Engineering Structures 161 (2018) 176–191

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

An explicit analytical model for seismic performance of an unbonded post-tensioned precast segmental rocking hollow pier

Zhen Wang[a], Jing-Quan Wang[a,*], Tong-Xu Liu[a], Jian Zhang[b]

[a] Key Laboratory of Concrete and Prestressed Concrete Structure of China Ministry of Education, School of Civil Engineering, Southeast University, Nanjing 210096, PR China
[b] Department of Civil and Environmental Engineering, University of California, Los Angeles, CA 90095, United States

ARTICLE INFO

Keywords:
Precast construction
Segmental piers
Unbonded post-tensioning
Rocking
Explicit analytical model
Flag-shaped hysteretic model
Fiber model
Dynamic history analysis

ABSTRACT

To avoid iterative calculation, an explicit analytical model was developed for the deformation capacity of an unbonded post-tensioned precast segmental rocking hollow pier and divided into three statuses: decompression status, yield status and large deformation status. The pier was regarded as an equivalent reinforced concrete monolithic pier at the decompression status, and the compression zone height at the base section was computed explicitly to make deformation calculation non-iterative at the other two statuses. A verified fiber model based on the *OpenSees* platform was proposed. The proposed deformation capacity model was validated with existing cyclic loading tests and the verified fiber model. A parametric study was conducted to determine the effects of the main design parameters on four coefficients of the idealized flag-shaped hysteretic model based on the proposed deformation capacity model. New formulas were proposed to determine the four coefficients through regression analysis. The flag-shaped hysteretic model with the coefficients determined by the proposed formulas was validated with cyclic loading tests and dynamic history analysis based on the fiber model. The results of this research show that the proposed model for deformation capacity may be simplified into two statuses, and it can serve as a tool to provide loading-deformation curves that have good agreement with experiments and the fiber model. The flag-shaped hysteretic model with the proposed coefficients can accurately predict the maximum displacement response and conservatively predict the dissipation energy capacity for the rocking pier under a strong earthquake shock.

1. Introduction

As a part of Accelerated Bridge Construction (ABC) techniques, separated segments can be connected to a whole by using post-tensioned (PT) tendons throughout joints according to precast segmental assembling construction technology [1,2]. The continuous bars across the joints are used to improve energy dissipation (ED) capacity, while the rebar cage composed of longitudinal and transverse bars in segments is expected to provide confinement and control shrinkage and creep [3]. The continuous reinforcements across the joints are called ED bars. The hybrid rocking piers are verified to have good self-centering and ED capacity so that the pier may be an alternative for ABC bridges in moderate and high seismic zones [4,5].

A series of experimental studies has been carried out to investigate the seismic performance of the rocking piers. Mander and Cheng [6] tested a near full-size precast concrete rocking pier to validate a paradigm called Damage Avoidance Design. Quasi-static tests of four large-scale precast concrete columns were conducted to study the hysteretic performance [7]. Engineered Cementitious Composite (ECC) was used at potential plastic hinge regions to reduce residual displacement and increase ED [8]. Chou and Chen [9] adopted a concrete-filled tube to be a segment for avoiding concrete crushing at the critical joint and used external steel ED devices. Palermo et al. [10] proposed to use partially unbonded ED bars to avoid premature low cycle fatigue failure. Four large-scale tall rocking piers with ED bars were subjected to cyclic loading, and ED bars were proven to be an effective ED solution [11]. A shake table test was conducted on an unbonded PT precast segmental pier with a hollow section to investigate its dynamic performance [12]. Cyclic loading tests, including six large-scale precast segmental concrete piers with hollow sections, were carried out to investigate the influence of the ED bar ratio, the initial PT forces and the material performance of the bar [3,13]. Elgawady et al. [14,15] experimentally investigated the seismic behavior of four rocking segmental piers and four relevant bents consisting of precast concrete-filled fiber tube segments. Various types of external ED devices including replaceable dissipater, viscous dissipater, etc., were used for the rocking piers [16–18].

* Corresponding author.
E-mail address: wangjingquan@seu.edu.cn (J.-Q. Wang).

https://doi.org/10.1016/j.engstruct.2018.02.025
Received 31 March 2017; Received in revised form 4 January 2018; Accepted 4 February 2018
0141-0296/

Motaref et al. [19] carried out shake table testing to study the effect of advanced materials including ECC, carbon fiber reinforced polymer (CFRP) and elastomeric bearing pad on the dynamic performance of the rocking piers. The unbonded PT precast segmental pier and the bonded PT companion were compared by quasi-static cyclic loading tests [20]. Moon et al. [21] proposed that shape-memory-alloy (SMA) used as ED bars was to improve self-centering capacity. Factorial analysis was conducted to evaluate the seismic behavior of the rocking piers based on an *Abaqus* finite model validated by experiments [22]. White and Palermo [23] conducted biaxial cyclic loading tests on three ABC specimens with new precast column-footing connections.

Moreover, many numerical models have been developed to simulate seismic performance of precast segmental piers. Based on the *Abaqus* software, a 3D finite element model was established to reproduce results of cyclic loading tests and verified to be effective [24,25]. A fiber model based on the *OpenSees* platform was an alternative with good computational accuracy to investigate the cyclic and dynamic behavior [1,26]. An analytical pushover procedure was proposed to calculate lateral force-deformation curves of precast segmental piers iteratively based on the sectional analysis [3,24,27]. Dawood and ElGawady [28] presented a design procedure for unbounded PT precast concrete-filled glass fiber-reinforced polymer (GFRP) tube piers using empirical equations based on an *Abaqus* finite model. Chou et al. [29] developed an iterative procedure to consider opening at the two base joints based on a two-plastic-hinge model. Roh and Reinhorn [30] suggested a simplified analytical element. Based on this element, a modeling technique was proposed for a PT rocking bridge pier with ED bars [31]. A flag-shaped hysteretic single degree of freedom (SDOF) model was proposed for the PT precast segmental piers, and relevant frequency response was studied based on the hysteretic model [17,32,33]. Some modified flag-shaped hysteretic SDOF models were developed to consider variation of reloading stiffness and peak values after yielding with cyclic loading history [24,34,35].

Many problems for calculation and design of the unbonded PT precast segmental rocking hollow piers still require more attentions to be solved. The objectives of this study were: (1) to predict deformation capacity with no iterative computations; (2) to establish the relationship between the coefficients of the flag-shaped hysteretic model and the main design parameters.

This paper was organized as follows: an explicit analytical model for deformation capacity is presented first. A validated fiber model based on the *OpenSees* platform was proposed. The proposed deformation capacity model was verified by the fiber model and existing cyclic loading tests. Based on the proposed deformation capacity model, a parametric study was conducted to determine the effects of the main design parameters on four coefficients of the idealized flag-shaped hysteretic model. New formulas were proposed to determine the four coefficients through regression analysis. The flag-shaped hysteretic model with coefficients known by proposed formulas was used to conduct cyclic loading simulation and dynamic history analysis, of which results were compared with those of cyclic loading tests and the validated fiber model, respectively.

2. Analytical model for deformation capacity

As seen in Fig. 1, three statuses are defined to calculate the mechanical behavior of a precast segmental rocking pier under a lateral loading: As shown in Fig. 1(a), the stress in concrete at the edge of the base joint is zero at the decompression status, which means that the pier may behave similarly to a monolithic pier. As shown in Fig. 1(b), joint opening has occurred at the base joint, and the outermost ED bars at the tensional side begin to yield at the yield status, while the compression stress of concrete is small and regarded as a linear distribution. From previous studies [7,13,27], for precast segmental rocking piers with no significant variation of stiffness and energy dissipation settings along the column direction, the opening of the joint between the foundation and the bottom segment dominates the lateral deformation at the large drift, though the opening of other joints may occur. As shown in Fig. 1(c), the drift ratio θ_{dr} is deemed to be equal to the rotation θ_c caused by the base joint opening at the large deformation status [3].

2.1. Decompression status

As mentioned above, the lateral behavior of precast segmental rocking hollow piers at the decompression status may be evaluated as an equivalent monolithic reinforced concrete pier.

At the initial status, the column is subject to the gravity loading P_G and the initial PT force P_{PT}. At the base joint, the curvature is zero, and the concrete compressive strain ε_{c0} is calculated as

$$\varepsilon_{c0} = \frac{P_G + P_{PT}}{E_c A_g (1-\rho_{EB}) + E_s A_g \rho_{EB}} \tag{1}$$

where E_c is the elastic modulus of the concrete and equal to $4730\sqrt{f_c}$ [36]; E_s and ρ_{EB} are the elastic modulus and the area ratio of the ED bars, respectively; A_g is the gross sectional area of the base joint.

At the decompression status, the lateral displacement Δ_d of the pier is generally small, which means that the tensioning force increment of the unbonded PT tendons is very limited. Therefore, the pier is still mostly subject to the gravity loading P_G and the initial PT force P_{PT} along the axis direction. As shown in Fig. 2, due to the plane section assumption, the average compressive strain of the ED bars is equal to the average compressive strain $\varepsilon_{c,d}$ of concrete at the base joint, when the curvature ϕ_d at the decompression status is reached. At the decompression status, the compressive stress-strain relationships are considered to be linear for concrete and ED bars. Therefore, the average value $\varepsilon_{c,d}$ of the concrete compressive strain is calculated as

$$\varepsilon_{c,d} = \frac{P_G + P_{PT}}{E_c A_g (1-\rho_{EB}) + E_s A_g \rho_{EB}} = \varepsilon_{c0} \tag{2}$$

As shown in Fig. 2, the corresponding curvature ϕ_d of the decompression status is calculated as

$$\phi_d = \frac{\varepsilon_{c0}}{h/2} = \frac{2(P_G + P_{PT})}{[E_c A_g (1-\rho_{EB}) + E_s A_g \rho_{EB}]h} \tag{3}$$

where h is the height of section at the base joint.

Based on the equivalent plastic hinge model of the monolithic piers [37], the lateral displacement Δ_d and the sectional moment M_d of the base section with a known ϕ_d can be evaluated as

$$\Delta_d = \frac{L^2}{3}\phi_d = \frac{2}{3}\frac{(P_G + P_{PT})L^2}{[E_c A_g (1-\rho_{EB}) + E_s A_g \rho_{EB}]h} \tag{4}$$

$$M_d = \phi_d EI_{eff} \tag{5}$$

where EI_{eff} is the sectional effective stiffness and is calculated as [38]

$$\frac{EI_{eff}}{E_c I_g} = 0.015 + 0.531\frac{P_G + P_{PT}}{f_c A_g} + 0.042\frac{L}{h} \leqslant 1.0 \tag{6}$$

where f_c is the compressive strength of unconfined concrete; L is the shear length of the pier.

The base shear F_d of the pier is given without the P-Δ effect

$$F_d = \frac{M_d}{L} \tag{7}$$

2.2. Yield status

At the yield status, the stress of ED bars at the web of the base section is small because of the low yield curvature ϕ_y. Therefore, the contribution from the ED bars at the web is neglected. Due to the base joint opening, the actual section may not conform to the plane section assumption shown in Fig. 3. At the yield status, the curvature ϕ'_y at the tensile side is different with ϕ_y at the compressive side. According to the