INELASTIC BEHAVIOR OF PRECAST CONCRETE SEGMENTAL BRIDGE PIERS WITH SHEAR RESISTANCE CONNECTING STRUCTURE

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ABSTRACT :

The purpose of this study was to investigate the inelastic behavior of precast concrete segmental bridge piers with shear resistance connecting structure. The goal of addressing system performance is to maximize post-earthquake functionality of a structure and to minimize direct and indirect societal losses. The system can also reduce work at a construction site and makes construction periods shorter. A model of precast concrete segmental bridge piers with shear resistance connecting structure was tested under a constant axial load and a cyclically reversed horizontal load. A computer program, RCAHEST (Reinforced Concrete Analysis in Higher Evaluation System Technology), for the analysis of reinforced concrete structures was used. Material nonlinearity is taken into account by comprising tensile, compressive and shear models of cracked concrete and a model of reinforcing steel. A bonded or unbonded tendon element based on the finite element method, that can represent the interaction between tendon and concrete of prestressed concrete member, is used. A joint element is newly developed to predict the inelastic behaviors of segmental joints with shear resistance connecting structure. The proposed numerical method gives a realistic prediction of inelastic behavior throughout the loading cycles for several test specimens investigated. This study documents the testing of precast concrete segmental bridge piers with shear resistance connecting structure under cyclic loading and presents conclusions and design recommendations based on the experimental and analytical findings.

KEYWORDS: Inelastic behavior, Precast concrete segmental bridge piers, Shear resistance connecting structure, Material nonlinearity, Joint element

1. INTRODUCTION

The use of precast segmental construction for concrete bridge has increased in recent years due to the demand for shortened construction periods and desire for innovative design that yield safe, economical and efficient structures. However, knowledge of the behavior and performance of precast segmental bridges during earthquake is lacking, and consequently their widespread use in seismic regions is yet to be realized. Also, previous research by others on the seismic response of precast concrete segmental bridge piers is limited (Billington et al., 2001; Hewes, 2002; Chou et al. 2006).

The behavior of a precast segmental bridge pier under seismic loading differs fundamentally from that of a conventional reinforced concrete bridge pier. In that precast concrete segmental bridge piers, large structural deformations are not due to plastic deformation within a hinge region, but rather, are due to rigid rotation of the entire bridge pier about its base. Hysteretic energy dissipation of the precast system is small relative to that of a conventional reinforced concrete bridge pier.

There is limited knowledge about the seismic behavior of segmental bridge piers, in particular, the seismic behavior of the segment joints in segmental bridge piers (Arai et al., 2000). The development of any new method of precast bridge construction will require rigorous research on the design details of precast connections to ensure that they will perform as expected over the lifetime of the bridge.

The aim of this study is to establish the behavior of precast concrete segmental bridge piers with shear resistance connecting structure under lateral seismic loading and to formulate a design procedure. Shear resistance connecting structure, which were continuous across the segment joints for enhanced shear transfer, were introduced in the prestressing tendon ducts. The proposed system exhibited relatively small residual displacement, high ductility and good hysteretic energy dissipation capacity.

This paper will present simulations performed on large-scale experiments on precast concrete segmental bridge piers. This study effort involved both the analytical and experimental investigations of the behavior of precast concrete segmental bridge piers under lateral seismic loading.

2. PRECAST CONCRETE SEGMENTAL BRIDGE PIERS WITH SHEAR RESISTANCE CONNECTING STRUCTURE

Figure 1 shows the design concept of the proposed segmental bridge piers with shear resistance connecting structure. A segmentally precast concrete bridge pier consists of relatively small, easily handled segments. The ends of each column segments have newly developed shear resistance connecting structure to facilitate shear transfer between segments (see Fig. 2). They also play an important role in its performance in terms of hysteretic energy dissipation and ductility.

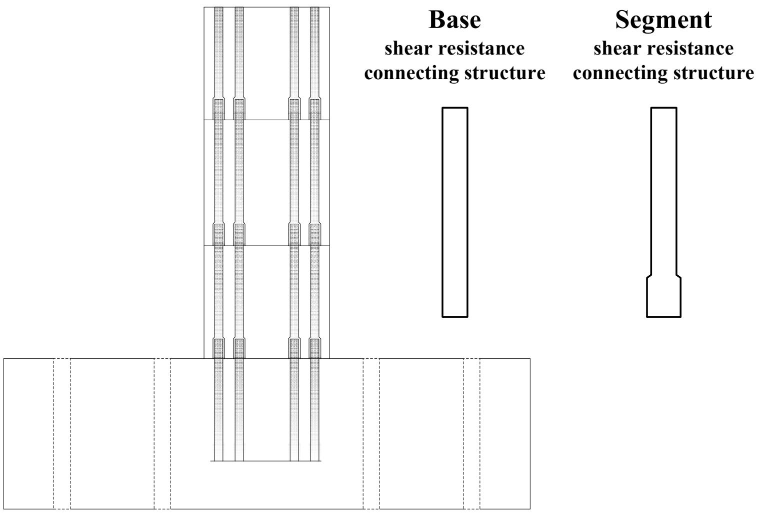


Figure 1 Proposed segmental bridge piers with shear resistance connecting structure

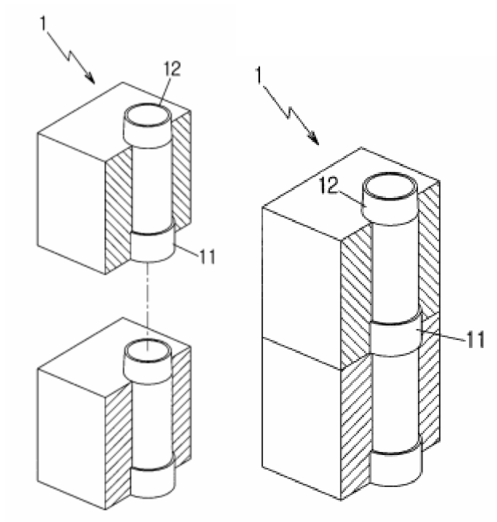


Figure 2 Design concepts of proposed shear resistance connecting structure

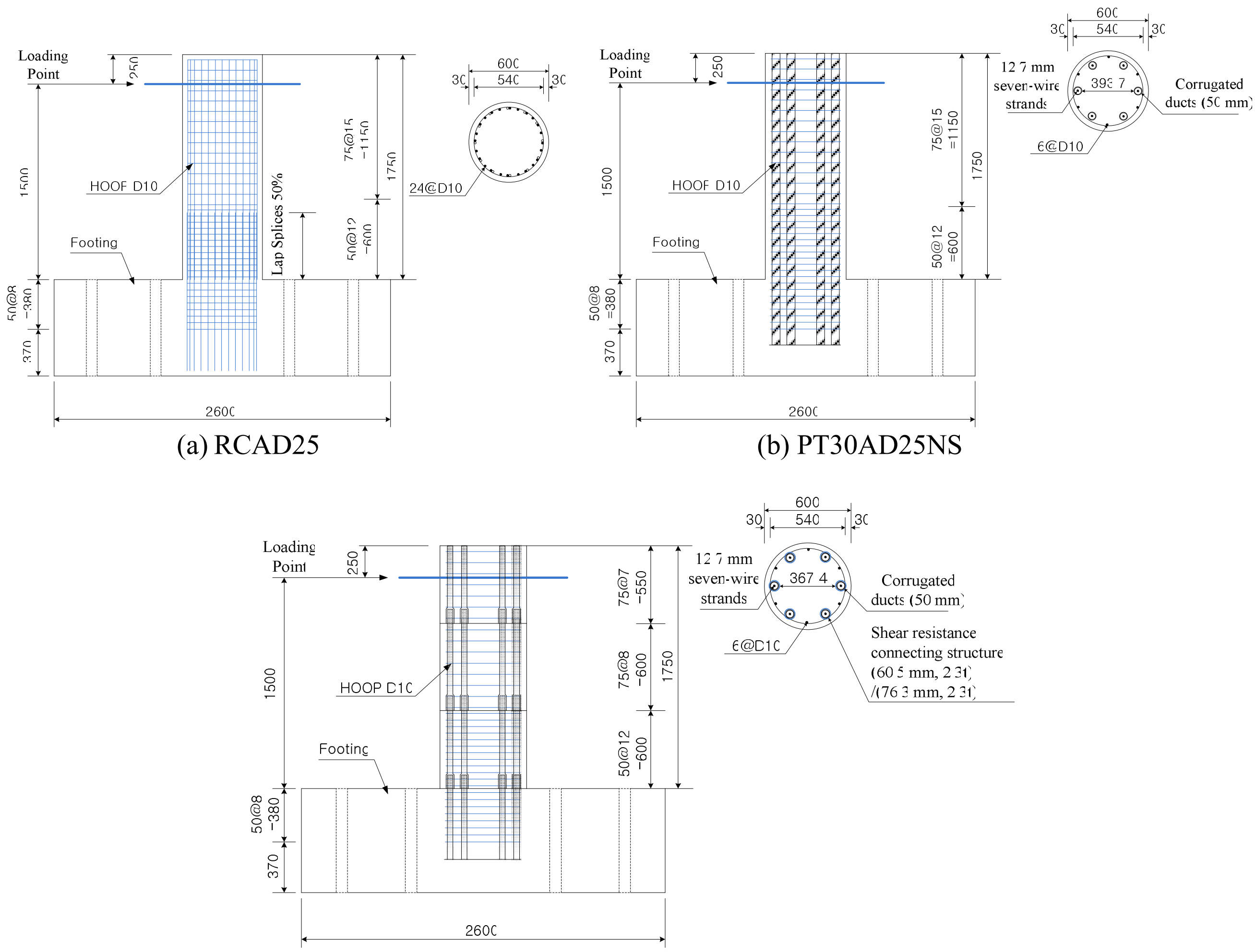
Only prestressing bonded tendons are continuous across the segment joints. The column is able to return back to its original position after large lateral drift. This becomes an increasingly favorable characteristic over time in the earthquake research community, since post-earthquake serviceability of key bridges is important.

A newly developed hybrid system is a precast concrete system that combines bonded post-tensioning tendons and shear resistance connecting structure across precast joints to exhibit hysteretic behavior with satisfactory hysteretic energy dissipation and small residual displacement upon unloading.

3. EXPERIMENTAL PROGRAM

Three column specimens were tested under cyclic lateral loads while simultaneously subjected to constant axial loads. The column segments were designed with sufficient shear capacity to prevent shear failure. It is considered appropriate to use current code provisions (KRBD, 2005) on the concrete confinement for the potential plastic hinge regions in the design of precast segmental bridge piers.

The geometric details are shown in Fig. 3 and the mechanical properties of the specimens are listed on Table 1. All column specimens were tested under $0.10 f_c^{'} A_g$ of constant compressive axial load to simulate the gravity load from bridge superstructures. For the specimens subject to cyclic loading, the loading was applied under displacement-control to drift levels of 0.25%, 0.5%, 1.0%, 1.5%, 2.0%, 2.5%, 3.0%, 3.5%, 4.0%, 4.5%, 5%, 5.5%, 6%, 7%, 8%, 9%, and 10%.

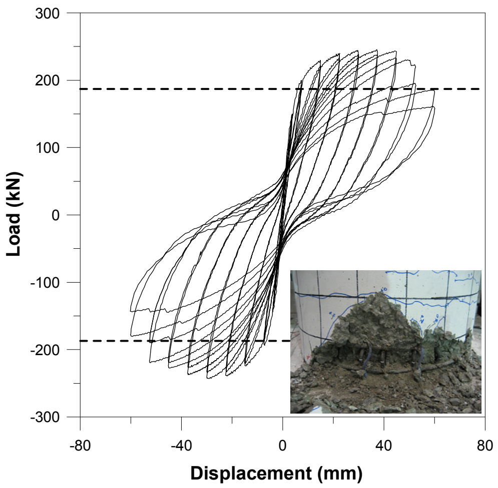


(a) RCAD25
(b) PT30AD25NS
(c) PT30AD25

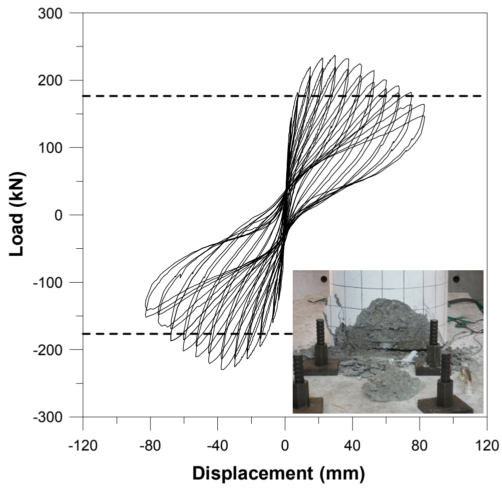
Figure 3 Details of specimens

Table 1 Properties of test specimens

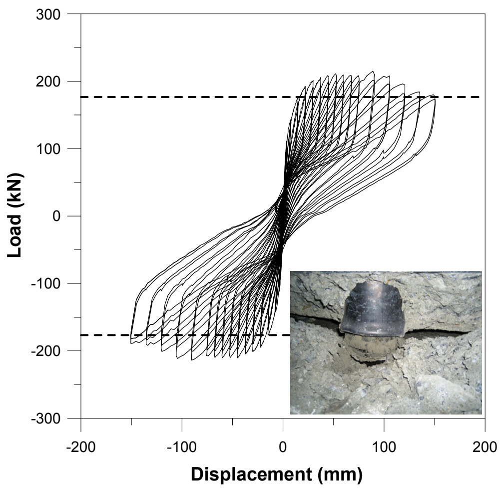
Specimen		RCAD25	PT30AD25NS	PT30AD25
Diameter of cross section (mm)		600		
Effective height (mm)		1500		
Prestressing steel	Material	-	6-F12.7 mm seven-wire strands	
	Yielding stress (MPa)		1600	
	Prestressing force (MPa)		480	
Longitudinal reinforcement	Material	SD40 D10		
	Yielding stress (MPa)	400		
	Reinforcement ratio (%)	0.605	Minimum	
Transverse reinforcement	Material	SD40 D10		
	Yielding stress (MPa)	400		
	Volumetric ratio (%)	0.66		
Shear resistance connecting structure	Material	-		STK490
	Yielding stress (MPa)			315
Strength of concrete (MPa)		24	35	



(a) RCAD25



(b) PT30AD25NS



(c) PT30AD25

Figure 4 Lateral load-displacement relationship for specimens

The lateral load-displacement responses for specimens are shown in Fig. 4. Figure 4 also shows the design shear strength of the columns and the damage pattern of the specimens at failure.

The design shear strengths obtained from the design code (KRBD, 2005) are conservative for column specimens. Damage was concentrated only at the column-footing joint. The recentering characteristic of the precast system is evidenced by the pinched hysteresis loops near the origin. The proposed segmental column specimen exhibited ductile behavior under cyclic loading.

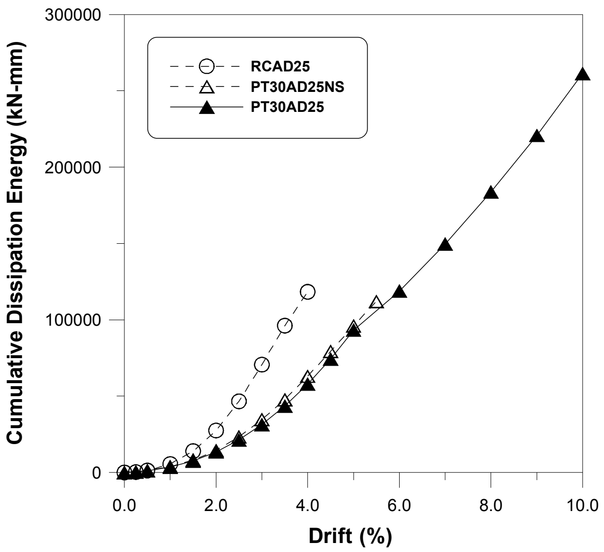


Figure 5 Hysteretic energy dissipation

The hysteretic energy dissipation of the specimens was evaluated based on the cumulative dissipation energy as shown in Fig. 5. It was found that the hysteretic energy dissipation increased as the column drift increased. In addition, the hysteretic energy dissipation increased as the shear resistance connecting structure used.

4. ANALYTICAL STUDY

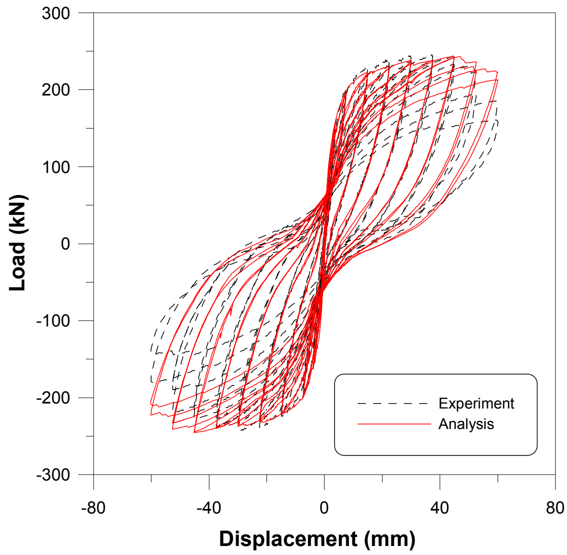
A two-dimensional finite element model for segmental bridge piers with shear resistance connecting structure is developed in this study. The model was created and analyzed using general-purpose finite element software, RCAHEST (Kim et al. 2003; Kim et al. 2006; Kim et al. 2007a; Kim et al. 2007b; Kim et al. 2008). RCAHEST is a nonlinear finite element analysis program for analyzing reinforced concrete structures.

Accompanying the present study, the authors attempt to implement a bonded or unbonded tendon element (Kim et al. 2008) and a newly developed joint element for the segmental joints.

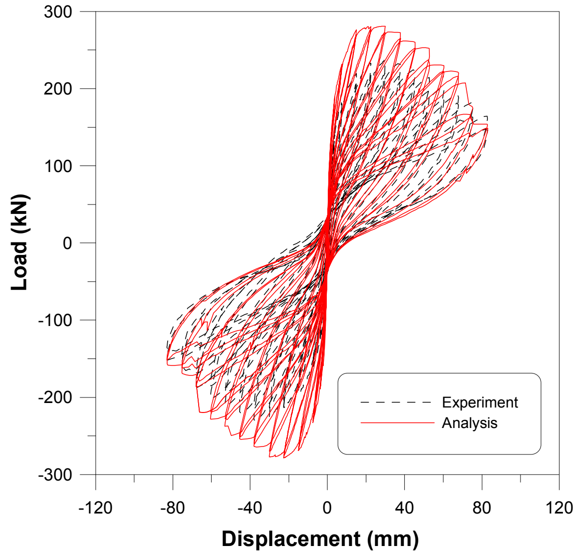
Joints between precast post-tensioned segments require special attention when designing and constructing precast segmental structures. In the joint model, the inelastic behavior of the joint elements is governed by normal and tangential stiffness coefficients. Since the joint element is very small with respect to the surrounding elements, linear elastic stress-strain relations can be used before failure without significantly affecting the behavior of the structure as a whole. After failing in shear it is also assumed that the joint is plastic.

A comparison of the simulated and experimental load-displacement values for the specimens is shown in Fig. 6. In general, the analytical model presented herein correlated reasonably well with the experimentally observed behavior of the columns for each test. In some cases, the predicted strength was higher than the actual column strength.

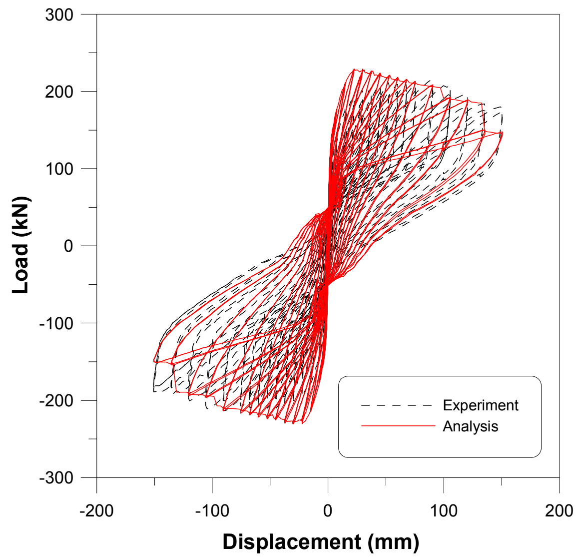
The joints between precast segments nearest to the foundation were found to have cracked and opened, as was expected due to the absence of continuous bonded reinforcement across them. In the simulation, the interface elements representing these joints had also cracked and opened.



(a) RCAD25



(b) PT30AD25NS



(c) PT30AD25

Figure 6 Comparison of results from the experimental results

5. CONCLUSIONS

This study investigated the use of precast segmental post-tensioned concrete bridge piers with shear resistance connecting structures in moderate seismic regions. The segmental column system under investigation in this study is designed with the goal of achieving some energy dissipation and ensuring ductility in a bonded system while maintaining the advantage of small residual deformations.

The proposed segmental bridge piers are capable of undergoing large nonlinear displacements without experiencing significant or sudden loss of strength. Residual displacements after the seismic event should be minimal, and the damage incurred low. Only minor repair work would be required after the earthquake, thus reducing costs and limiting the amount of disruption of normal use of the bridge structure.

Considerable testing is yet required before this pier system should be implemented into design practice. Regarding implementation of full-scale structures, investigation of alternative construction details, performance under seismic rather than quasi-static lateral loading and development of design procedures and guidelines also remain ahead. Completion of this work could generate substantial economical benefits for bridge construction in moderate seismic zones.

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