Canadian Conference - Pacific Conference on Earthquake Engineering 2023

Vancouver, British Columbia

June 25th – June 30th, 2023

Precast Bridge Columns with Quick Repair Detailing

Mostafa Tazarv[1*], Kallan Hart[2] and Theodore Sjurseth[3]

[1]Associate Professor, Dept. of Civil & Env. Engineering, South Dakota State University, Brookings, SD, USA
[2]Graduate Research Assistant, Dept. of Civil & Env. Engineering, South Dakota State University, Brookings, SD, USA
[3]Graduate Research Assistant, Dept. of Civil & Env. Engineering, South Dakota State University, Brookings, SD, USA
*mostafa.tazarv@sdstate.edu (Corresponding Author)

ABSTRACT

RC columns, which are usually the main source of energy dissipation and ductility in bridges, are widely used in seismic regions of the USA. Even though current bridge design specifications ensure collapse prevention, damage of bents is expected in extreme events. Minor damage such as cover spalling can be repaired. Nevertheless, severe damage such as buckled reinforcement and core concrete failure of RC bents cannot be easily repaired, which usually results in the column/bridge total replacement. A new detailing has been developed for RC bridge columns in which all components are precast to accelerate construction and the damage is limited to exposed and replaceable reinforcement to minimize bridge repair time and cost. The new joint detailing incorporates (1) detachable external fuses such steel tendons or steel bars restrained against buckling to develop plastic bending moments, (2) a steel pin connection to resist plastic shear forces, and (3) detachable mechanical bar splices to connect and/or replace damaged reinforcement as a quick repair technique. The seismic performance of the proposed precast detailing was investigated through testing of three half-scale precast bridge columns under a slow cyclic loading. A conventional cast-in-place (CIP) column was also tested as the benchmark model. The precast columns were tested twice to practice the repair-by-replacement technique. The precast columns showed minor to insignificant damage, comparable or higher displacement capacity and lateral strength, and smaller residual displacements compared with those of the CIP column. However, the initial stiffness of all precast columns was substantially lower than that of CIP. The repair of the two precast columns incorporating tendon fuses and ultra-high performance concrete was very simple and quick confirming the feasibility of the proposed repair-by-replacement technique.

Keywords: Repairable Column, UHPC, Replaceable Fuses, Seismic Performance.

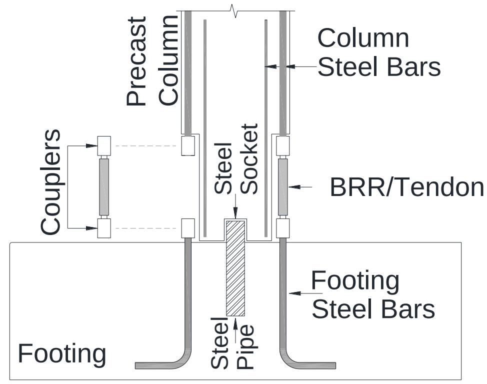
INTRODUCTION

RC columns, which are usually the main source of energy dissipation and ductility in bridges, are widely used in seismic regions of the USA. Even though current bridge design specifications ensure collapse prevention, damage of bents is expected in extreme events. Minor damage such as cover spalling may be repaired. Nevertheless, more severe damage such as buckled reinforcement, core concrete failure, or bar fracture of RC bents cannot be easily repaired, which usually results in the column or bridge total replacement. Novel bridge columns incorporating enhanced materials and new detailing are emerging with reduced damage and minimal repair need. xamples of advanced materials used in bridge columns are engineered cementitious composites (ECC) [1] and ultra-high performance concrete (UHPC) [2] as alternatives to conventional concrete, and stainless steel [3] and shape memory alloy (SMA) [4] to replace conventional steel. Innovative detailing includes rocking columns [e.g., 5-7] and accelerated bridge construction (ABC) details such as socket, grouted duct, and mechanical bar coupler connections [e.g., 8-10].

It is feasible to combine innovative detailing such as ABC with advanced materials to expedite construction, provide additional ductility to RC columns, and reduce column damage. The main objective of this study was to develop new details for RC bridge columns that are fully precast, high performance, and repairable through component replacement. Twenty new detailing alternatives were developed meeting the abovementioned objectives and were assessed using a 13-parameter rating method to select the best details for testing. Three candidates were selected, 50%-scale column models of each alternative were constructed, and the columns were tested to failure. All precast specimens were tested twice under a slow cyclic loading at the Lohr Structures Laboratory on the campus of South Dakota State University. In the second test of each specimen, the column exposed bars were replaced to practice repair through replacement. The results were compared with a reference cast-in-place (CIP) column.

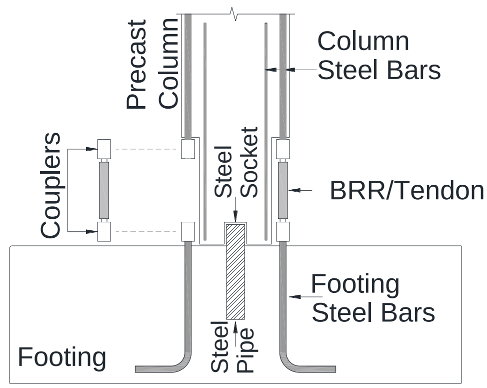
TEST SPECIMENS

Figure 1 shows the key elements of a repairable column including a precast column, a shear-pin connection, exposed reinforcement (fuse), and couplers. If a type of steel bar is used in this detailing as the exposed fuse, it must be restrained against buckling to avoid low-cycle fatigue. Buckling restrained reinforcement (BRR) is a bar that is confined in a steel tube to minimize buckling (Fig. 1b). Alternative to BRR is a fuse with tension-only members such as steel tendons (Fig. 1d). Furthermore, the column diameter must be reduced at the ends to accommodate the exposed fuses and couplers. The reduced section of a repairable column is called "neck region". The proposed detailing is moment-resisting since the exposed bars are axial members forming a tension-compression couple. The shear forces associated with the moment will be resisted by the shear pin connection.



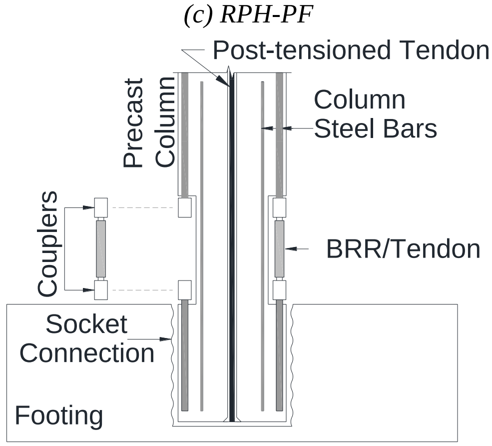
(a) RPH-PC

(b) RPH-PC with BRR Fuses



(c) RPH-PF

(d) RPH-PF with Tendon Fuses



(e) RPH-NP

(f) RPH-NP with Tendon Fuses

Figure 1. Repairable Precast Bridge Columns

The three precast column test specimens were labeled starting with RPH referring to "repairable precast with headed longitudinal bars/couplers" followed by the connection type: "PC" for the column utilizing a pipe-pin connection at the column base with the pipe embedded in the column, "PF" for a pipe-pin connection with the pipe embedded in the footing, and "NP" for the column with no pin connection but instead using a socket connection. A third term, "R", was used indicating that the column was repaired by component replacement and retested.

CIP was designed to achieve a minimum displacement ductility capacity of 7 based on AASHTO SGS (2011). A half-scale model of the prototype column was constructed due to size limitations in the laboratory. Since precast members are usually cast horizontally in plants, circular sections are not preferred. An octagonal cross section was selected for all columns with a medium diagonal of 24 in. (610 mm) and a height of 8 ft (2.44 m) resulting in an aspect ratio of 4. The CIP column model was longitudinally reinforcement with 10, No. 8 (Ø25-mm) bars and transversely with No. 4 (Ø13-mm) hoops at 2 in. (51 mm). The column longitudinal reinforcement ratio and transverse volumetric steel ratio were 1.66% and 2.0%, respectively. CIP was cast in the Lohr Structures Laboratory and all precast columns were built by a leading precast company in the region. The geometry of all precast columns was generally the same as that of CIP, but a neck was included at the base to accommodate the exposed components. The neck length was 24 in. (610 mm), and the neck diameter was 16.5 in. (419 mm). The longitudinal bars of the precast columns were oversized to limit the yielding to the exposed fuses. The replaceable fuses were either BRR in RPH-PC or steel tendons in RPH-PF and RPH-NP. These fuses could be replaced using a headed mechanical bar coupler (HRC 500 Series), which was detachable. Conventional concrete was used in CIP, self-consolidating concrete (SCC) was used in RPH-PC and UHPC was used in RPH-PF and RPH-NP. Pipe-pin connections of all precast columns were designed using the recommendations of Zaghi and Saiidi [11].

All columns were tested in a cantilever setup following a drift-based cyclic loading protocol by ACI 374.2R [12]. Drift is the ratio of the column lateral displacement to the column length. Two full cycles were completed at each drift level. The columns were heavily instrumented to measure bar and concrete strains, plastic hinge curvatures, column lateral displacements, and column axial and lateral forces. A constant axial load of 155 kips (689 kN) was applied to each test specimen.

TEST RESULTS

The compressive strength of conventional concrete, SCC, and UHPC at the column test day was 4300 psi (29.6 MPa), 10699 psi (73.8 MPa), and 15144 psi (104.4 MPa), respectively. The tensile strength of longitudinal bars/fuses in CIP, RPH-PC, RPH-PF, and RPH-NP was respectively 97.4 ksi (672 MPa), 113.4 ksi (782 MPa), 306.5 ksi (2113 MPa), and 306.5 ksi (2113 MPa). The strain at the peak stress of these bars/fuses was 12%, 16.6%, 6.2%, and 6.2%, respectively.

Figure 2 shows the damage of the CIP and precast columns at a 2% drift ratio. Flexural and shear cracks can be seen in CIP. A few flexural cracks were also seen in RPH-PC with stainless steel BRR and SCC. However, the damage of the two UHPC columns (RPH-PF and RPH-NP) was insignificant.

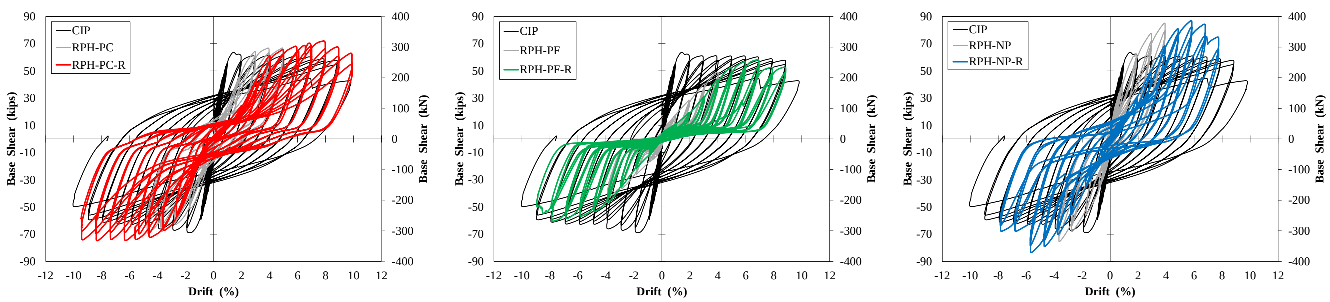
(a) CIP *(b) RPH-PC* *(c) RPH-PF* *(c) RPH-NP*

Figure 2. Damage of Columns at 2% Drift Ratio

Figure 3 shows the damage of the columns at their failure drift cycles. Note that all precast columns were repaired by BRR or tendon fuse replacement after the first round of testing. Different colors or marks on the fuses were used for a quick identification of the repaired columns. RPH-PC was repaired by BRR replacement at 5% drift and then was retested to failure as RPH-PC-R. The other two precast columns were first tested to 4%, repaired by replacing their tendon fuses, and then retested to failure. The damage of CIP at its failure displacement was significant including core crushing and reinforcement fracture. SCC of RPH-PC-R also crushed at the top of the neck due to compressive forces of BRR. Furthermore, a Z-shape buckling of BRR and bending the column/footing dowel bars were observed. Nevertheless, the damage of RPH-PF-R and RPH-NP-R was insignificant, limited to with a few hairline cracks and minor spalling at their rocking faces.

(a) CIP at 10% Drift *(b) RPH-PC at 10%* *(c) RPH-PF at 9% Drift* *(c) RPH-NP at 8% Drift*

Figure 3. Damage of Columns at Failure



(a) RPH-PC & RPH-PC-R *(b) RPH-PF & RPH-PF-R* *(c) RPH-NP & RPH-NP-R*

Figure 4. Measured Force-Drift Response of Columns

Figure 4 shows the force-drift hysteretic response of the precast columns superimposed on the CIP response. CIP failed by the longitudinal bar fracture at 8.96% drift ratio. RPH-PC-R did not fail at 10% drift cycles where the test was stopped, but the column drift capacity was assumed to be 9.8%. RPH-PF-R failed by the tendon rupture at 8.9% drift ratio. RPH-NP-R failed by the neck bar rupture at 7.7% drift ratio. Therefore, the displacement capacity of RPH-PC-R was 9% higher than that of CIP and the displacement capacities of RPH-PF-R and RPH-NP-R were 0.6% and 14% lower than that of CIP, respectively. All precast columns exhibited the same or higher lateral strength than CIP.

Even though no specific self-centering mechanism was used, RPH-PC and its repaired version, both with stainless-steel BRR, showed a moderate-level reduction (e.g., 44% at the last cycle) in residual displacements compared with CIP. However, the residual displacement reduction at high drifts was not sufficient in this column to allow an easy BRR replacement. The column/footing dowels were also bent limiting the repair-by-replacement technique in RPH-PC. RPH-PF and RPH-PF-R exhibited insignificant residual displacements throughout the entire testing/retesting, which also made the tendon replacement very easy at 4% drift. Despite the use of rocking detailing in RPH-NP and RPH-NP-R, the residual displacements of this column were not as small as those of RPH-PF but smaller than CIP. The repair of this column at 4% drift was also very easy and quick due to its low damage and small residual displacements.

One major drawback of the proposed precast columns was their low initial stiffness compared with that of CIP and some levels of stiffness degradation between testing and retesting. The initial stiffness of RPH-PC, RPH-PF, and RPH-NP was 80%, 85%, 46% smaller than that of CIP, respectively. RPH-PC showed the highest stiffness degradation between the two tests (41%) while RPH-PF and RPH-NP showed 8.5% to 21% stiffness degradation between the two tests. Lower initial stiffness usually results in a higher displacement demand for bridge columns. Further dynamic testing is needed to completely understand the effects of the lower initial stiffness of the proposed precast columns on displacement demands.

CONCLUSIONS

Three precast columns with a new detailing that allows reinforcement replacement were tested twice under the same cyclic loading protocol. The test specimens were labeled starting with RPH referring to "repairable precast with headed longitudinal bars/couplers" followed by the connection type: "PC" for the column utilizing a pipe-pin connection at the column base with the pipe embedded in the column, "PF" for a pipe-pin connection with the pipe embedded in the footing, and "NP" for the column with no pin connection but instead using a socket connection. A third term, "R", was used indicating that the column was repaired and retested. The precast columns were repaired at 4% or 5% drift ratio by replacing their exposed fuses, which were made of either buckling restrained reinforcement (BRR) or steel tendons, and then retested. One reference cast-in-place (CIP) was also tested. A summary of the experimental findings is as follows:

- The mode of failure for CIP was the longitudinal bar rupture.
- RPH-PC-R did not fail at 10% drift ratio, but the test was stopped to prevent setup damage.
- The mode of failure for RPH-PF-R was tendon rupture while the mode of failure for RPH-NP-R was rupture of the neck bars.
- The drift ratio capacities for CIP, RPH-PC-R, RPH-PF-R, and RPH-NP-R were 8.96%, 9.8%, 8.9%, and 7.7%, respectively.
- The Z-shape buckling of stainless steel BRR used in the RPH-PC column, the bending of their adjoining dowel bars, and some residual displacements made the repair by replacement very difficult for this column at 5% drift. Nevertheless, the incorporation of the steel tendons as the tension-only fuses eliminated any column/footing dowel bar damage in RPH-PF and RPH-NP and further helped with the recentering of these columns.
- All repairable columns showed smaller residual displacements compared with CIP. However, the residual displacement of RPH-PF was insignificant throughout the entire testing.
- UHPC substantially reduced the damage of the precast columns, even at their fuse failure.

Overall, the study confirmed the feasibility of the repair-by-replacement technique in bridge columns. Especially, the precast columns with exposed tendon fuses and UHPC were found to be the most feasible alternatives and are recommended for future investigations. Further strength and dynamic tests are required to better understand the behavior of the proposed detailing.

ACKNOWLEDGMENTS

The work presented herein was conducted with a joint support from the Precast/Prestressed Concrete Institute (PCI), South Dakota State University, and the National Center for Transportation Infrastructure Durability and Life-Extension (TriDurLE), a University Transportation Center (UTC) funded by the U.S. Department of Transportation. The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the information presented.

REFERENCES

[1] Saiidi, M.S., O'Brien, M. and Sadrossadat-Zadeh, M. (2009). "Cyclic response of concrete bridge columns using superelastic Nitinol and bendable concrete." ACI Structural Journal, 106(1).

[2] Aboukifa, M. and Moustafa, M.A. (2021). "Experimental seismic behavior of ultra-high performance concrete columns with high strength steel reinforcement." Engineering Structures, 232, p.111885.

[3] Panagiotou, M., Trono, W., Jen, G., Kumar, P. and Ostertag, C.P., (2015). "Experimental seismic response of hybrid fiber-reinforced concrete bridge columns with novel longitudinal reinforcement detailing." Journal of Bridge Engineering, 20(7), p.04014090.

[4] Tazarv, M. and Saiid Saiidi, M., (2016). "Low-damage precast columns for accelerated bridge construction in high seismic zones." Journal of Bridge Engineering, 21(3), p.04015056.

[5] Marriott, D., Pampanin, S. and Palermo, A., (2009). "Quasi-static and pseudo-dynamic testing of unbonded post-tensioned rocking bridge piers with external replaceable dissipaters." Earthquake engineering & structural dynamics, 38(3), pp.331-354.

[6] Thonstad, T., Mantawy, I.M., Stanton, J.F., Eberhard, M.O. and Sanders, D.H., (2016). "Shaking table performance of a new bridge system with pretensioned rocking columns." Journal of Bridge Engineering, 21(4), p.04015079.

[7] Nikoukalam, M.T. and Sideris, P., (2017). "Resilient bridge rocking columns with polyurethane damage-resistant end segments and replaceable energy-dissipating links." Journal of Bridge Engineering, 22(10), p.04017064.

[8] Haraldsson, O.S., Janes, T.M., Eberhard, M.O. and Stanton, J.F., (2013). "Seismic resistance of socket connection between footing and precast column." Journal of Bridge Engineering, 18(9), pp.910-919.

[9] Tazarv, M., Shrestha, G. and Saiidi, M.S., (2021). "State-of-the-art review and design of grouted duct connections for precast bridge columns." Structures, 30, pp.895-909.

[10] Tazarv, M. and Saiidi, M.S., (2016). "Seismic design of bridge columns incorporating mechanical bar splices in plastic hinge regions." Engineering Structures, 124, pp.507-520.

[11] Zaghi, A.E. and Saiidi, M.S., (2010). "Seismic performance of pipe-pin two-way hinges in concrete bridge columns." Journal of Earthquake Engineering, 14(8), pp.1253-1302.

[12] ACI 374.2R-13. (2013). "Guide for testing reinforced concrete structural elements under slowly applied simulated seismic loads." American Concrete Institute (ACI) Committee 374, Farmington Hills, MI.