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# Cyclic Tests on Prefabricated Bridge Piers

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## ABSTRACT

Prefabricated bridge substructures provide new possibility for designers in terms of creativity, fast construction, geometry control and cost. In this paper, experimental research works are presented to verify enhanced design concepts of prefabricated bridge piers. Integration of precast segments was done by axial prestressing tendons and mild reinforcing bars. Cyclic tests were conducted to investigate the effects of the design parameters on seismic performance. Based on the test results, design recommendations were suggested.

## 1. INTRODUCTION

Construction industry requires more innovative design and construction technologies to improve current practices. Prefabrication of structures has recently attracted much attention from bridge engineers. Prefabrication of bridge substructures is essential for accelerated bridge construction. Precast segmental columns may have bonded or unbonded posttensioning systems according to their required structural performance. These applications still lack of knowledge of seismic design parameters according to the required performance.

Currently, many research works on precast columns has constantly been accomplished in experiments and analysis. Billington *et al*. (2001) improved the alternative substructure system by using precast system. They found that prefabricated application increased the substructure durability. Experiment of small-scale experiment precast columns was conducted (Billington and Yoon 2004). Hysteretic energy dissipation of precast columns was improved until exceeding 3% to 6% of drift ratio. Hewes *et al.* (2002) completed the experiment on the performance of unbonded post-tensioned precast concrete segmental bridge columns under lateral earthquake loading. The precast columns withstood without significant or sudden loss of strength up to 4.0% drift ratio. Chiewanichakorn and Aref (2006) implemented the finite element simulation of seismic response of the precast concrete segmental columns. The analysis schemes were developed considering the interface between segments with opening-closing under cyclic loading. FEM analysis was able to capture the actual behavior of this new structural system. Ou *et al.* (2007) has done the experiment and pushover analysis on

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segmental precast unbonded posttensioned bridge columns with a hollow cross section. They found that the enhancement of column hysteretic energy dissipation was improved. Shim *et al.* (2008) conducted the experiment on six precast piers to evaluate on seismic performance of precast segmental bridge piers with a circular solid section. By increasing the steel ratio, the plastic deformation and its energy absorption capacity increased after exceeding its maximum strength. Shim *et al.* (2011) accomplished the extensive tests to observe the cyclic behavior of prefabricated circular composite columns with low steel ratio. Higher prestressing gave greater flexural strength to the composite columns with prestressing and better energy absorption capacity. A prefabricated composite column with embedded circular tubes showed ultimate reflected the increasing Ultimate strength and energy absorption capacity (Shim *et al.* 2012). Nikbakht *et al.* (2014) implemented a numerical study on seismic response of self-centering precast segmental columns at the difference of posttensioning forces. The higher initial prestressing strand levels reflected greater initial stiffness and strength, but show a higher stiffness reduction at large drifts.

In this paper, an experimental program was conducted to investigate seismic performance of precast segmental bridge columns with combination of bonded tendons and continuous mild reinforcements crossing precast joints. Geometry of the precast joints was enhanced. Essential design parameters for seismic behavior of the precast columns were discussed based on the cyclic tests.

## 2. EXPERIMENTAL PROGRAM

### *2.1. Test Specimens*

A laboratory testing program was conducted to assess the static and seismic performance of the proposed prefabricated bridge pier system under cyclic loading. To prove the effect of parametric design, five prefabricated bridge pier specimens were tested, as shown in Fig. 1. The design specimens consisted of two segments with 800 mm diameter circular sections. The footing segment was fixed to the strong floor. The effective length from the loading point to plastic hinge point is 2750 mm. Aspect ratio of the column was 3.44, which leads to flexural failure.

Fig. 2 shows the fabrication procedure of the precast pier system. The fabrication contains three segments for the precast pier specimen. A concrete footing segment had details of the tendon anchorages at side surfaces, and geometry control of the location of the ducts and longitudinal reinforcing bars was crucial for assembly as shown in Fig. 2. In order to assure accurate geometry control, 3D models for the precast segments and formworks were developed. The mild reinforcing steel bar was connected with coupler, and the design jacking force was introduced by prestressing at the anchorage of the footing. Axial prestressing was introduced sequentially with symmetric order. The measurement of initial prestressing was performed by pressure gauge of a hydraulic jack and elongation of the tendon.

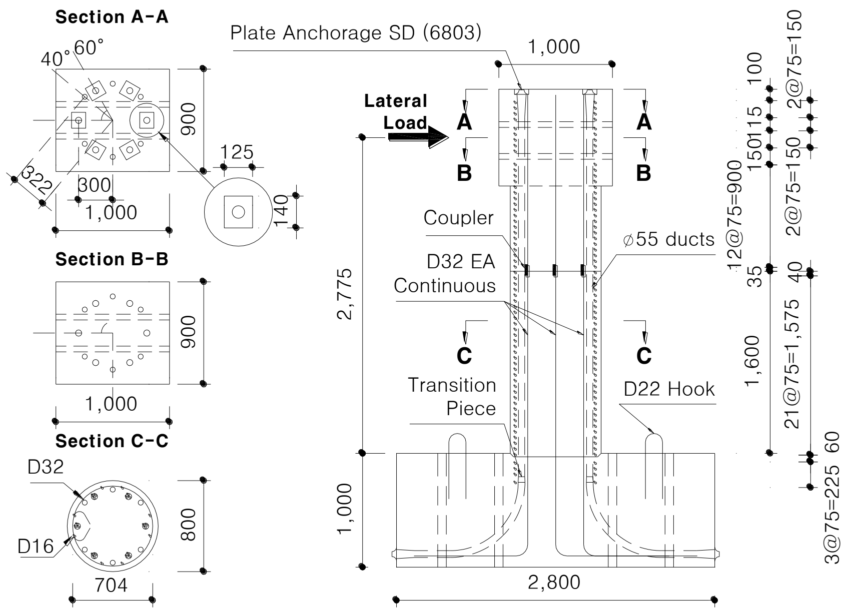


Fig. 1 Typical detail arrangement of precast bridge pier

(a) Reinforcing Detailing (b) Segments (c) Pier Assemblage

Fig. 2 Prefabrication Procedures of precast column

The axial steel in each pier specimen consisted of six bonded prestressing tendons and mild reinforcing bars. The prestressing tendons were arranged with 15.2 mm diameter ASTM S779 Grade270 (1860 MPa) and 2496.6 mm$^2$ of the total nominal sectional area. Mild reinforcing bars of 32 mm diameter with 400 MPa yield strength were used as continuous longitudinal reinforcement except T75PT1B specimen. The overall steel ratio of the longitudinal steel was 1.45%, including both prestressing and non prestressing steel for four specimens, and 0.5% for the test specimen (T75PT1B) without continuous mild steel. For confinement control, the circular hoop transverse reinforcement was uniformly distributed with 16 mm diameter at 75 mm spacing for four specimens and 50 mm for T50PT1A specimen.

### 2.1. Test Setup

The precast piers were installed as a cantilever structural system as shown Fig. 3. The footing was tightly attached to strong floor. Quasi static tests were conducted to evaluate the cyclic response of the precast bridge piers. The test setup was designed to test column-footing assemblage subjected to a combination of an axial load and a cyclically applied lateral load.

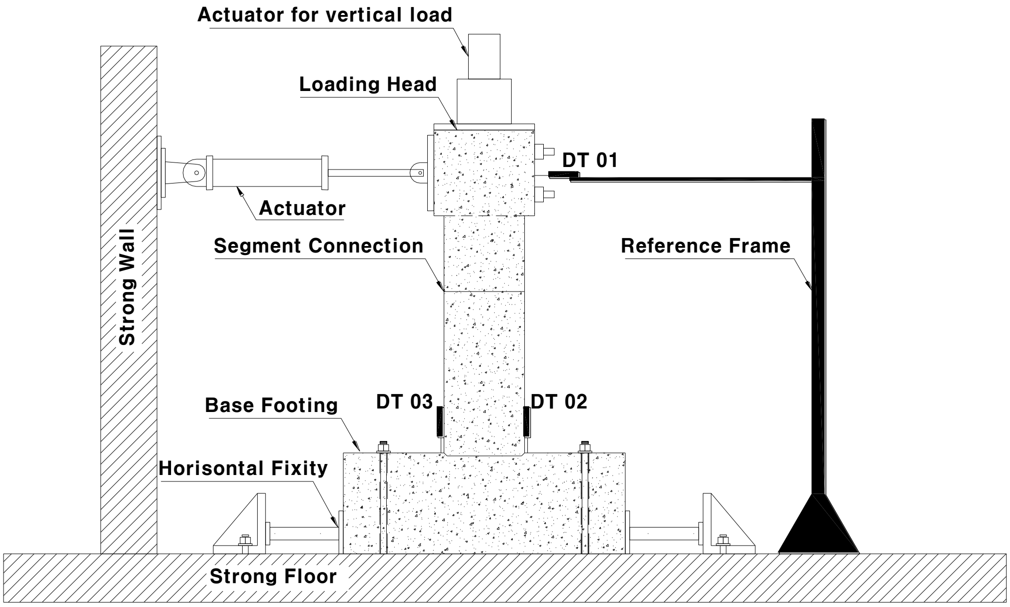


Fig. 3 Schematic general arrangement of experimental setup

A set of repeated lateral force was simultaneously applied to the column by the hydraulic actuator mounted on the strong reaction wall. By using displacement control, cyclic load tests were conducted. The magnitude of each was subsequently increased to 0.5%, 1.0%, 2.0%, 2.5%, 3.0%, 4.0%, etc., until failure. The drift level was calculated as the ratio of input displacement to column height. The maximum stroke of the actuator was $\pm$250 mm, and each displacement was applied twice.

## 3. EFFECTS OF PRESTRESSING LEVEL

There is a risk to have cracks or partial crushing of concrete during prestressing process if there is misaligned geometry of segments. Perfect match of the segment joints is essential for appropriate assembly. In this test, detailed observation of fabrication problems was conducted but there was no premature failure of columns during pretressing or tests.

Due to the limitation of actuator's strokes, all the specimens were loaded up to drift ratio of 8%. The prestressing tendon had important function to strengthen the precast column, prevent the joint opening, and restore the column stiffness in reverse loading. The increase of the initial prestressing force resulted in earlier yielding of the tendons by the applied lateral displacement. As shown in Fig. 4, effective prestress by the introduced prestressing forces for T75PT1A, T75PT2A, and T75PT2A were 1270 MPa, 918 MPa, and 711 MPa, respectively. T75PT1 specimen showed high flexural strength, but earlier spalling out at reverse loading stage because of the high compressive due to the prestressing force. T75PT2A induced the high flexural strength with stable load-displacement behavior. Fig. 6 shows reduction of secant stiffness of the precast columns. The secant stiffness of the column system was obtained by measuring maximum load and its displacement at each drift level.

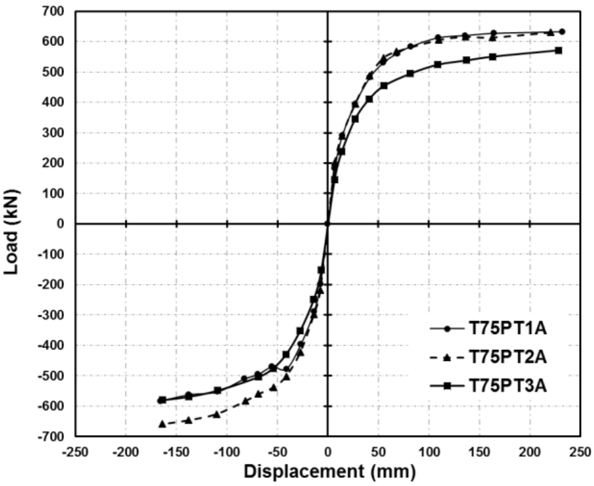


Fig. 4 Prestressing level effect on envelope curves

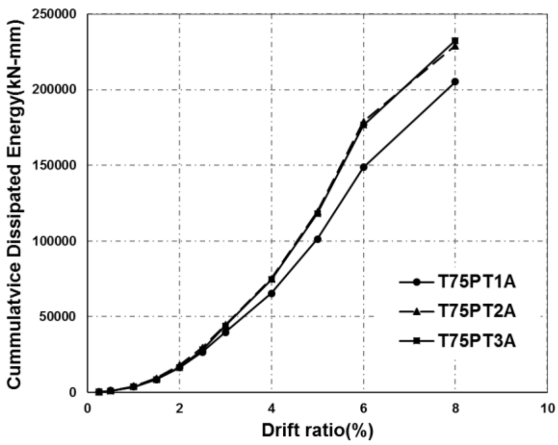


Fig. 5 Prestressing effect on energy absorption capacity

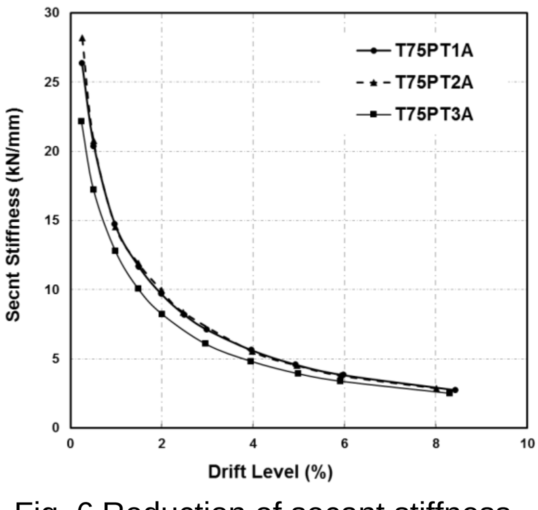


Fig. 6 Reduction of secant stiffness

## 4. EFFECTS OF CONFINEMENT

The prefabricated pier with lower confining reinforcement showed the worst seismic behavior in the previous research (Shim *et al.* 2008). By increase amount of transversal reinforcement from 50 mm spacing to 75mm spacing, the precast pier showed negligible effect on ultimate flexural strength as shown Fig. 7. The seismic performance can be illustrated using ductility and energy absorption capacity according to individual load cycle. Displacement ductility of precast columns was greater than 3.7 when the applied maximum displacement was used for the calculation. In the range of spacing of the transverse reinforcement, there was no significant difference in the displacement ductility. In Fig. 8, the comparison of accumulative energy dissipation showed the similar values before reaching drift ration of 4%. After cracking and crushing of concrete, less confined columns showed 9.5% higher energy dissipation capacity. At the lateral displacement of 1.0% drift ratio, the flexural stiffness of T75PT1A and T50PT1A was reduced to around 55% and 45%, respectively.

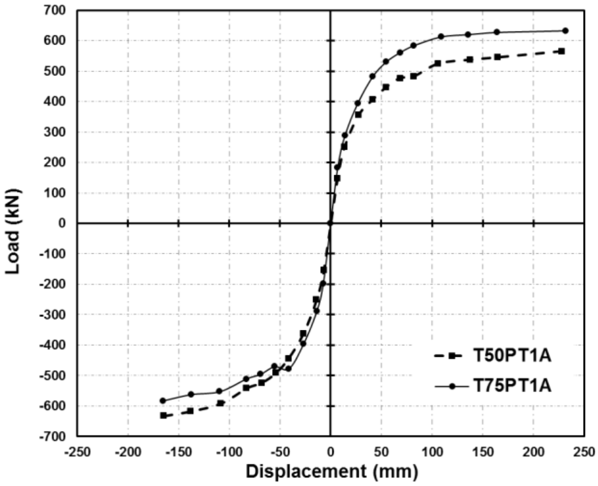


Fig. 7 Confining effect on envelope curves

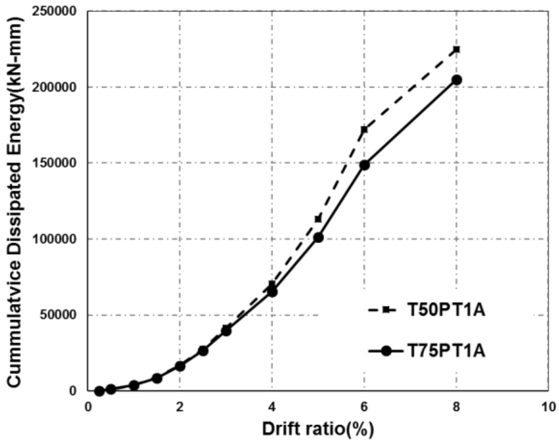


Fig. 8 confining effect on energy absorption capacity

## 5. ANALYSIS RESULTS

In this paper, the finite element analysis was conducted to simulate behavior of the precast column to validate the experimental result. T75PT1A, one of the 5 specimens, was selected. In the nonlinear analysis, the mechanical behavior of materials, contact criteria, analytical technique should be well-considered and realistic. Concrete damage plasticity model was utilized for concrete. Prestressing tendons and mild reinforcing bars were modelled as bilinear stress-strain curves. Surface-to-surface contact condition by allowing the open-closed at joint were selected in this simulation. The pier system was modeled with 8-node, reduced integrated, 3D linear continuum brick elements to represent the concrete element for both circular section and base footing. Non-uniform mesh sizes were created approximately 75 mm at plastic hinge zone and 200 mm at other sections as shown in Fig. 9. Proposed mesh type and size of the prestressing tendon and reinforcement was a two-node first-order 3D truss element with 100 mm approximated mesh size.

As shown in Fig. 10, a load-displacement curve from the analysis showed good agreement with test results. According to the effective prestress and location of the tendons, yielding and fracture strain of the tendon was different. In order to fully utilize material capacity of each component of the axial steels, it is important to decide proper level of prestress according to target drift level of the columns under seismic actions.

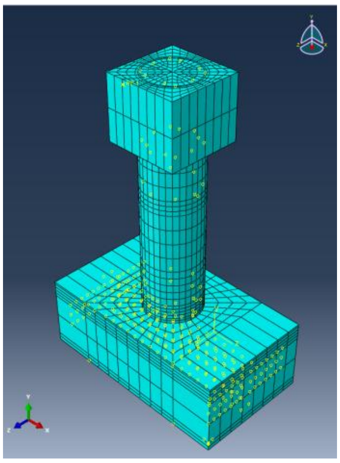

Fig. 9 FE model of a precast column

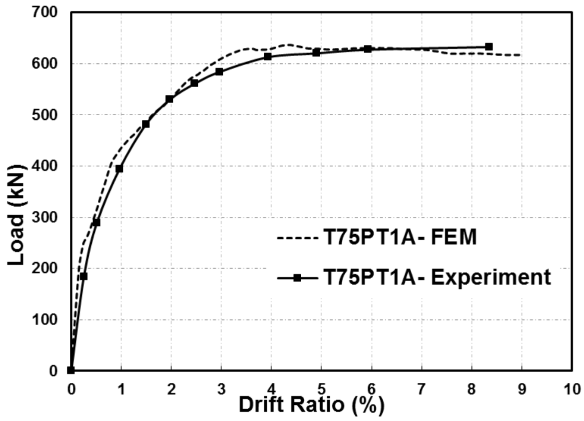


Fig. 10 Analysis results

## 6. CONCLUSIONS

The major findings of the experiments on precast segmental bridge columns discussed in this paper are:

1) Geometry control of precast segments is essential to assure structural performance of precast concrete bridge columns.
2) Enhanced details of the precast concrete columns improved structural performance up to drift level of 8.0% without strength reduction. Re-centering capability of the prestressed concrete columns was observed at low drift ratio.
3) Effective prestress and location of axial steels should be designed to have optimal plastic behavior at target lateral deformation of the column.
4) In the range of test parameter of transverse reinforcement, there was no significant difference in strength and displacement ductility of the precast columns.
5) Nonlinear analysis of the precast columns showed good agreement with test results and it can be used for further studies.

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