Performance of Ultra-high Performance Concrete Self-centering Bridge Piers under Seismic Loads

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Abstract Precast concrete columns with unbonded post-tensioning have great self-centering capabilities and can keep important bridges operational after a major earthquake. Rocking of column segments over the foundation under seismic excitation reduces the overall damage, however, causes damage to concrete near joints. This research assessed the seismic performance of post-tensioned precast segmental piers with ultra-high performance concrete (UHPC) through large scale laboratory testing. Pier specimens were constructed with the same configuration, except that the segment of the column right above the precast foundation had varying material and design details: conventional concrete with mild steel reinforcing bars, UHPC with mild steel reinforcing bars, and UHPC without mild steel reinforcing bars. Specimens were tested under quasi-static cyclic lateral loading. Reinforcing bars in UHPC segments did not contribute to damage resistance. Specimens with UHPC, regardless of the reinforcement amount, had minimal damage, even at displacements much larger than the seismic demand. All specimens had great self-centering but minimal energy dissipation capability. Specimens with UHPC had higher stiffness and strength.

1 Introduction

Precast concrete bridge construction accelerates construction and improves production quality by moving some critical construction activities to a prefabrication plant. Due to large size and weight, bridge elements often have to be built in segments. Precast concrete segmental joint locations typically coincide with the locations of expected plastic hinges in equivalent monolithic structures. For this reason, previous research on developing seismic resistant segmental
bridge structures focused on emulative systems [Marsh et al. 2011]. Emulative systems mimic cast-in-place connection details and rely on the inelastic response of structural materials to dissipate energy during extreme events. While emulative systems work well in preventing collapse, they also cause significant structural damage, leading to long downtimes for structures and large economic losses. Construction time required to replace structures or perform major repairs may not be affordable for structures connecting lifelines.

To minimize seismic damage, advanced materials [Andrawes et al. 2009; Hosseini et al. 2015; Tazarv and Saiid Saiidi 2015], self-centering systems [Hewes and Priestley 2002; Ou et al. 2007; Yamashita and Sanders 2009] or both [Billington and Yoon 2004; ElGawady et al. 2010; Roh and Reinhorn 2010; Trono et al. 2014] have been explored for concrete bridge columns. These systems lower seismic damage to plastic hinge region or confine damage to replaceable components.

This paper presents a low seismic damage non-emulative, precast concrete, segmental bridge pier system and its response to quasi-static cyclic loading. Low damage and low residual displacement are achieved by the use of UHPC and unbonded post-tensioning, respectively. UHPC was implemented on a precast concrete system developed by Sideris et al. [2014] and the system was tested under quasi-static cyclic loading. UHPC is a cementitious material with discontinuous steel fiber reinforcement. It has considerably higher compressive strength, sustained tensile strength after cracking and improved toughness and durability compared to conventional concrete. The bottom column segment which rocks over the foundation was built with UHPC to control seismic damage due to rocking. The feasibility of eliminating mild reinforcement bars with the use of UHPC was also explored.

2 Description of Specimens

Bridge pier specimens were composed of a precast concrete foundation, precast concrete cap beam, and five precast concrete hollow column segments. Three specimens were tested at 1 to 2.4 length scale. The difference between the three specimens was the bottom column segment as described in Table 1. Precast pier cap, and precast foundation segments were also made up of conventional concrete. Conventional concrete was 34.5 MPa (5 ksi) compressive design strength concrete. UHPC was the Ductal® JS1000 mix [Lafarge Canada Inc. 2009] of LafargeHolcim with mean characteristic compressive strength of 138 MPa (20 ksi) and steel high strength fiber reinforcement.

Eight unbonded post-tensioning strands went through the foundation, column segments, and cap beam. Post tensioning strands were 7 wire, 15.2 mm (0.6 in.) diameter, low relaxation strands, with 1862 MPa (270 ksi) ultimate strength. Each unbonded strand had 89 kN (20 kips) of post-tensioning force. Although there were no shear keys between segments, shear-slip was minimal due to friction between segments. There was no bonded reinforcement between segments.
Table 1. Specimen Details

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Bottom column segment</th>
<th>Upper column segments</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Conventional concrete with mild reinforcement bars</td>
<td>Conventional concrete</td>
</tr>
<tr>
<td>II</td>
<td>UHPC with mild reinforcement bars</td>
<td>Conventional concrete</td>
</tr>
<tr>
<td>III</td>
<td>UHPW without mild reinforcement bars</td>
<td>Conventional concrete</td>
</tr>
</tbody>
</table>

3 Testing Protocols

Two tests were performed on each specimen: 1) Quasi-static cyclic loading to determine the hysteretic response and evaluate damage, 2) Impact hammer testing before and after cyclic testing to determine any changes in dynamic properties. Cyclic loading was quasi-statically applied through a 978 kN (220 kip) capacity hydraulic actuator with a 1,016-mm (40-in.) stroke. The weight of the superstructure was simulated by placing two post-tensioning strands on each side of the cap beam and post-tensioned to 91 kN (20.5 kips). Displacement of each segment, gap opening and shear-slip between each column segment were measured during cyclic loading. Additionally, instrumentation included accelerometers to measure the accelerations at different heights in two horizontal directions during impact hammer testing. The experimental set up for the cyclic testing is shown in Figure 1.

Figure 1. Experimental set up

The quasi-static test, was conducted on specimens previously tested to small lateral displacements but not damaged. Lack of damage was documented by measuring dynamic properties before and after testing. All specimens were loaded until the maximum stroke of the actuator was reached or until specimens failed.
The test was conducted using displacement control. Loading was applied quasi-statically at an average velocity of 0.25 to 1.27 mm/sec (0.01 to 0.05 in./sec). The loading (displacement) time history is shown in Figure 2.

![Figure 2. Loading protocol](image)

### 3 Test Results

The lateral force versus lateral displacement hysteretic response of specimens to the quasi-static test is shown in Figure 3. All specimens had similar lateral strength as they had similar post-tension levels. The hysteretic curves enclosed a small area indicating low energy dissipation. On the other hand, residual displacements were small at the end of each cycle, indicating self-centering capability. Rocking initiated after 12.7 mm (0.5 in.) of lateral displacement for all specimens after decompression. Abrupt degradations in strength were caused by sudden shear-slip at large displacements due to lack of shear keys. Shear-slip led to an increase in the area under the hysteretic loops and energy dissipation. The lateral strength plateaued at larger displacement due to strand yielding. All specimens maintained their strength, stiffness and self-centering capability throughout the test. UHPC specimens had a smaller decrease in stiffness with larger displacements.

![Figure 3. Hysteretic response of (a) Specimens I, (b) Specimens II, and (c) Specimens III](image)
4 The Impact of UHPC on Damage Resistance

The damage condition of the three specimens before and after cyclic loading was quantitatively assessed by impact hammer testing, and qualitatively assessed by visual inspection.

4.1 Changes in Dynamic Properties

The damage to specimens after testing was firstly assessed by measuring dynamic properties of each specimen before and after testing. The dynamic properties were measured by impact hammer testing which created a free vibration. Data from the accelerometers were used to identify the natural frequency and damping ratios of specimens. Damping ratios were calculated by fitting an idealized free vibration response curve to acceleration time history response obtained through testing. Table 2 present the measured natural frequencies and damping ratios of each specimen in the direction of applied quasi-static cyclic loading before and after each test. The properties that are not shown belong to impact tests with inaccurate data or with lack of fit of theoretical free vibration equations to test data in the calculation of damping ratio. Average post-tensioning force on specimens before and after testing is also presented in Table 2.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Average PT force (kN)</th>
<th>Fundamental Frequency (Hz)</th>
<th>Damping ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Before test</td>
<td>92.0</td>
<td>10.3</td>
</tr>
<tr>
<td></td>
<td>After test</td>
<td>38.6</td>
<td>4.3</td>
</tr>
<tr>
<td>II</td>
<td>Before test</td>
<td>104.5</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>After test</td>
<td>10.1</td>
<td>5.1</td>
</tr>
<tr>
<td>III</td>
<td>Before test</td>
<td>92.0</td>
<td>8.1</td>
</tr>
<tr>
<td></td>
<td>After test</td>
<td>9.3</td>
<td>4.8</td>
</tr>
</tbody>
</table>

All specimens had post-tension levels within 15% of the target post-tensioning. Variations of post-tensioning stemmed from the manual post-tensioning method. All specimens had post-tension loss due to yielding of strands, or concrete cross-section loss. Fundamental frequency was measured as a direct indicator for initial stiffness and stiffness loss due to cyclic loading. Initial stiffness was a function of post-tensioning and segment surface characteristics. For Specimens I and III, fundamental frequency or stiffness at the end of the test was 42% and 59% of the initial stiffness, indicating damage. Despite the fact that the remaining post-tensioning force in Specimen I after test was more than three times the ones for
other specimens, the three specimens had similar fundamental frequencies. The source of damage in Specimen I was concrete damage and post-tension loss, while it was mainly post-tension loss for Specimen III. In addition, the damping ratio was the highest in Specimen I at the end of testing. This is a quantitative indicator of severe concrete damage in Specimen I.

### 4.2 Visual Damage

All specimens remained in a low damage state where confined core concrete remained intact. Figure 4 shows damage to each specimen on the front face perpendicular to the loading direction at the end of test. Both UHPC segments had minor damage even at large displacements, regardless of the reinforcement amount. The damage was confined to an area less than 25.4 mm (1 in.) wide near the rocking edges and was in the form of steel fiber breaking and concrete crushing. Fiber breaking was audible at large displacements but fibers were able to prevent concrete spalling. Reinforcement in UHPC did not contribute to damage control any further than UHPC did. Conventional concrete had severe concrete spalling and cross section loss, despite mild reinforcement. Spalling damage was spread to an area 254 mm (10 in.) wide. Rocking edge was rounded due to excessive corner spalling. The change in the rocking edge reduced the elongations in post-tensioning strands and hence the post-tension loss.

![Figure 4](image.png)

**Figure 4.** Comparisons of (a) Specimen I (b) Specimen II, and (c) Specimen III after test
5 Conclusions

The stiffness and strength of UHPC specimens at large displacements were higher than conventional concrete due to elimination of damage to concrete. All specimens displayed minor energy dissipation but good self-centering capacity.

All specimens, regardless of the bottom segment type and reinforcement amount, had acceptable damage at displacement levels of maximum considered earthquake, i.e. repairable damage. UHPC specimens performed exceptionally under cyclic loading at 15% lateral drift ratio with no visible damage. UHPC specimen with no reinforcing bars performed comparable to the UHPC specimen with reinforcing bars. Based on these results, it was concluded that segmental, re-centering bridge piers built with UHPC and no reinforcing bars would not require any repairs after a major earthquake and therefore can help maintain functionality of bridges immediately after an earthquake. This system is therefore particularly suitable for essential bridges. The higher cost of UHPC can be partially offset by elimination of mild reinforcing bars.

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References


