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Analysis of segmental piers consisted of concrete filled FRP tubes

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ABSTRACT

Precast segmental construction technique is an excellent candidate for economic rapid bridge construction in highly congested urban environments and environmentally sensitive regions. This paper presents three dimensional nonlinear finite element models using ABAQUS\Standard for evaluating the behavior of segmental precast post-tensioned piers under lateral loads. The piers were constructed by stacking precast concrete filled fiber reinforced polymer tube segments one on top of the other and then connecting the assembly structurally with vertical post-tensioning tendons passing through ducts located in the precast segments. A stress–strain relationship for confined concrete was used to model the concrete. The post-tensioning tendons were modeled with beam elements. The model was able to predict the backbone curves for two piers subjected to cyclic loads. A parametric study indicated that increasing the applied post-tensioning force increases nominal strength. Finally, the model showed that the pier aspect ratio, cross sectional diameter size, pier size, and confinement have significant effects on the performance of the investigated piers.

1. Introduction

Significant number of existing reinforced concrete (RC) structures including bridges were built under the current prevailing capacity design concept in combination with ductile design which permits structures to dissipate the input seismic energy in predefined plastic hinge regions. In the case of a strong earthquake, the energy that is dissipated in plastic hinge regions causes extensive damage and permanent drifts that is generally expensive to repair or irreparable at all and may leave the bridge unserviceable. One alternative solution to avoid residual displacements and extensive damage in design of RC structures is to use base isolation. However, such alternative is quite expensive and requires advanced dynamic analysis.

Several ancient "multi-drum" Greek columns have withstood numerous strong earthquakes with limited, if any, damage [1]. The Greek columns are made by carefully fitted stone blocks "drums" which placed on top of each other without mortar (dry joints). During an earthquake ground motion, the blocks rock back and forth and dissipate the input seismic energy through radiation damping, sliding, and minimal damage.

Segmental precast post-tensioned (PPT) concrete bridge piers are constructed by stacking precast concrete segments one on top of the other and then connecting the assembly structurally with vertical post-tensioning tendons passing through ducts located in the precast segments. Hence, it represents a modern and improved version of the multi-drum Greek columns. The tendons are anchored in the concrete foundation and in the cap beam. A segmental PPT bridge pier will rock back and forth during ground motion excitation and the inelastic deformations are accommodated within the interface joints between the segments. Fig. 1 shows a schematic drawing of a rocking pier indicating stresses and strains at different heights of the pier. As shown in the figure, during ground motion excitation, the interface joint at the base will open and stretch the tendon leading to increase in the post-tensioning force. If the tendon is unbonded, the increase in the axial strain will be uniformly distributed over the whole length of the tendon and the tendon remains elastic at large displacements. Thus, the pier will remain nearly elastic and re-center upon unloading as a result of the restoring nature of the applied post-tensioning force.

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 and the desire for innovative designs that yield safe, economical and efficient structures. Recently, New Jersey Department of Transportation (NJDOT) reduced the construction duration of the Victory Bridge by at least 1 year using precast segmental construction for the superstructure and substructure. Such reduced construction time saved NJDOT millions of dollars [2]. Examples of bridges constructed with segmental piers include Louetta Road Overpass (SH-249, Texas), Linn Cove Viaduct

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List of symbols

f'_c	concrete unconfined compressive stress,
f'_c	concrete ultimate compressive strength,
ε_{cu}	ultimate concrete strain,
E_1	modulus of elasticity of the unconfined concrete,
E_j	modulus of elasticity of FRP tube
t_j	thickness of FRP tube
f_j	hoop strength of the FRP
D	concrete core diameter
AR	pier aspect ratio
f_t	the maximum permissible tension stress in the concrete
U_x, U_y, and U_z	degrees of freedom in the x, y, and z direction
DL	axial stresses due to applied axial load, normalized by f'_c
PT	axial stresses due to post-tensioning forces, normalized by f'_c

(Grandfather Mountain, North Carolina), Sunshine Skyway Bridge (I-275, Florida), Varina-Enon Bridge (I-295, Virginia), John T. Collinson Rail Bridge (Pensacola, Florida), Seven Mile Bridge (Tallahassee, Florida), and the Chesapeake and Delaware Canal Bridge (St. Georges, Delaware). However, knowledge of the behavior and performance of segmental precast bridges during earthquakes is lacking, and consequently their widespread use in seismic regions such as California is yet to be realized. Recent tests showed that segmental PPT piers can safely resist lateral cyclic forces without experiencing significant or sudden loss of strength [3–11].

A typical rocking pier will have an equivalent viscous damping of about 5% even at higher drift ratios. To overcome this drawback, researchers supplied post-tensioned precast piers with simple yield-dampers. Both internal mild steel at the interface joints and/or external fuses were used to increase the system energy dissipation. However, the provided mild steel increased the residual displacements and damage compared to piers without mild steel [3,5,6,8–11].

Since the 1980s, concrete filled fiber reinforced polymer tubes (CFFTs) were used as piles for bridges. These piles have two main structural components: a fiber reinforced polymer (FRP) shell and a concrete infill. The FRP shell provides a stay-in-place concrete form, confinement to the concrete, shear reinforcement, and corrosion protection. The continuous confinement by the jacket significantly improves the ductility and the strength of the concrete [12]. In addition, CFFT has been successfully used as bridge piers, girders, and piles in different field applications by several United State Departments of Transportation.

Several studies investigated the seismic behavior of reinforced concrete piers encased in FRP tubes [13,14]. Various construction details between the piers and foundations were investigated. The reinforced CFFT piers behaved similarly to conventional reinforced concrete piers. An experimental study investigated the cyclic performance of six CFFT beams under four-point bending and found that CFFT beams can be designed with a ductility level comparable to conventional reinforced concrete beams. Adding a moderate amount of steel reinforcement improved the cyclic performance of the beams [15].

This paper presents a three dimensional finite element model for bridge piers constructed out of segmental precast post-tensioned concrete filled fiber reinforced polymer tubes (PPT-CFFTs). The model was first validated against the results of experimental investigations on two PPT-CFFT piers. Then, the effects of the applied post-tensioning force, load combination, pier aspect ratio, pier size, pier cross sectional diameter size, and pier confinement on the lateral performance of the piers were investigated.

2. Experimental investigation

In this section the cyclic behavior of two PPT-CFFT piers, namely, FRP1 and FRP4 is presented [4]. Fig. 2 shows the dimensions of the two piers. Each pier had a diameter of 203 mm [8 in] and a clear height of 1524 mm [60 in]. The actuator for lateral

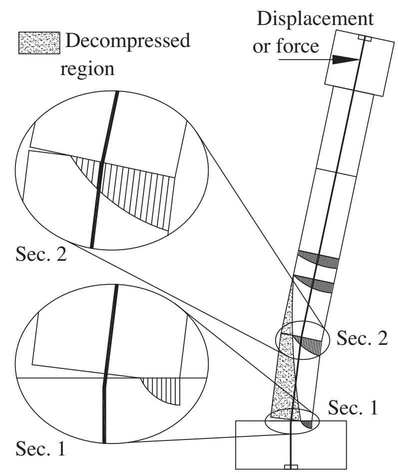

Fig. 1. A schematic drawing of a rocking pier indicating stresses and strains at different heights of the pier.

loading was attached to a 254 mm [10 in] reinforced concrete loading stub placed atop of the pier. The lateral load was applied halfway up the loading stub giving a total height above the top of the footing for the load application of 1651 mm [65 in]. Pier FRP1 was constructed using a single segment of CFFT while pier FRP4 was constructed using four segments of CFFT each having a height of 381 mm [15 in].

The circular tubes were made by filament-winding technique with ±55° glass fiber orientation with respect to the longitudinal axis of the tube. The tube had a nominal wall thickness of 3.18 mm [0.125 in] and interior diameter of 203 mm [8 in]. This wall thickness was designed to avoid brittle shear failure under the anticipated ultimate lateral load of the piers [4].

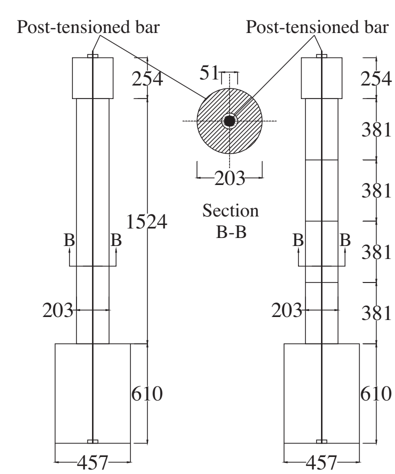

Fig. 2. Schematic drawings of piers FRP1 and FRP4 [mm].