Performance of Seismic Behavior and Design of Segmental Precast Post-Tensioned Concrete Piers

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ABSTRACT

Segmental precast post tensioned (SPPT) bridge pier is an economical construction system, and a re-centering structural system. Understanding the seismic behavior of the SPPT system is an important step towards its application in high seismic zones. First, the thesis presents a detailed three-dimensional finite element model developed using the ABAQUS platform. A brief description and discussion of cyclic tests on eight large scale SPPT piers was also presented. The finite element model was validated against the experimental results and it showed good agreement. Sensitivity analyses using the finite element model showed that the model is sensitive to the softening behavior of the concrete material constitutive law. Then, the FE model was used to discuss the design parameters that potentially affect the lateral seismic response of the SPPT bridge piers. Design parameters investigated include the initial post-tensioning stress as a percentage of the tendon yield stress, the applied axial stresses on concrete due to post-tensioning, pier aspect ratios, construction details, steel tube thicknesses, and internal mild steel rebar added as energy dissipaters.

INTRODUCTION

The use of precast segmental construction for concrete bridges in the United States has increased in recent years due to the demand for shortened construction periods, low environmental impacts and the desire for innovative designs that result in safe, economical and efficient structures. However, the behavior and performance of precast segmental bridges during earthquakes is of concern, and consequently their widespread use in moderate to high seismic regions such as the West Coast of the United States is limited.

Innovative Precast Post-Tensioned Bridge Piers and Bents Developed at Washington State University

During the last few years, an innovative segmental precast post-tensioned bridge construction system was developed at Washington State University. The piers of the developed system consist of segmental concrete filled fiber reinforced polymer tubes (SPPT-CFFT), superimposed one on top of the other, and then connected structurally with vertical post-tensioned tendons passing through ducts located in the precast segments. The tendons are anchored in the foundation of the pier and in the bent cap at the pier top Fig. 1.1. Constructing bridge piers in this manner offers several structural, construction and environmental advantages over conventional R.C. designs.

A schematic deformed shape of the SPPT-CFFT segmental pier under transverse loading is shown in (Fig. 1.1). The post-tensioning load keeps the whole system as one unit. Under lateral loads, the stresses under the precast segments start to be a combination of the normal force induced by prestressing and moment induced by the lateral load. Once the stresses reach a zero value at a point under a segment, any increase in the lateral load leads to an opening between that segment and the one beneath it. This opening continues to propagate with the load increase until it reaches the prestressing bars at the G.C. of the cross section. This is when the post-tensioning steel bar is stretched and the stress in the tendons increase. The fact that the opening between the components propagates means that the stiffness of the system decreases and as a result the energy absorbed from the seismic event decreases.

Construction Advantages

Construction schedules can be shortened significantly since bridge components can be rapidly produced at the precasting facility, where assembly lines and steam curing increase the efficiency of concrete construction. Additionally, the erection of a segmental bridge in the field can proceed rapidly, thus reducing the disruption to existing traffic infrastructure.

Research Objectives

This study started with the development of a FE model capable of capturing the behavior of the segmental precast post-tensioned (SPPT) pier system. The model was calibrated against three different experimental studies with different configurations of the SPPT system. The model was then used to conduct a parametric study to have a better understanding of the effect of different parameters and configurations on the seismic behavior of the SPPT piers. The data collected from a large number of analyzed piers was then used to develop a design procedure for the system using empirical equations.

LITERATURE REVIEW

Experimental Studies

Hewes and Priestley (2002) conducted cyclic loading on four, 40% scaled, unbonded segmental post-tensioned piers with different aspect ratios. Each pier was tested twice under low and high initial post-tensioning stress. Two different thicknesses of steel confinement were used for the lower segments only, while the upper segments were reinforced concrete.

Chang et al. (2002) conducted a study on four large-scale hollow precast unbonded post- tensioned reinforced concrete segmented piers. Each specimen consisted of nine or ten 100 cm [39.4 in] tall, precast pier segments.

Chou and Chen (2006) tested two one-sixth scale (16.67%) precast unbonded post- tensioned concrete filled steel tube segmental piers through cyclic loading tests.

Marriott et al. (2009) tested three, one-third scale (33%) piers. Two were segmental piers while the third was of monolithic reinforced concrete (RC) construction as a control specimen.

Simple Models

A simplified analytical three-stage model was developed by Hewes and Priestley (2002); their results showed that the model was able to predict the backbone curves of the tested piers quite well.

Ou et al. (2007) used the experimental data obtained by Chang et al. (2002) to develop a simplified analytical model for static pushover analysis as well, but also taking into consideration the presence of longitudinal mild steel reinforcement across the pier segment joints.

El Gawady et al. (2010) attempted to verify the simplified analytical model originally developed by Hewes and Priestley (2002) against their test results. The model overestimated the yield point of the system (Fig. 2.4). To capture the experimental backbone curve, the plastic hinge length definition was changed according to Hines et al. (2001). This proved that the model is not yet accurate enough to capture the behavior of different systems.

Lumped-mass Models

In this approach, the piers are assumed to be a single degree of freedom system (SDOF) with a lumped mass at the top. The hysteretic diagrams developed by experimental tests and/or FE models are then modified to an idealized flag-shape hysteretic for the SDOF.

Ou et al. (2007) used the 3D FE analyses and the cyclic test data from Chang et. al (2002) to develop a flag-shaped (FS) model. By assuming that the piers are a lumped-mass SDOF, the response-history of the piers under 25 near-fault ground motions was easily computed in order to study the behavior of the system under seismic loading.

Compared to piers without mild steel. External energy dissipaters “fuses” have also been investigated as a means of enhancing energy dissipation (Chou and Chen 2006, Marriott et al.2009, Rouse 2009, ElGawady et al. 2010(a), ElGawady et al. 2010(b), and ElGawady and Shaalan 2010). These external simple yield-dissipaters significantly increased the energy dissipation with minor effects on the residual displacement of the system.

Finite Element Modeling of Self-Centering Piers

ABAQUS/Standard version 6.8-2, a general-purpose finite element code, was selected as a basic platform for this study. For the simulation of the SPPT pier system a built-in first-order full integration 8-node linear brick element (C3D8) was used to represent the concrete and the confining material in the model (Fig. 3.1). A 2-node linear beam element in space (B31) was used to simulate the post-tensioning tendon. The mesh size was selected based on a sensitivity analysis such that the analyses converge to the same output while maintaining a reasonable computation effort.

Test Pier Design Details

Four large-scale precast concrete segmented piers (Table 3.1) were constructed and tested at the Powell Structural Research Laboratories on the University of California at San Diego (UCSD) to investigate their strength – deformation characteristics and failure modes under simulated lateral seismic loading (Hewes 2002). The following primary features were investigated in the experimental program: (1) Pier aspect ratio, (2) Lateral confinement level at the maximum moment location, (3) Initial tendon stress, and (4) Damage reparability. The piers were circular in cross-section with diameter of 610 mm [24 in], and the main longitudinal reinforcement in each pier consisted of a single unbonded concentric tendon comprised of 27 – 12.7 mm [0.5 in] diameter ASTM A779 Grade 270 (1860 MPa [270 ksi]) low-relaxation steel prestressing strands with a total cross-sectional area of 2665 mm^2[4.13 in^2]. Two test piers had an aspect ratio (AR) of 6, and the other two piers had AR = 3, where aspect ratio is defined as the height between point of lateral loading and pier base divided by pier diameter.

Analyses results

The FE models were able to capture the behavior of the eight specimens described previously (Fig. 3.6). While applying the lateral load, the lateral displacement of the pier increased approximately linearly while all the interface joints between the different segments remained intact. This linear behavior continued until the normal stress under the heel of the pier reached zero (neutral axis at the edge of the cross section). Beyond that, the first opening at the interface joint between the foundation and the bottommost segment was observed and softening in the stiffness was observed as well. While increasing the lateral load, the neutral axis continued to move through the pier"s crosssection towards its geometric centroid, and the opening of the interface joint between the bottommost segment and the foundation increased. Fig. 3.6(b) shows the discontinuity of the normal strains at the interface joints which was expected once the interface joints opened. Once the neutral axis reached the geometric centroid of the pier"s cross section, more softening in the stiffness of the system occurred rapidly while the post-tensioning stresses increased rapidly. The same interface joint opening mechanism occurred at the second interface joint between the first and the second segments.

Effects of initial post-tensioning level in the tendon

The first parameter investigated in this study – the PT series – was the level of initial tendon stress. The initial post-tensioning stress ranged from 30% to 90% of the yield strength of the tendons while changing the cross sectional area from 4000 mm^2 [6.2 in^2] to 1300 mm^2[2.0 in^2], respectively, to maintain the axial stresses on the concrete invariant at 7.17 MPa [1040 psi] whichcorrespondsto17%off'_c.Fig.4.3shows the lateral drift at the loading point (middle of the loading stub) versus the measured the lateral resistance of the different piers. The lateral drift was defined as the ratio of the measured lateral displacement divided by the height of the loading point above the pier base. As shown in the figure, all the piers reached their ultimate strengths at a lateral drift angle of approximately 3%. Beyond that, a gradual degradation in the strength occurred and the analysis ended at a lateral drift angle of 5%. At this drift level, a reduction of approximately 14% occurred in the strengths of the piers. The analysis truncated due to spalling and compression failure at the bottom of the second segment.

Effects of initial stresses on the concrete

The second parameter investigated in this study – the IS series – was the level of the initial axial compressive stress imposed on the concrete due to post-tensioning forces. This was achieved by maintaining the tendon"s post-tensioning stress constant at 45% of its yield stress while changing the tendon cross-sectional area from 1980 $mm^2$to 4990 mm^2[3.07 in^2to7.73 in^2]. This resulted in axial stresses in the concrete ranging from 5.38 MPa [780 psi] to 12.83MPa [1860psi] which corresponds to13%to31%off'_c.

As shown in the figure, adding internal mild steel rebar, as energy dissipaters, increased the ultimate strength. However, failure of the piers having such rebar was quite brittle with limited drift angle capacity. Adding the rebar changed the mode of failure from compression controlled, for pier IED#0- without internal rebar, to anchorage failure in the rebar due to the limited development length (Fig. 4.18).

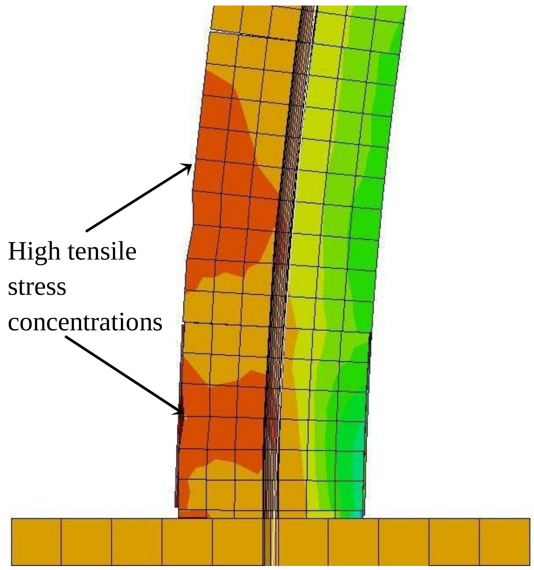

Figure 4.18: High stress concentrations in the segments due to the insufficient development length of the IED bar

Effects of confinement

Figs. 5.17 and 5.18 show the backbone curves for four piers: two from the S series and two from the L series. All piers have a height of 5487 mm [216 in]. The piers were subjected to PT ranged from 10% to 30%. The piers were constructed with two different FRP tubes. Both tubes have the same thickness of FRP but the second tube having a tensile stress of 275.79 MPa [40 ksi] and E modulus of 24,821 MPa [3600 ksi] representing a stronger and stiffer FRP tubes available in the market. Fig. 5.19 shows the stress-strain behavior for the S series and L series confined using the different FRP materials. As shown in Figs. 5.17 and 5.18, increasing the modulus of elasticity and tensile strength of the tubes significantly increased the strengths and the post-elastic stiffness of the piers. The increase in the strength and post-elastic stiffness is more significant in the case of the piers from the Sseries.

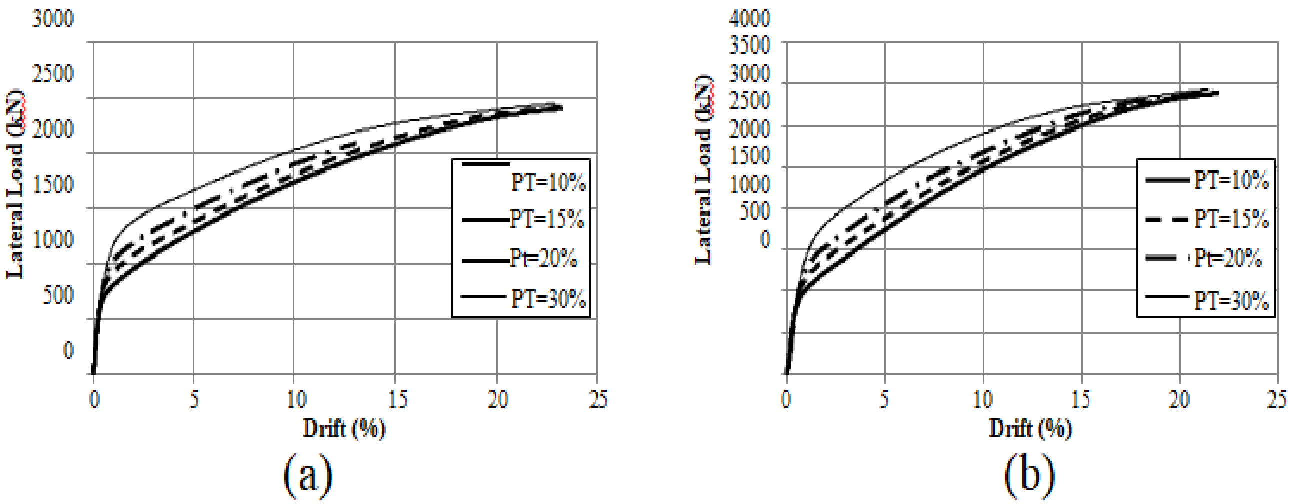

Figure 5.17: Backbone curves for piers of the L series constructed using
(a) weak FRP and (b) strong FRP (Note the vertical axis different limits)

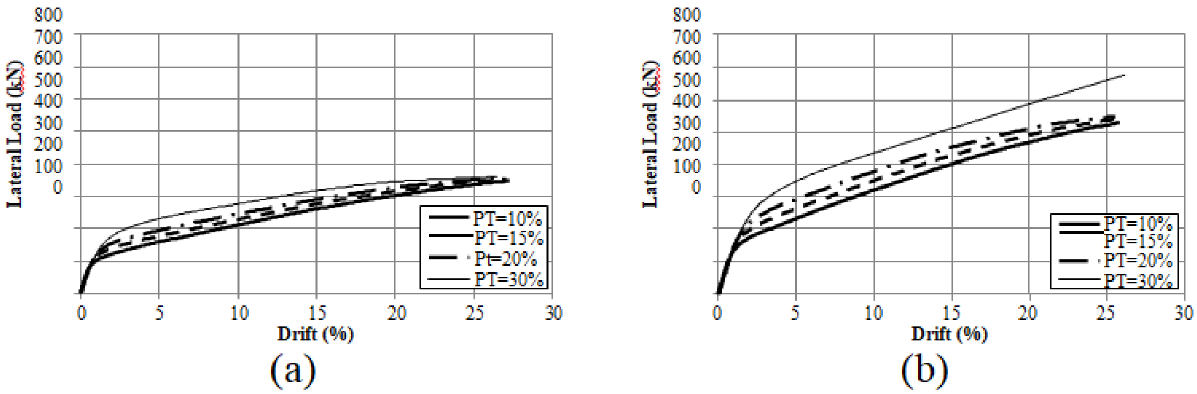

Figure 5.18: Backbone curves for piers of the S series constructed using (a) weak FRP and (b) strong FRP

CONCLUSIONS

This chapter introduces the implementation of different material behaviors in the previously developed FE model to be able to capture the backbone behavior of SPPT concrete piers and bents tested in Washington State University. This investigation revealed that:

- The FE model was able to capture the backbone behavior of both SPPT concrete piers and bents quitewell.
- The grout layer behaved quite well at the beginning of testing, but after that the damage induced by high stress concentrations on it made it softer. This led to reduction in the post-tensioning stresses in the tendon.
- The grout layer used to level the foundation surface, in the case of piers, affected the lateral load at which the tangent stiffness of the system reduces.
- The cement pastes as well affected the initial and post-elastic tangent stiffnesses of the SPPT concrete bents.
- Including the cement paste layer in the FE model proved its efficacy as the FE model was then able to capture the bent‟s behavior very well.
  Based on the results of the presented parametric study:
- The level of the applied post-tensioning forces has a significant effect on the backbone of SPPT-CFFT piers. Increasing the applied post-tensioning increased the yield strength of the piers. However, increasing the post-tensioning stresses in the tendons combined with
  Decreasing the pier‟s height led to yielding of the trend on at relatively small drifts.
- For the parameters chosen for this study and within the feasible drift angle for a pier, the analysis was more sensitive to the total applied axial loads than to the ratio of the applied post-tensioning to gravity loads.
- Increasing the piers"aspect ratios decreased the initial stiffness, ultimate strength, and yield strength but increased the deformation capacity. In addition, tendons in squat piers tend to yield at small drift angles compared to relatively slender piers.
- The analysis showed that the pier size played an important role in the behavior of the piers once the interface joint opened.
- For the same pier height, increasing the pier diameter size significantly increased the pier shear stress capacity but had minimal effect on the pier deformation capacity.
- Increasing the tensile strength and E-modulus of the confining tube significantly improved the strength and post-elastic stiffness of the piers. However, it did not have significant effect on the deformation capacity of the piers.

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