown in Fig. 1. The precast concrete column is compressed to the foundation using the unbonded post-tensioned BFRP tendons, which provide the self-centering capacity. As shown in Fig. 1(b), the top of the threaded aluminum bar passes through the duct in the corbel and is fastened using nuts. The bottom of the threaded aluminum bar is connected with the threaded rod partly embedded in the footing using a connecting sleeve. To achieve stable energy dissipating capacity, the middle part of the aluminum bar is confined using a steel tube and injected epoxy to avoid the bar buckling in compression. The total moment capacity at the pier-foundation interface is given by the contributions of the moment induced by the PT force resultant (plus axial load) and the moment induced by the EDs. To prevent the concrete at the pier toe from damage during rocking, the bottom part of the pier is encased in a GFRP tube.

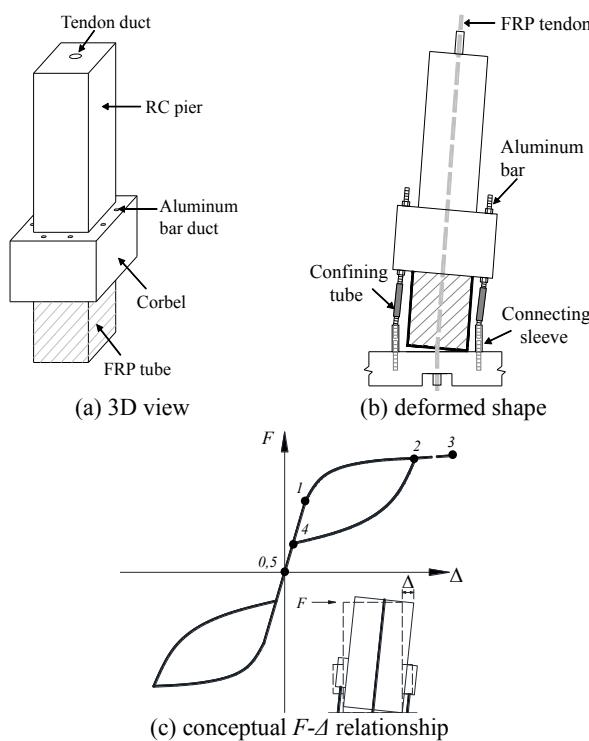


Fig. 1. SCPC pier with external energy dissipators

Under cyclic loading, the behavior of an SCPC pier with external EDs is characterized by the gap opening and closing at the pier-foundation interface. A flag-shaped cyclic hysteretic response is typically used to define the conceptual $F-\Delta$ relationship of the pier, as shown Fig. 1(c), where F is the lateral load, Δ is the lateral displacement. The pier-foundation interface remains in complete contact until the applied lateral load exceeds a certain value. With continued loading, gap-

opening occurs (at event 1 in Fig. 1(c)) at the pier-foundation interface, and the aluminum bars yield. With continued loading, the tendons will elongate to produce additional PT force, and the maximum tendon strain is reached at event 3. If unloading occurs at event 2, the yielding aluminum bars will dissipate energy between events 2 and 4. If the initial PT force and yielding force of the aluminum bars could be properly combined, the SCPC pier will return to its original position at event 5, when the pier self-centers upon unloading. A complete reversal of the lateral load will result in a similar hysteretic response in the opposite direction of loading.

3 Development of the numerical model

3.1 Model description

The numerical model of the SCPC pier with external energy dissipators is developed based on the cyclic load testing results of 1/3-scaled specimens [11], as shown in Fig. 2. The post-tensioning system consists of two 16-mm diameter BFRP tendons placed in 45-mm diameter ducts. 16 longitudinal reinforcing bars with a diameter of 10 mm were used in the pier, corresponding to a longitudinal reinforcement ratio of 1.03%. Steel rebars of 6-mm diameter were placed throughout the pier as transversal reinforcement with spacing of 100 mm, corresponding to a transversal reinforcement ratio of 0.71%. The footing was 1500-mm long by 800-mm wide by 500-mm deep.

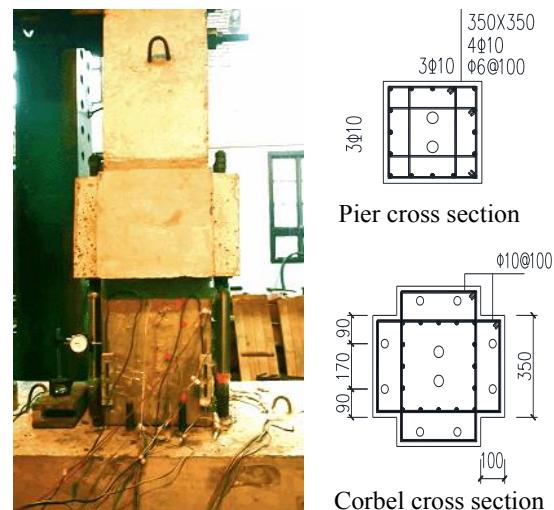


Fig. 2. Cyclic load testing setup

For the BFRP tendon, the elastic modulus and ultimate strength of the basalt fibers are 44 GPa and 1080 MPa, respectively. For the aluminum bar, a diameter of 25 mm was used for the top and bottom parts, and the diameter was reduced in the middle part to realize controlled plastic deformation. According to the tensile tests, the elastic modulus and ultimate strength of the aluminium alloy material are 66.2 GPa and 220 MPa, respectively. According to the data of the manufacturer, the elastic modulus of saturated GFRP plates was

approximately 32 GPa and the ultimate strength was 558 MPa with an ultimate strain of 1.7%.

The mean cubic compressive concrete strength was 40.8 MPa. The longitudinal reinforcing bars used HRB335 steel with nominal yield strength of 335 MPa, and the transversal reinforcing bars used HPB300 steel with nominal yield strength of 300 MPa. The threaded rods and connecting sleeves used the Q235 and Q345 steel with nominal yield strength of 235 MPa and 345 MPa, respectively.

The cyclic load tests of the SCPC pier specimens were conducted using the displacement-based loading protocol. Gradually increasing reversed cyclic displacements were applied to the pier specimens. The displacement cycles had drift amplitudes of $\pm 0.25\%$, $\pm 0.5\%$, $\pm 1.0\%$, $\pm 2.0\%$, $\pm 3.0\%$ and $\pm 4.0\%$. Complete information about the experiment can be found in Guo et al. [11].

3.2 Finite element model

The three-dimensional numerical model was developed using the finite element software package ANSYS. Fig. 3 shows the proposed numerical model in this study. The structural concrete of the column and foundation is modelled using the 3D SOLID65 element in ANSYS. This solid element has eight nodes with three degrees of freedom at each node and has the capability to model the compressive crushing and tensile cracking of concrete in three orthogonal directions.

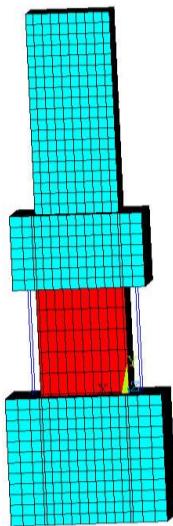


Fig. 3. Numerical model

The 3D 2-node spar element (LINK180 element) is used to model the steel reinforcing bar. This element can simulate the tensile and compressive behaviour, with the plasticity, creep, large deflection and strain capabilities considered. The bond-slip between the longitudinal reinforcing bar and surrounding concrete is modelled using a COMBIN39 nonlinear spring element, which connects the node of the LINK180 element modelling the reinforcement and the node of the SOLID65 element modelling the concrete.

To model the contact at the pier-foundation interface, 3D four-node surface-to-surface contact element (CONTA173 element), which introduces a deformable surface on the solid model is used. The Penalty method is chosen as the contact algorithm. The sliding is expected to be minimal at the pier-foundation interface and is not considered in this study.

An elasto-plastic multilinear kinematic hardening model is used to define the compressive stress-strain relationship of concrete. The elasto-plastic material property of the core concrete confined by stirrups is determined according to the Kent-Scott-Park model [12]. The confinement effect to the core concrete by stirrups is considered by increasing the strength and deformation capacity of unconfined concrete. A linear stress-strain relationship is assumed for concrete in tension until the uniaxial cracking stress is reached. The uniaxial cracking stress is 1.7 MPa and Poisson's ratio is assumed to be 0.2. Shear transfer coefficients are taken as 0.3 and 0.6 for an open crack and a closed crack, respectively.

An elasto-plastic bilinear kinematic hardening material model is used to define the stress-strain relationship of steel. The elastic modulus of steel is considered to be 200 GPa, and Poisson's ratio is assumed to be 0.3.

The GFRP tube is modelled using the 3D SOLID65 element. The FRP failure and FRP-concrete interaction are not considered in this study. The stress-strain relationship of core concrete confined by both stirrups and the GFRP tube is determined based on the model proposed by Braga et al. [13].

The BFRP tendons and the aluminum bars are modelled using the LINK180 elements. The effect of the anchorage hardware on the FRP tendon response is not considered. The material property of the aluminum bars is defined by a multi-linear curve that approximates the measured stress-strain relationship [11].

Using this FE model, reversed cyclic analyses are conducted for the lateral displacement-controlled loading. The loading protocol, as used in the tests performed by Guo et al. [11], is utilized in the nonlinear static analyses of the pier. All the analyses are conducted by two steps. In the first step, the PT force and the gravity load are applied. In the second step, several load steps are defined to apply gradually increasing displacement drift cycles to the pier.

3.3 Validation of the numerical Model

The developed FE model is validated using the existing test data [11]. Fig. 4 shows the comparisons of lateral load-drift relationships between the numerical simulation and experimental results. Fig. 4(a) shows the results of the SCPC pier with no energy dissipators. It can be seen that the strength and stiffness of the pier predicted by the FE model agree well with the experimental results. The lateral force-drift relationships are essentially bilinear because there are no energy dissipators. The slim hysteretic loops in the experimental data are mainly due to the inherent friction in the structure, which is not included in the numerical model. Fig. 4(b) compares the

results of the SCPC pier with energy dissipators, where good agreement can be seen. The seismic behaviors of the pier, such as gap opening and closing, energy dissipation, and self-centering ability, can be effectively replicated, implying the accuracy of the proposed numerical model.

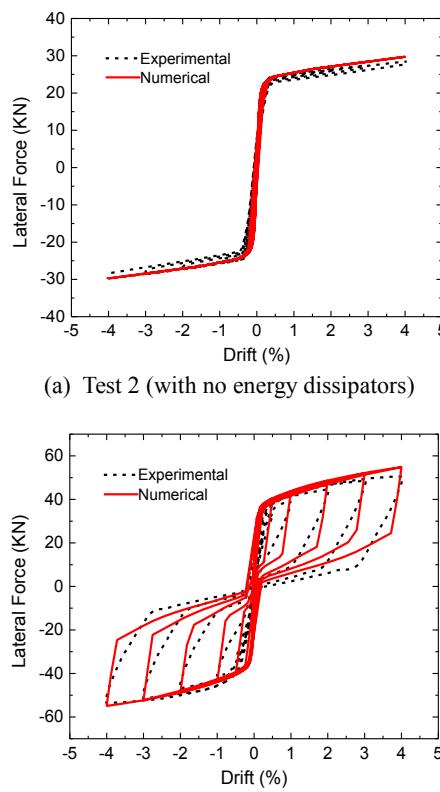


Fig. 4. Comparisons of numerical and experimental results.

4 Conclusions

This study details the development of 3D finite element (FE) model representing the self-centering prestressed concrete (SCPC) pier with external energy dissipators (EDs), in which the internal post-tensioned basalt fiber-reinforced polymer (BFRP) tendons and the external aluminum bars are used to provide the self-centering and the energy dissipation capabilities. The FE model is used to examine the cyclic performance of the SCPC pier with external EDs in terms of stiffness, strength, energy dissipation, gap opening/closing and self-centering behavior. Existing experimental data is used to validate the accuracy of the FE model. Good agreement is observed between the numerical simulation and the experimental results, demonstrating the effectiveness of the numerical simulation model. The developed FE model can be used to perform parametric studies to investigate the effects of different design parameters on the cyclic response of SCPC pier with external EDs.

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