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# CYCLIC BEHAVIOR OF POST-EARTHQUAKE REPAIRED POST_TENSIONED PERCAST COLUMNS WITH HPFRCC

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## *Abstract*

Post-tensioned precast concrete columns are known to have re-centering capability for seismic actions. This paper presents cyclic behavior of repaired precast concrete columns which experienced lateral movement up to drift level of 8%. The damage by the lateral load was repaired by removing cover concrete and thickening by high performance fiber reinforced cementitious composite. Strengthening part had additional details of chemical anchors into the foundation. Additionally provided transverse reinforcing bars in the thickened concrete showed significant effect on failure mode. When the post-tensioned precast columns do not have tendon fracture by lateral load, the proposed strengthening method enhanced structural performance in terms of maximum strength, deformation capacity and energy dissipation capacity. The repaired columns showed more than 30% increase of flexural strength and 1.45 times higher cumulative energy dissipation capacity than the original precast columns. Design recommendations are summarized using the experimental results.

*Keywords: post-tension, precast concrete column, high performance fiber reinforced cementitious composite, cyclic behavior, repair*

## 1. Introduction

Prefabricated bridge substructures are increasingly adopted for accelerated bridge construction in the congested area. Precast prestressed concrete columns are commonly used for the rapid construction. In low seismicity zone, prefabricated concrete components and system have widely adopted since 1970s [1]. For application of posttensioning system in prefabricated bridge piers, the interaction between tendons and surrounding concrete can be either bonded or unbonded. There were experimental programs and analytical studies to investigate structural performance of the precast columns, especially in terms of seismic behavior.

Hews and Priestley has conducted experimental and analytical studies on precast concrete segmental bridge columns with high and low aspect ratio [2]. The proposed analytical model was used to predict column response and the bridge columns had an unbonded posttensioned system. Billington *et al*. proposed unbonded posttensioned precast columns with ductile fiber-reinforced concrete [3]. The system did not require continuous non-prestressing steel at precast joints to minimize labor and time. The unbonded precast columns showed nonlinear elastic response and lower hysteretic energy dissipation capacity comparing to bonded posttensioned system. Bu et al. had conducted cyclic loading tests on unbonded and bonded posttensioned segmental bridge piers with ED bars [4]. Bonded posttensioning bars were adopted for prefabricated bridge columns and experimental evaluation was performed [5]. The prestressing bars were connected by mechanical couplers. Total axial compressive forces by deadweight of bridge superstructures and the axial prestressing significantly influenced on seismic behavior. In order to minimize the use of prestressing steel in precast concrete segmental bridge piers, continuous mild reinforcing bars were used [6]. Combination of prestressing and non-prestressing steels and their location in a column section significantly improved displacement ductility of the columns. From this experiments, strengthening of earthquake-damaged precast prestressed columns was started to be considered. Self-centering capability of posttensioned columns is one of the most important aspect because it provides restoring force to bridge columns to minimize residual displacements. Replacing the entire damaged bridge by earthquake is time consuming and expensive. Post-earthquake damage repair of reinforced concrete bridge components was investigated by Saini and Saiiddi [7]. Repair methods depends on the severity of earthquake damage. There are epoxy injection into cracks, patching of spalled zones, jacketing using FRP, RC and steel. For RC jacketing method, anchoring of the added longitudinal reinforcement and added stirrups with half of the spacing of the original transverse reinforcement is recommended [8]. The RC jacketing method leads to a uniformly distributed increase in strength and stiffness of columns. Experimental studies were conducted to verify the effectiveness of steel cage battens within potential plastic hinge regions [9]. Due to the external confinement, the strengthening method showed excellent behavior in terms of flexural strength, stiffness and ductility. However, there is no experimental studies on strengthening method for earthquake-damaged posttensioned segmental bridge columns.

In this paper, fiber-reinforced concrete jacketing method was proposed to repair severely damaged posttensioned precast columns up to drift level of 8%. After cyclic tests on precast columns, damaged parts of cover concrete and joints were repaired. Additional details of longitudinal bars and transverse confinement were added. Seismic behavior of the repaired columns were investigated by cyclic tests.

## 2. Repair and strengthening of damaged concrete columns

### 2.1 Experiments on posttensioned concrete segmental columns

Design of segmental concrete bridge piers using full-prestressing concept may result in too large compression force to the column. In common practices, the applied compression force by deadweight of bridge superstructure is around 10% of column's compressive strength. For serviceability limit state of the precast joint, tensile stress by lateral forces from service loads should be controlled by the posttensioning. When continuous longitudinal mild reinforcements are used crossing the precast joints, it can be more effective to control cracking of the joints and to provide safety during assembly process of the segments.

Common failure modes of reinforced concrete columns by lateral force are crushing of cover concrete, buckling and fracture of main reinforcing bars at plastic hinge region. When flexible prestressing tendons are located at extreme fiber of the column section instead of the reinforcing bars, the buckling and fracture can be delayed resulting in improved seismic performance [6, 10]. From these considerations, a new details of prestressed precast concrete columns with combination of prestressing tendons and mild reinforcing bars was proposed as shown in Fig. 1. From observation of concrete damage of the first precast segment by lateral displacement [5, 11], the bottom edge of the segment was chamfered to mitigate stress concentration. Geometry control is crucial issue to prevent any local failure during prestressing work. 3D engineering technologies were adopted for design, fabrication and error adjustment of the segments during assembly [12].

Two precast columns with aspect ratio of 3.44 were fabricated. Six bonded prestressing tendons of 15.2mm (ASTM A779 Grade 270, 1860MPa) were used for both the specimens. Six mild reinforcing bars with diameter of 32 mm were used for axial steel only for PT1A but there was no continuous reinforcements for PT1B. The steel ratio of the column was 1.45% for PT1A specimen. The first precast column segment on the footing had height of 2.0D considering common plastic hinge length of columns. The average compressive strength of concrete was 37 MPa. Yield strength of the reinforcement was 400 MPa. Applied effective prestress for both specimens was 1270 MPa which is 77% of yield strength of the tendon.

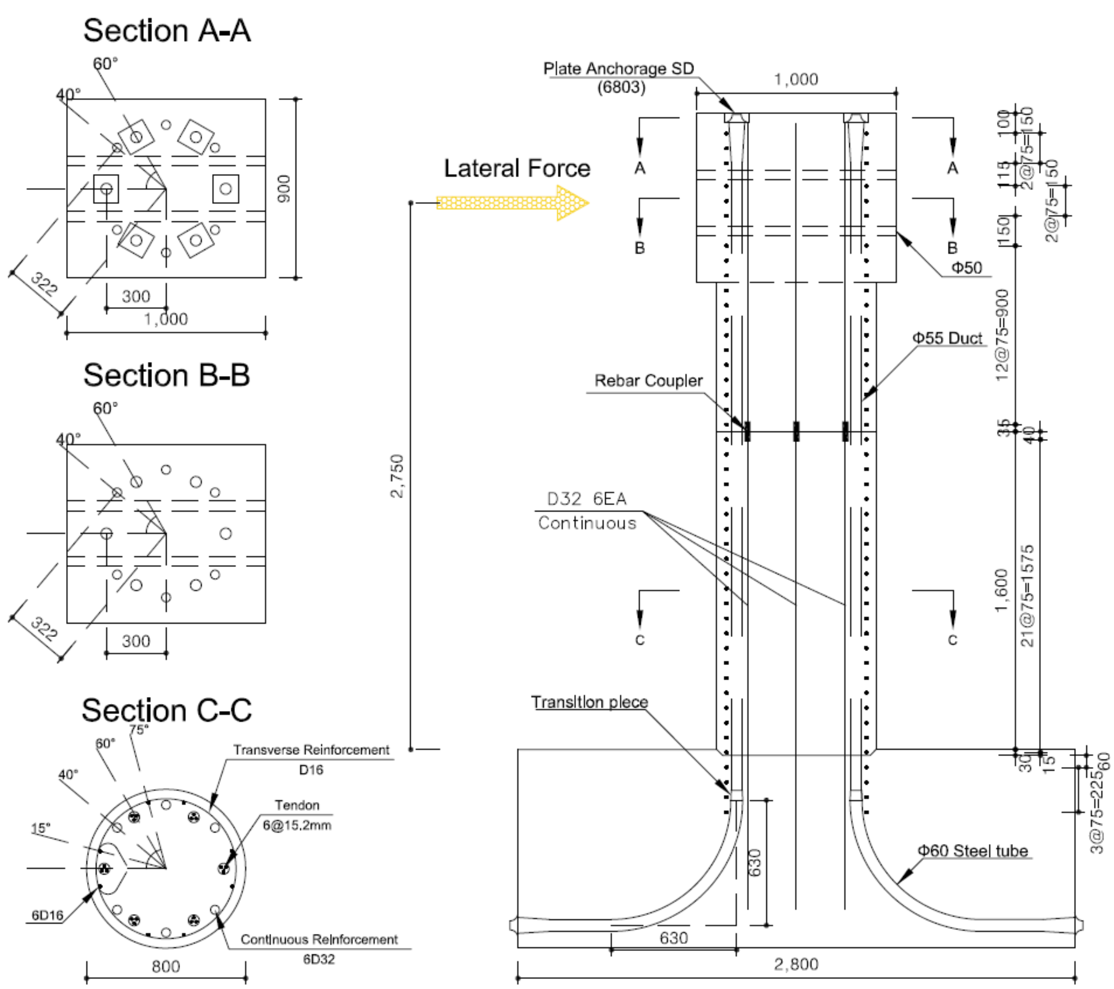



Fig. 1 – Test specimen of prefabricated segmental concrete column

Cyclic tests were performed by a hydraulic actuator of 2,000 kN and a constant axial force of 1,000 kN was applied at the top of the column. Fig. 2 presents test results of load-displacement. Up to drift level of 8% of the column, both the specimens showed ductile flexural response without strength reduction. From the observation of damage by the lateral force, there was no buckling and fracture of main reinforcing bars. Self-centering capability by the prestress was obtained up to drift level of 2%. The continuous mild reinforcing bars provided 20% increase of maximum strength of the column. Up to the lateral displacement of 3% drift level, energy dissipation capacity was similar for both the specimens. However, after spalling of cover concrete, PT1B specimens provided 41% lower energy dissipation capacity [10]. Main reinforcements and prestressing tendons experienced yielding without fracture after the lateral load of 8% drift level.

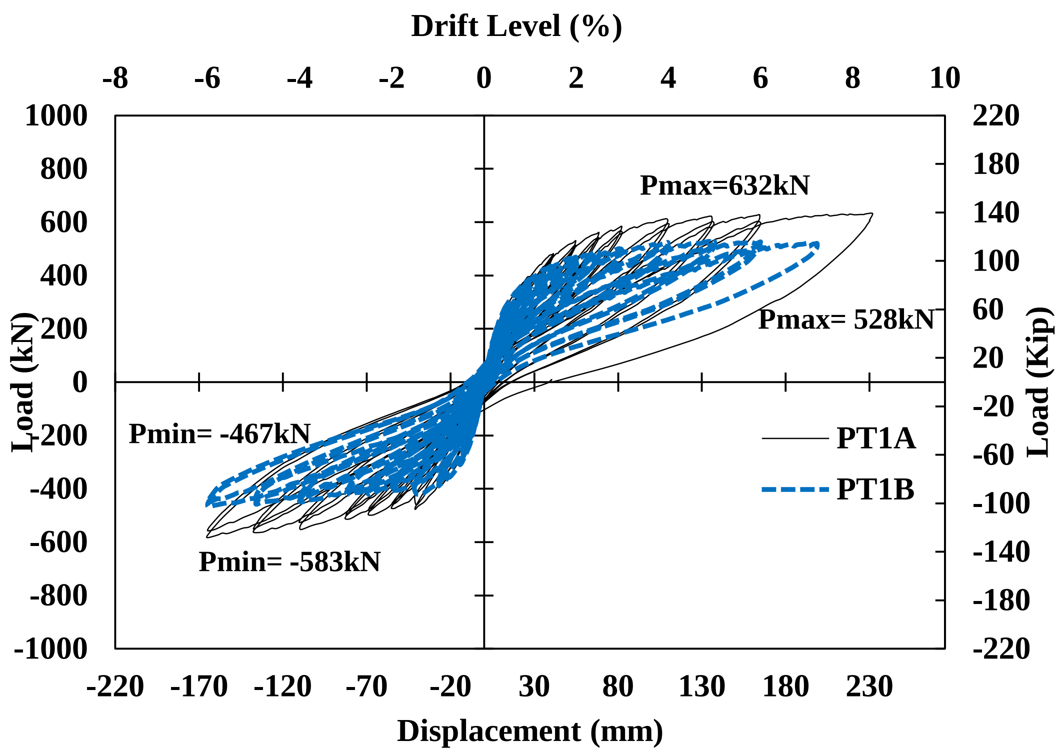



Fig. 2 – Test results

2.2 Repair and strengthening

The precast columns after large lateral displacement showed damage of joint opening, cracking, crushing and residual deformation by yielding of axial steels. Repair and strengthening of the damaged columns was decided to investigate validity of the repair method. Recovering the original structural capacity and appropriate seismic performance of the column are main objectives of the repair. Before the repair, damaged part was removed and steel brushing was applied to improve interface bonding. As shown in Fig. 3, the opened joint was repaired by epoxy injection after recentering the residual deformation. Additional longitudinal reinforcing bars (8@D10) were placed by chemical anchoring to the footing with depth of 315 mm. PT1A specimen had additional transverse reinforcements (6@D8) with 75 mm spacing. PT1B specimen had larger transverse reinforcement (6@D13) with the same spacing. High-performance fiber reinforced cementitious composite (HPFRCC) was added to the column with 100mm thickness. The HPFRCC showed enough workability to cast in narrow area.

The reinforcement of 8 mm diameter was fabricated to have yield and ultimate tensile strength of 358 MPa and 471 MPa, respectively. Average compressive strength of the HPFRCC at the time of the test was 44 MPa. Due to yielding of the tendon, remained prestressing force was unknown. The additional chemical anchors are expected to provide higher flexural capacity.

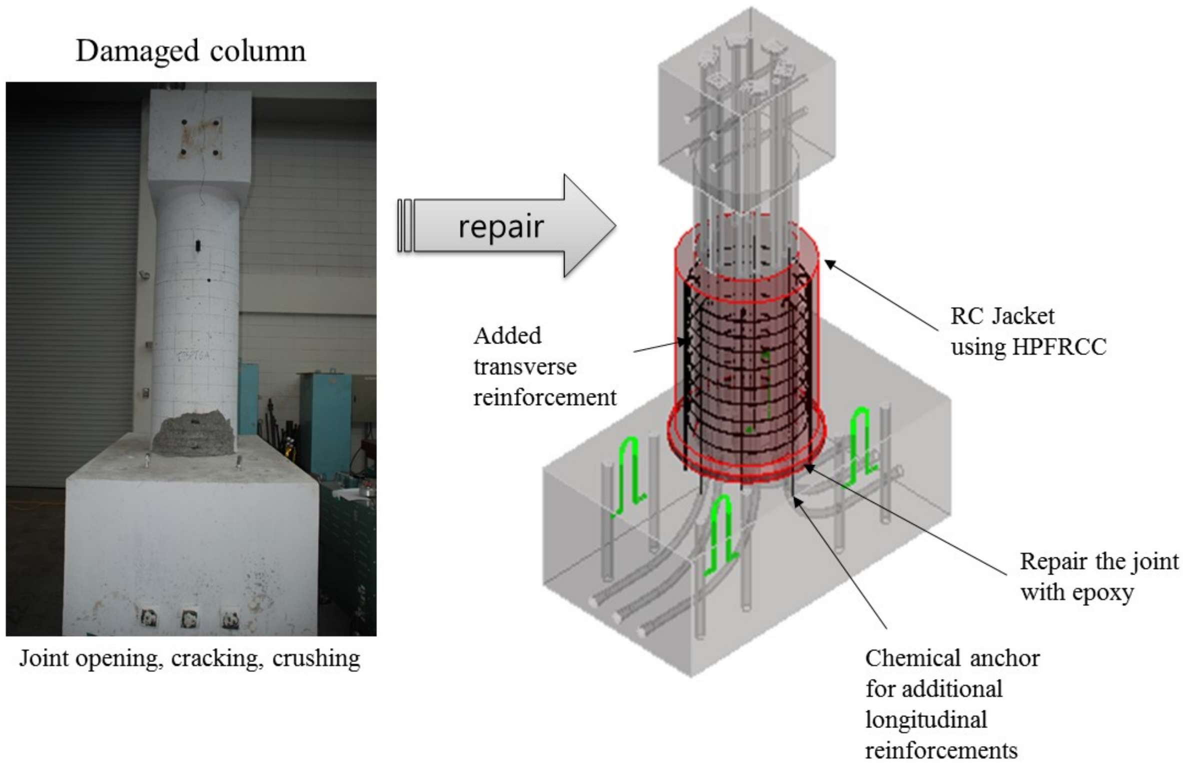



Fig. 3 – Repairing an earthquake-damaged column

## 3. Cyclic tests on repaired precast columns

Fig. 4 represents test setup with column-footing assemblage. The column was subjected to a combination of a constant axial compression of 1,000 kN and a cyclically applied lateral load. The axial force was applied by a hydraulic adjustment system to maintain the constant axial force even though there is lateral displacement. A quasi-static test was performed by displacement control. The specimen was initially loaded by drift level of 0.25% in both directions. The drift level is defined as the ratio of the lateral displacement to the column height. Then the lateral displacement was subsequently increased to 0.5%, 1.0%, 1.5%, 2.0%, 2.5%, 3.0%, 4.0%, 5.0%, 6.0%, and 8.0%. Global response was measured by displacement transducers and a load cell and local behavior was observed by strain gauges at concrete and reinforcing bars.

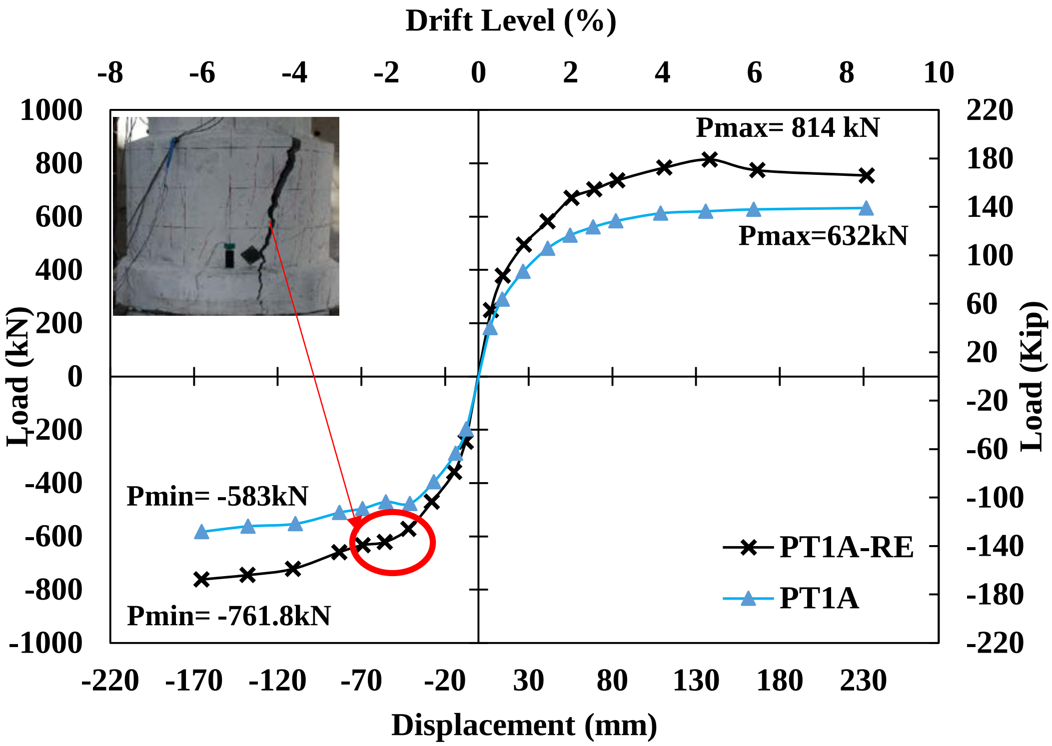
Even though the prestressing tendons were expected to experience yielding by the previous cyclic test, two repaired columns, PT1ARE and PT1BRE, showed re-centering behavior up to the lateral displacement of drift level of 1%. PT1ARE specimen had smaller transverse reinforcements in the concrete jacket section. During the cyclic test, the added concrete part showed a vertical failure crack with fracture of the transverse reinforcements at the lateral displacement of 50 mm as shown in Fig. 5(a). Interface between the original column and the jacket showed separation. However, the flexural strength was regained after sudden drop of the strength. PT1ARE specimen provided 30% increase of the flexural strength at both directions. The chemically anchored longitudinal reinforcing bars actively resist the lateral force without fracture.

PT1BRE specimen had larger confining reinforcement than PT1ARE specimen resulting in no failure of the jacket up to the maximum lateral displacement. Distributed transverse cracks were observed up to the height of the second joint between precast column segments. This is due to higher flexural stiffness of the strengthened section. Without severe failure of the jacket section, PT1BRE specimen provided 34% higher strength in positive direction and 54% in negative direction than PT1B specimen as shown in Fig. 5(b).

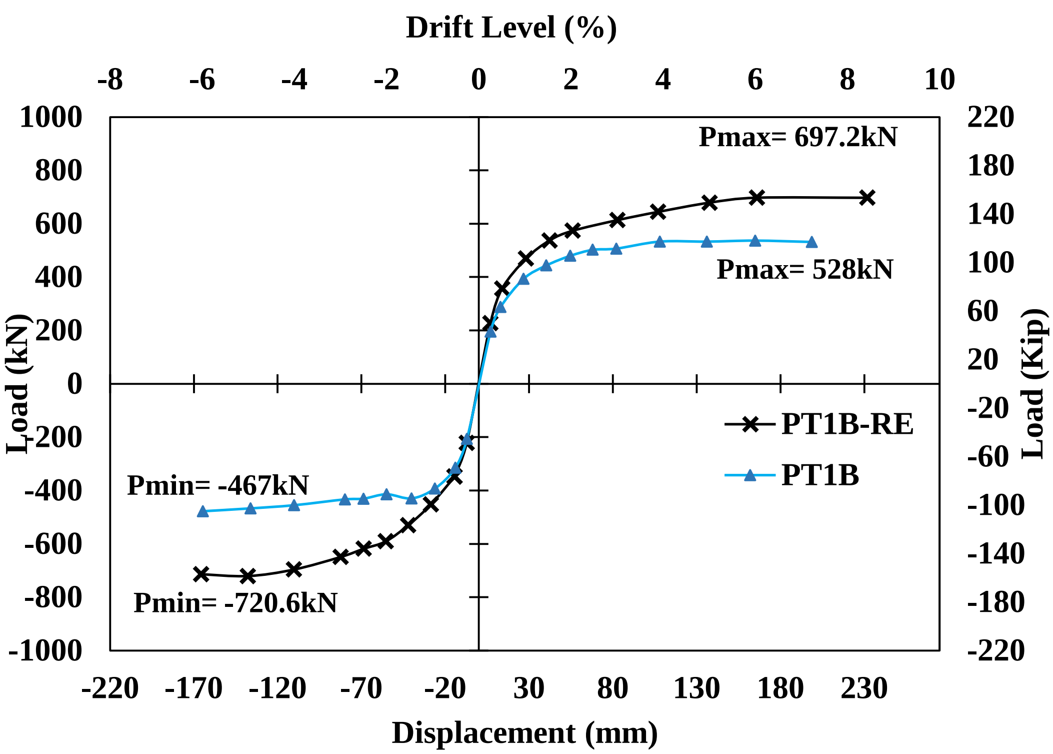
Displacement ductility is defined by $\mu_\Delta = \Delta_u / \Delta_y$ from the envelop curves. The yield displacement $\Delta_y$ is defined as the displacement of the intersection point of the following two lines: the straight line that passes through the origin and $0.75\,V_{\max}$ of the envelope curve, and the straight line that passes through $V_{\max}$ on the envelope curve and is parallel to the x-axis. The ultimate displacement $\Delta_u$ is defined as the displacement that occurs when the strength of the descending branch of the force-displacement envelope curve becomes less than $0.85\,V_{\max}$ [13]. In this experiment, there was no value for the ultimate displacement up to the lateral displacement of 8% drift level. However, the displacement ductility of the repaired columns was expected to be same or greater than that of the original precast columns.

Cumulative energy dissipation capacity of the repaired columns was estimated from the hysteresis curves. Energy dissipation capacity of the repaired columns was significantly increased after the lateral displacement of 3% drift level for both specimens. PT1ARE specimen showed 1.45 times greater cumulative energy dissipation capacity than that of PT1A specimen at the drift level of 8%. PT1BRE specimen showed 1.57 times greater cumulative energy dissipation capacity than that of PT1B specimen at the drift level of 6%.


Fig. 4 – Test setup




(a) PT1A and PT1ARE




(b) PT1B and PT1BRE

Fig. 5 – Envelope curves of the specimens

## 4. Design recommendations

There are many considerations in design of repair when columns had severe damage by an earthquake. RC jacketing method does not have a specialized work demand. Main considerations for the repair design are removing the damaged zone, interface surface preparation, bonding agent, anchoring the added longitudinal reinforcement, added stirrups and added concrete.

From the experiments on the repaired precast concrete columns, the following recommendations were derived.

- Damaged parts of the cover concrete need to be removed by hand chipping or jack hammering. The interface between original column part and added concrete jacket needs to be roughened by simple steel brushing or sand blasting.
- Opened precast joint should be repaired by injection of epoxy resin.
- Anchoring of the additionally placed longitudinal reinforcing bars should be anchored to the footing by appropriate chemical anchor. Commercial product has recommended depth of the hole and it is recommended from this experiment to have the anchoring depth for cyclic events at least 1.5 times greater than the required depth for static strength. Arrangement of the reinforcement is recommended to be same as the original axial steel in the direction of lateral loading.
- Added stirrups should prevent premature failure of the jacket section by the lateral displacement. It is recommended to have smaller spacing than the original transverse reinforcement.
- High performance fiber reinforced cementitious composite is recommended for added concrete to obtain better ductility and durability to control minor cracks by shrinkage.
- Target performance of the jacket section need to be the same or slightly higher than the original performance of the column for preventing change of global seismic behavior of the entire bridge structures.

## 5. Conclusions

This paper presents experimental results of repaired precast prestressed concrete columns by jacketing method with HPFRCC. When the prestressed precast column has moderate damage by earthquake, re-centering capability provides fast repair and strengthening. Main advantage of the prestressed segmental concrete column is re-centering capability for lateral displacement of the column. When the precast columns have no fracture of axial steel, it is possible to repair and strengthen the column by the proposed jacketing method even after severe damage of plastic hinge region. Properly designed jacket provided higher flexural strength and energy dissipation capacity than the original precast concrete column. Displacement ductility was also obtained to be similar to the original column. Design considerations were summarised based on the experimental program. In order to minimize on-site work for the repair, it is necessary to develop a prefabricated jacketing method.

## 6. Acknowledgements

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