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A COMPUTATIONAL PLATFORM FOR SEISMIC PERFORMANCE ASSESSMENT OF PRECAST CONCRETE SEGMENTAL BRIDGE COLUMNS WITH SHEAR RESISTANCE CONNECTING STRUCTURE

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ABSTRACT

This paper presents a nonlinear finite element analysis procedure for the seismic performance of precast concrete segmental bridge columns with shear resistance connecting structure. A computer program, RCAHEST (Reinforced Concrete Analysis in Higher Evaluation System Technology), for the analysis of reinforced concrete structures was used. 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 modified in order to predict the inelastic behaviors of segmental joints with shear resistance connecting structure. The proposed numerical method for the seismic performance assessment of precast concrete segmental bridge columns with shear resistance connecting structure is verified by comparison of its results with reliable experimental results.

Introduction

The use of precast segmental construction for concrete bridges has increased in recent years due to the demand for shorter construction periods and the desire for innovative designs that yield safe, economical and efficient structures (Billington et al. 2001). However, there is a lack of knowledge of the behavior and performance of precast segmental bridges during earthquakes, and consequently their widespread use in seismic regions is yet to be realized (Hewes 2002; Chou and Chen 2006; Wang et al. 2008).

In that precast concrete segmental bridge column, most of large structural deformations are not due to plastic deformation within a hinge region, but are rather caused by the rigid rotation of the entire column about its base. Hysteretic energy dissipation of the precast system is small relative to that of a conventional reinforced concrete column.

This paper will present simulations performed on large-scale experiments on precast concrete segmental bridge columns. An evaluation method for the performance of precast

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concrete segmental bridge columns with shear resistance connecting structure is proposed. The proposed method, uses a nonlinear finite element analysis program (RCAHEST, Reinforced Concrete Analysis in Higher Evaluation System Technology), developed by the authors (Kim et al. 2003; Kim et al. 2007b; Kim et al. 2008). A modified joint element is incorporated into the structural element library for RCAHEST so that it can be used to predict the inelastic behaviors of segmental joints with a shear resistance connecting structure.

Precast concrete segmental bridge columns with shear resistance connecting structure

Figure 1 shows the design concept of the proposed segmental bridge columns with shear resistance connecting structure. A segmentally precast concrete bridge columns 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. They also play an important role in its performance in terms of hysteretic energy dissipation and ductility.

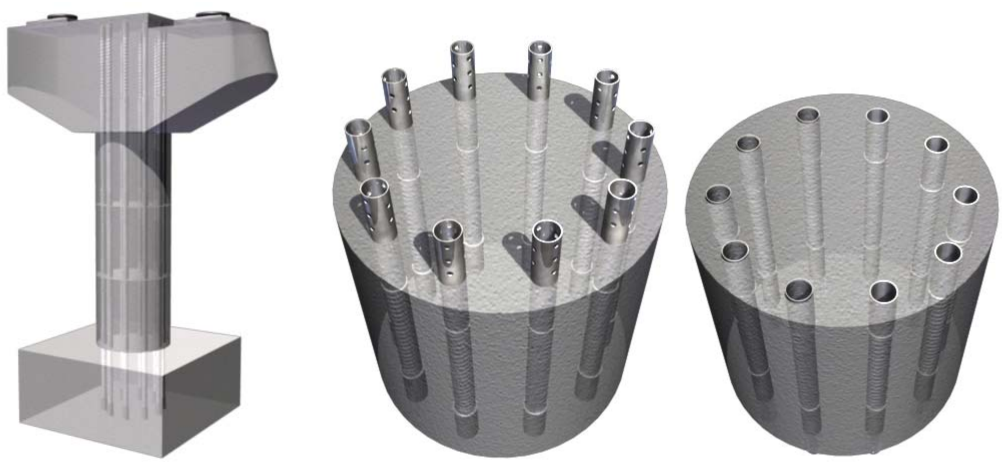


Figure 1. Proposed segmental bridge columns with shear resistance connecting structure

Only the prestressing bonded tendons are continuous across the segment joints. The column is able to return back to its original position after lateral drift. This has become an increasingly favorable characteristic over time in the earthquake research community, since the 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 a shear resistance connecting structure across precast joints to exhibit hysteretic behavior with satisfactory hysteretic energy dissipation and small residual displacement upon unloading.

Experimental Program

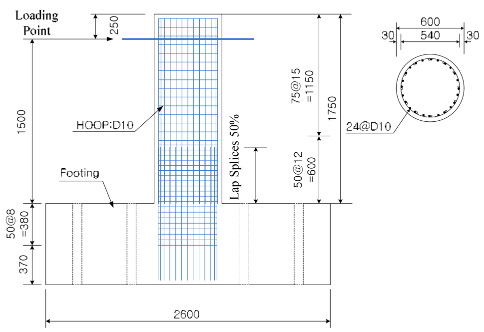
Five column specimens were tested under cyclic lateral loads while being simultaneously subjected to constant axial loads. The concrete segments and segment joints were designed with sufficient shear capacity to prevent shear failure.

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 columns for use in moderate seismic regions.

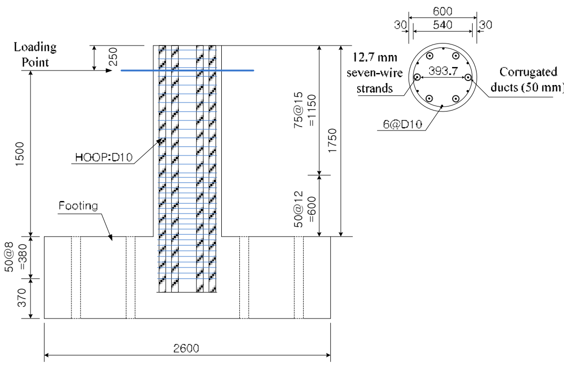
Three segmental column specimens were designed for testing under lateral loading, designated as PT10AD25, PT30AD25, and PT50AD25. The prestressing force varies from $0.1f_{py}$ to $0.5f_{py}$. In addition, two column specimens were designed for conventional columns under lateral loading, designated as RCAD25, PT30AD25NS. The mechanical properties of the specimens are listed on Table 1 and the geometric details are shown in Fig. 2. All column specimens were tested under a $0.10f_c^{'}A_g$ 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%. Each cycle was repeated twice to allow for the observation of strength degradation under repeated loading with the same amplitude.

Table 1. Properties of test specimens

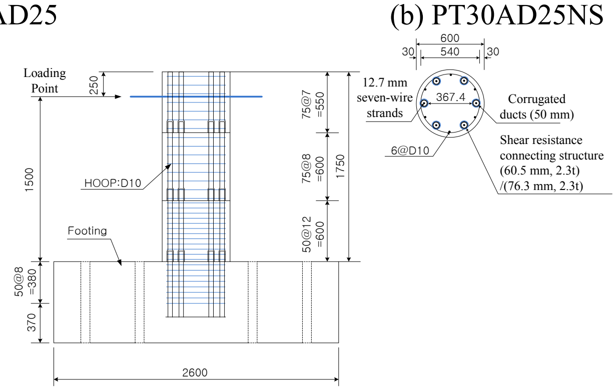
Specimen		**RC AD25**	**PT30 AD25NS**	**PT10 AD25**	**PT30 AD25**	**PT50 AD25**
Diameter of cross section (mm)		600				
Effective height (mm)		1500				
Prestressing steel	Material	-	6-Φ 12.7 mm Seven-wire strands			6-Φ 15.2 mm Seven-wire strands
	Yielding stress (MPa)	-	1600			1600
	Prestressing Force (MPa)	-	480	160	480	800
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	-	-	SKT490 (60.5/76.3 mm)		
	Yielding stress (MPa)	-	-	315		
Strength of concrete (MPa)		24	35			



(a) RCAD25



(b) PT30AD25NS



(c) PT10AD25, PT30AD25, PT50AD25

Figure 2. Details of specimens

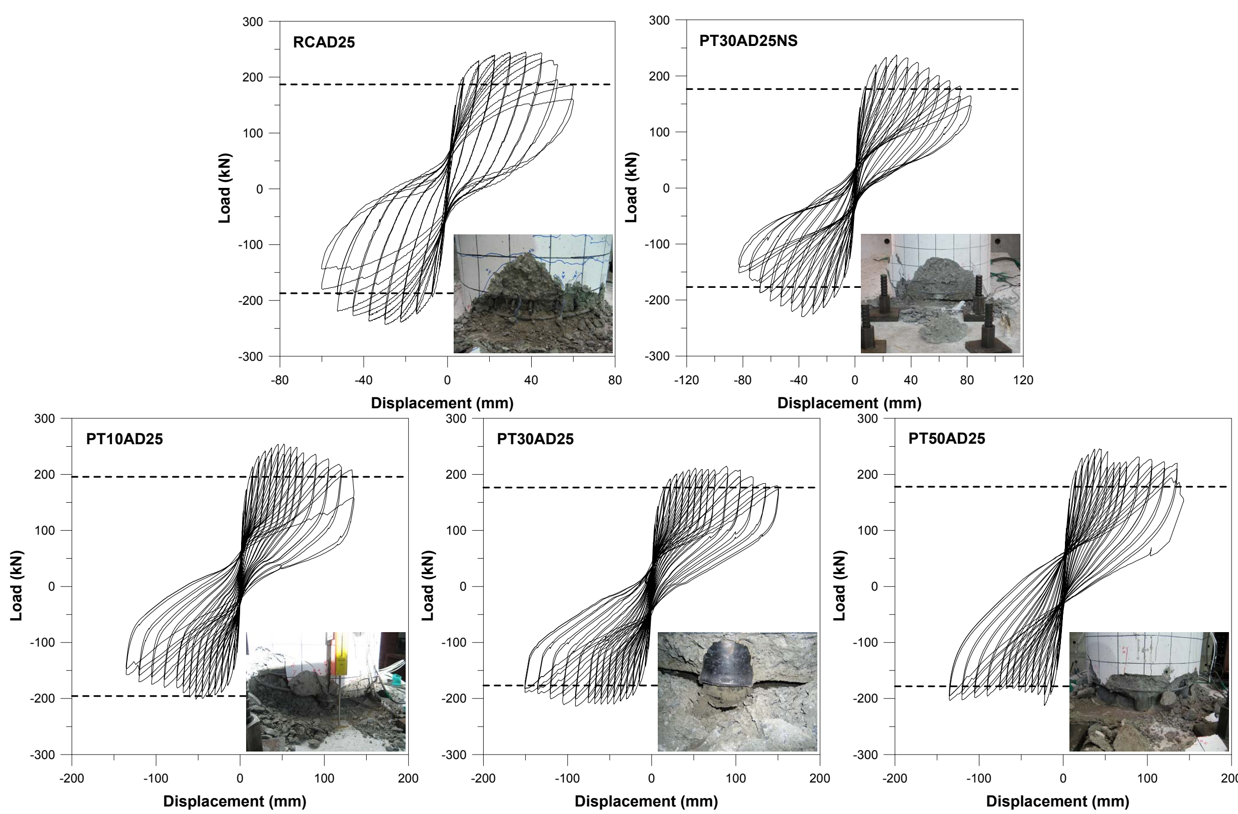


Figure 3. Lateral load-displacement relationship for specimens

The lateral load-displacement responses for specimens are shown in Fig. 3. Figure 3 also show 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 five column specimens (RCAD25, PT30AD25NS, PT10AD25, PT30AD25, and PT50AD25). Damage was concentrated only at the column-footing joint.

The re-centering characteristic of the precast system is evidenced by the pinched hysteresis loops near the origin. The re-centering behavior was due to the horizontal component of the prestressing force, which acts on the column as it deflects laterally. The proposed segmental column specimen exhibited ductile behavior under cyclic loading.

Analytical Study

A two-dimensional finite element model for segmental bridge columns 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. 2007b; Kim et al. 2008). RCAHEST is a nonlinear finite element analysis program used for analyzing reinforced concrete structures.

The elements developed for the nonlinear finite element analyses of reinforced concrete bridge columns are a reinforced concrete plane stress element and an interface element. Accompanying the present study, the authors attempted to implement a bonded tendon element (Kim et al. 2008) and a modified joint element (Kim et al. 2007a) for the segmental joints.

Nonlinear Material Model

The nonlinear material model for the prestressed concrete comprises models for concrete and models for the reinforcing bars and tendons. Models for concrete may be divided into models for uncracked concrete and for cracked concrete. For cracked concrete, three models describe the behavior of concrete in the direction normal to the crack plane, in the direction of the crack plane, and in the shear direction at the crack plane, respectively. The basic model adopted for crack representation is the non-orthogonal fixed crack approach of the smeared crack concept, which is widely known to be a robust model for crack representation.

The transverse reinforcements confine the compressed concrete in the core region and inhibit the buckling of the longitudinal reinforcing bars. In addition, the reinforcements also improve the ductility capacity of the unconfined concrete. This study adopted the model proposed by Mander et al. (1988) for normal strength concrete of below 30 MPa and adopted the model proposed by Sun and Sakino (2000) for high strength concrete of above 40 MPa. An analytical model was proposed for confined intermediate strength concrete from 30 MPa to 40 MPa. The model incorporates all relevant parameters of confinement with a smooth transition from 30 MPa to 40 MPa (Kim et al. 2008).

For prestressing tendons that do not have a definite yield point, a multilinear approximation may be required. High strength steel used for prestressing shows a rather large proportional behavior followed by a progressive yielding. A trilinear model has been used for the stress-strain relationship of the prestressing tendon (Kim et al. 2008).

Joints between precast post-tensioned segments require special attention when designing and constructing precast segmental structures. These joints must transmit the large compressive, shear and sometimes tensile stresses that may develop in the joint locations. In the joint model, the inelastic behavior of the joint elements is governed by normal and tangential stiffness coefficients. A material law is formulated which models the experimentally obtained data for adhesive joints in concrete. Since the joint element is very small with respect to the surrounding elements, linear elastic stress-strain relationships 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. Experimental evidence indicates that the failure of this material can be described by a Coulomb type relationship (Kim et al. 2007a).

Finite Element Model

Figure 4 shows the finite element discretization and the boundary conditions for two-dimensional plane stress nonlinear analyses of the column specimen. The figure also shows a method for transforming a circular section into rectangular strips when using plane stress elements. For rectangular sections, equivalent strips are calculated. After the internal forces are calculated, the equilibrium is checked.

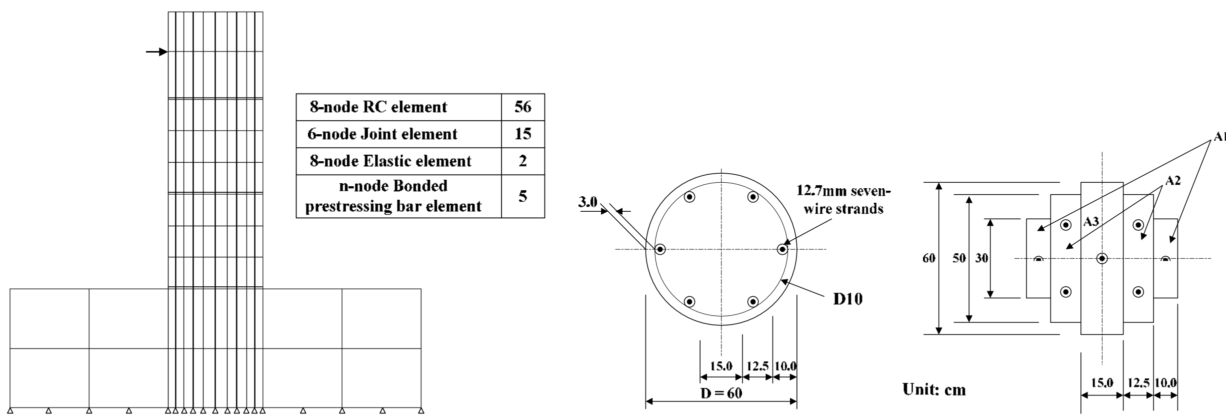


Figure 4. Finite element mesh for segmental specimens (PT10AD25, PT30AD25, PT50AD25)

Comparison with Experimental Results

A comparison of the simulated and experimental load-displacement values for the specimens is shown in Fig. 5. The value given by all specimens was similar to the analytical results; comparative data is summarized in Table 2. In predicting the results of the specimens under a variety of prestressing forces, the mean ratios of experimental-to-analytical maximum strength were 0.96 at a COV of 11%.

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 difference between the analytical and experimental force-displacement response at moderate to high drift levels is less than 10%. In light of this, and of the uncertainty in the initial prestress force and the fact that the column had been tested previously, it can be said that the analytical prediction concurs well with the experimental behavior.

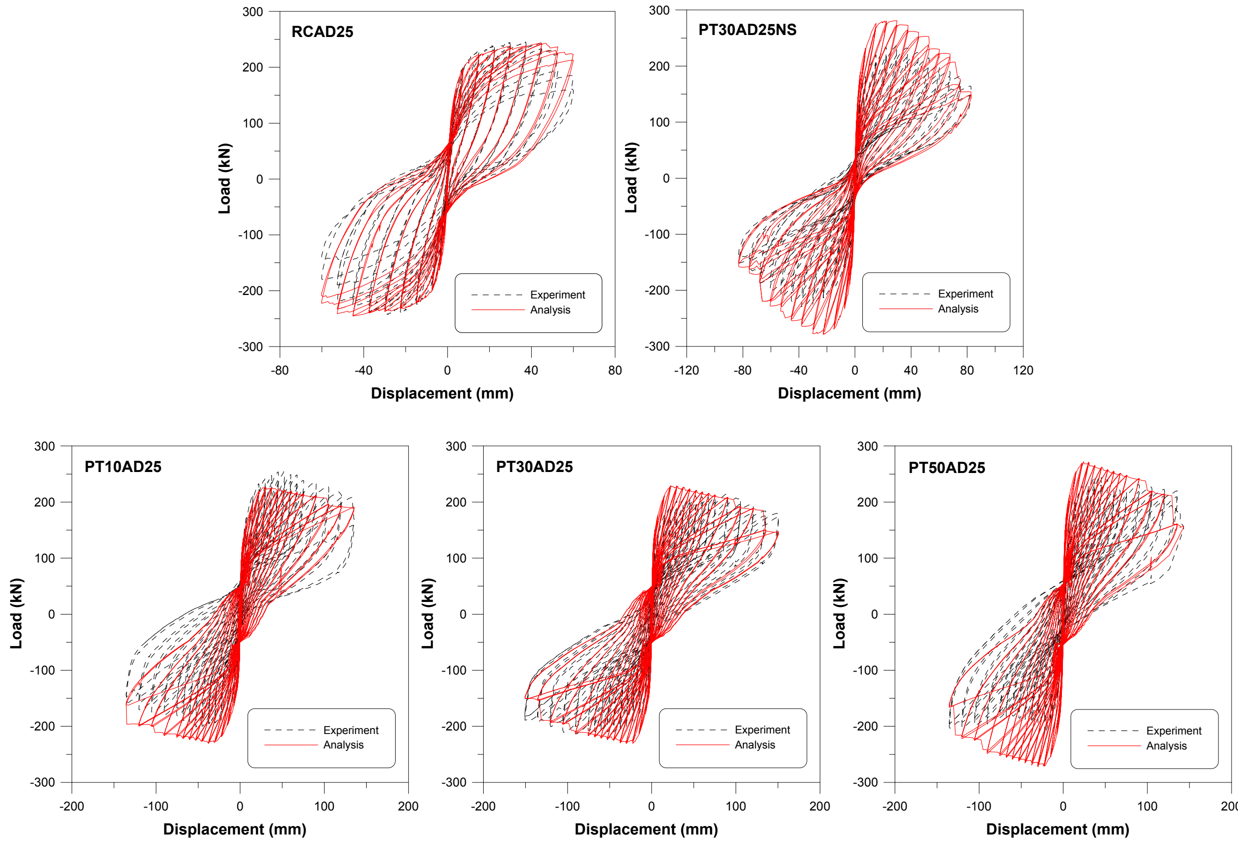


Figure 5. Comparison of results from the experimental results

Table 2. Experiment and analysis results

Specimen	Experiment		Analysis		Ratio of Experimental and Analytical Results	
	V_{max} (kN)	μ	V_{max} (kN)	μ	V_{max}	μ
RCAD25	245.3	6.8	243.2	8.0	1.01	0.85
PT30AD25NS	237.6	5.6	280.9	7.2	0.85	0.78
PT10AD25	254.6	7.3	226.8	9.0	1.12	0.81
PT30AD25	214.9	8.3	229.1	9.9	0.94	0.84
PT50AD25	245.8	8.0	272.1	9.4	0.90	0.85
Total			Mean		0.96	0.83
			COV		0.11	0.04

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

Conclusions

This study investigated the use of precast segmental post-tensioned concrete bridge columns 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 a degree of energy dissipation and ensuring ductility in a bonded system while maintaining the advantage of small residual deformations.

An experimental and analytical study was conducted to quantify performance measures and examine one aspect of detailing for a developed system. The concurrence between the analytical and experimental force-displacement response curves was generally sound.

Future work by the authors will include the formulation of a constitutive model for time-dependent effects such as concrete creep, shrinkage and relaxation of prestressing tendons. Also, parametric studies will be conducted in order to investigate the effects of prestressing the steel area and initial stress and the level of confinement at the column base, on the force-displacement response of the columns.

References

Billington, S. L., Barnes, R. W., and Breen, J. E., 2001. Alternative substructure systems for standard highway bridges, *Journal of Bridge Engineering ASCE* 6(2), 87-94.

Chou, C.-C., and Chen, Y.-C., 2006. Cyclic tests of post-tensioned precast CFT segmental bridge columns with unbonded strands, *Earthquake Engineering and Structural Dynamics* 35, 159-175.

Hewes, J. T., 2002. Seismic design and performance of precast concrete segmental bridge columns, *Ph.D. Dissertation*, Department of Structural Engineering, University of California at San Diego.

Kim, T.-H., Kim, Y.-J., Jin, B.-M., and Shin, H. M., 2007a, Numerical study on the joints between precast post-tensioned segments, *International Journal of Concrete Structures and Materials*19(1E), 3-9.

Kim, T.-H., Kim, Y.-J., Kang, H.-T., and Shin, H. M., 2007b. Performance assessment of reinforced concrete bridge columns using a damage index, *Canadian Journal of Civil Engineering* 34(7), 843-855.

Kim, T.-H., Lee, K.-M., Yoon, C.-Y., and Shin, H. M., 2003. Inelastic behavior and ductility capacity of reinforced concrete bridge piers under earthquake. Ⅰ : theory and formulation. *Journal of Structural Engineering ASCE* 129(9), 1199-1207.

Kim, T.-H., Park, J.-G., Kim, Y.-J., and Shin, H. M., 2008. A computational platform for seismic performance assessment of reinforced concrete bridge piers with unbonded reinforcing or prestressing bars, *Computers and Concrete* 5(2),135-154.

Mander, J. B., Priestley, M. J. N., and Park, R., 1988. Theoretical stress-strain model for confined concrete, *Journal of Structural Engineering ASCE* 114(8), 1804-1826.

Ministry of Construction and Transportation, 2005. *Korea roadway bridge design code*.

Sun, Y. P., and Sakino, K., 2000. A comprehensive stress-strain model for high strength concrete confined by circular transverse reinforcement, The 6th ASCCS International Conference on Steel-Concrete Composite Structures, University of Southern California, 1067-1074.

Wang, J.-C., Ou, Y.-C., Chang, K.-C., and Lee, G.-C., 2008. Large-scale seismic tests of tall concrete bridge columns with precast segmental construction, *Earthquake Engineering and Structural Dynamics* 37, 1449-1465.