Experimental Validation of Repair Methods for Earthquake-Damaged Bridges Incorporating Pipe-Socket Precast Pier System

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Abstract

This project focuses on the retrofitting of concrete bridge piers. In the first phase of the project, a half-scale bridge bent was designed and experimentally tested in the Idaho State University (ISU) Structural Lab (SLAB) under earthquake-style loading. The bents modeled a pier connection developed by ISU and Idaho Transportation Department (ITD) (pipe-socket connection). The bridge bent was tested until failure and the results were processed and compared to one another. After testing the bent specimens ISU and ITD have come back to work on another project to retrofit the half-scale bridge piers and experimentally test and quantify the design. Many post-earthquake repair methods have been suggested by ISU and ITD to repair the pier's stiffness, strength, and ductility after a design-level event. This paper focuses on ultra-high-performance concrete (UHPC) jacketing as the retrofit method. Methods to retrofit concrete-filled steel tubes (CFSTs) have only been used in analytical studies and have not been experimentally tested. In order to combat this issue of lack of experimental data, ISU is testing four piers with a UHPC jacket retrofit. The objective of this research is to experimentally validate the proposed UHPC retrofit for the pipe connection.

Keywords: Seismic retrofit; Bridge piers; UHPC; CFST; Jacket

1 Introduction

The first phase of this project was to test the pipe connection of an Accelerated Bridge Construction (ABC) bridge bent and compare the results to a typical cast-in-place (CIP) bridge bent. A diagram showing the design of the pipe connection can be seen in Figure 1. The pipe connection is advantageous because it incorporates ABC, it has ample installation tolerance, it has improved onsite safety, and it allows deformation during smaller movements.

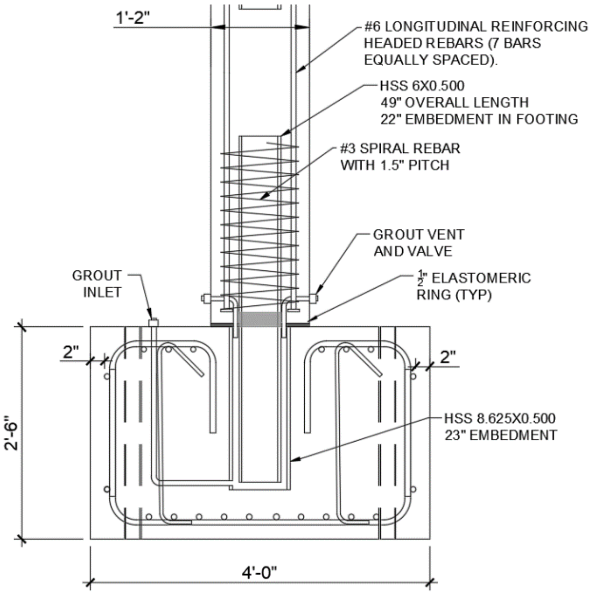
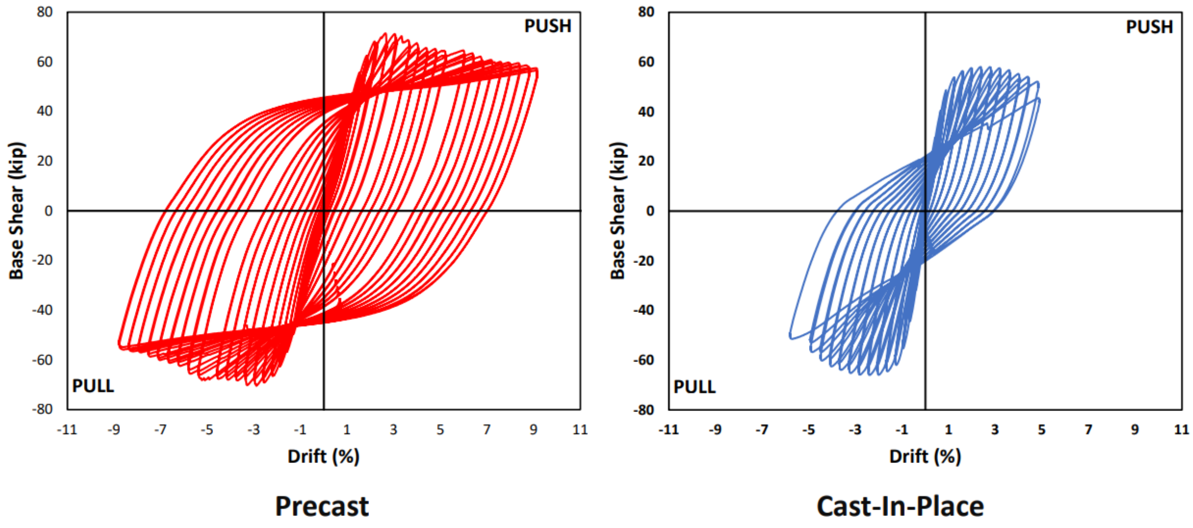


Fig. 1: Pipe-Socket Connection for Column-to-Footing Connection

In the first phase of the project, both bents were tested under quasi-static loading using a hydraulic actuator. The results from comparing the half-scale bridge bents show that the precast bent had more ductility and energy dissipation compared to the CIP bent. Figure 2 shows the numerical results in the form of the hysteresis loops.



Precast

Cast-In-Place

Fig. 2: Hysteresis Graphs of Half-scale Bridge Bents (1 kip = 1.45 kN)

After the specimens were tested, they were dissembled and stored at ISU. As shown in Figure 2, the precast bent with the pipe connection outperformed the CIP bent. Now ISU and ITD are presented with an opportunity and interesting research question: What is the best method for retrofitting of bridge piers with a pipe connection after an earthquake event?

The objective of this research is to experimentally validate some of the proposed retrofitting options for the pipe connection. The final design for the retrofit needs to be effective in restoring stiffness, strength, and displacement ductility of the pier by 70-80%. The design must also be practical, fast, cost-effective, and durable.

2 Literature Review

To find a sufficient repair method for the pipe-socket connection, a literature review of retrofitting methods for bridge piers was conducted. Through the review the following methods were investigated: steel jacketing (Bemstead et al., 2019), concrete jacketing (Krish et al., 2018), fiber-reinforced polymers (FRP), and external yielding elements (Wang et al., 2017). From the literature review it was obvious that a UHPC jacket would be the most ideal retrofit method for the project.

2.1 Steel Jacketing Literature Review

Many research projects have been conducted to investigate steel jacketing to seismically retrofit bridge piers. The concept is to confine the original concrete pier with a steel jacket through bolting or welding. The gap between the jacket and the damaged concrete is then filled with grout. Steel jackets can be the partial or full height of the pier. Steel jacketing significantly increases the pier stiffness due to an increase in the size of the cross-section of the pier (Chail et al., 1991). While steel jacketing is effective in restoring seismic performance; it is considered very costly and labor-intensive (Raza et al., 2019).

2.2 FRP Literature Review

FRP is advantageous compared to traditional jacketing methods (concrete and steel jacketing) because installation of FRP is less labor-intensive, installation is easy and relatively quick, and minimizes changes to the cross-sectional geometry of the bridge piers. The biggest disadvantage to FRP is de-bonding. In a study performed by Kotynia et al. (2008) on the strengthening of reinforced concrete beams using FRP, failure occurred in all specimens due to premature de-bonding of the FRP from the concrete surface which led to a lower strength utilization ratio (i.e. the ratio of strain in FRP at failure to its ultimate strain). Another disadvantage of FRP is that it is expensive and does not perform as well as in high temperatures or wet environments (Raza et al., 2019). The most common type of FRP used in seismic retrofitting is carbon fiber reinforced polymers (CFRP). Many studies have been conducted on the use of CFRP as a seismic retrofit technique. In an experimental study, it was found that CFRP can increase lateral load capacity by 7% in bridge piers, (Faustino & Chastre, 2016).

2.3 UHPC Jacketing Literature Review

UHPC is a concrete material that is composed of steel fibers, silica fume, fly ash, Portland cement, fine aggregates, admixtures and water. UHPC typically has a compressive strength of 18 to 35 ksi (124-228 MPa). A comparison of UHPC to normal-strength concrete (NSC) and high-strength concrete (HSC) can be seen in Table 1. The comparison in Table 1 shows that UHPC has many beneficial qualities over typical concretes.

Table 1: Comparison of properties of UHPC with NSC and HSC (Ahlborn et al., 2011)

Property	NSC	HSC	UHPC
Compressive Strength	3,000-6,000 psi (20.7-41.3 MPa)	6,000-14,000 psi (41.3-96.5 MPa)	18,000-33,000 psi (124.11-227.5 MPa)
Tensile Strength	400-500 psi (2.75-3.45 MPa)	-	1,000-3,500 psi (6.89-24.13 MPa)
Elastic Modulus	2,000-6,000 ksi (13.8-41.4 GPa)	4,500-8,000 ksi (31.02-55.16 GPa)	8,000-9,000 ksi (55.16-62.05 GPa)
Poisson’s Ratio	0.11-0.21	-	0.19-0.24
Porosity	20-25%	10-15%	2-6%
Chloride Penetration	>2000	500-2000	<100
Water-Cement Ratio	0.40-0.70	0.24-0.35	0.14-0.27

UHPC has been a popular repair method recently in Canada. Many retrofit projects in Canada are using UHPC jacketing methods. For example, Mission Bridge was recently seismically retrofitted in Abbotsford, British Columbia (Figure 3). Mission Bridge is a 1,126-meter bridge that crosses the Fraser River. One of the nineteen V-shaped concrete piers was retrofitted with UHPC jackets for two of the existing concrete columns. The jackets incorporated UHPC with a mild steel reinforcing cage. The retrofit was the final step in a series of seismic upgrades performed over several years, to ensure the integrity of this vital link in a high seismic zone. The project was completed in June 2014 (Doiron, 2016).

Fig. 3: Mission Bridge Seismic Retrofit Project Abbotsford, British Columbia, Canada, Doiron (2016)

3 Concept for Retrofit

After some preliminary literature review and discussion with ITD, the basis of retrofitting the precast pier is to utilize a UHPC jacket in the plastic hinge zone of the pier. The concept can be seen in Figure 4.

Preliminary calculations have been done for the design of the UHPC jacket using SAP2000. The precast column section with the UHPC jacket can be seen in the cross-section (Figure 5). Note that it has been decided to test using twelve no. 6 rebar dowels to push the plastic hinge above the jacket/pipe region and provide sufficient shear and flexural resistance at the column-to-footing interface for the first specimen. The first specimen will also include circular stirrups (no. 3 at a 1.5 in. spacing) for better confinement.

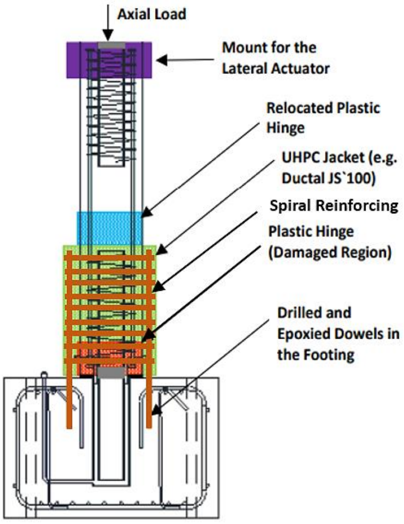


Fig. 4: Concept for UHPC Jacket (Green Section)

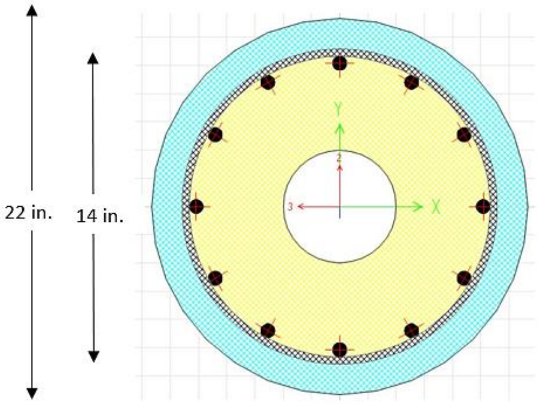


Fig. 5: Precast 1 Design

Note that since the pipe in this specimen is fractured, the moment capacity contribution from the pipe is conservatively taken to be negligible. Also note that for this specimen all of the cover concrete spalled, therefore the entire section, excluding the pipe, is taken to be UHPC. The jacket is designed to sit at a 4 in. (10.16 cm) thickness out from the original column diameter (14 in. or 35.56 cm), with an overall diameter of 22 in (55.88 cm).

4 Experimental Program

The experimental program follows the flowchart in Figure 6. Preliminary testing is done to quantify UHPC and NSC bond strength, tensile strength, and compressive strength. The UHPC used in the experimental program is JS1000 provided by Ductal.

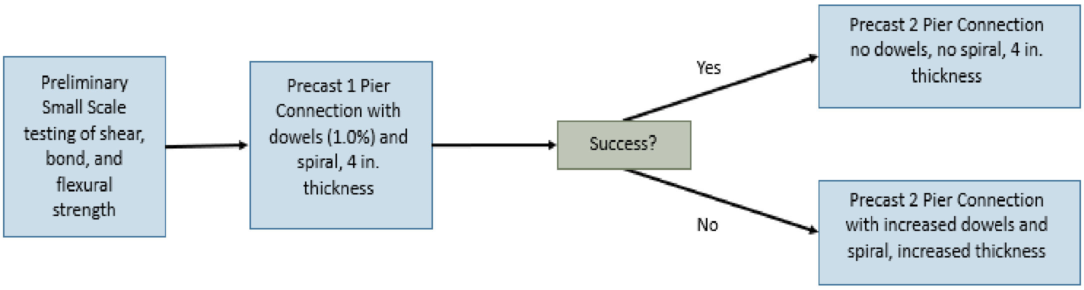


Fig. 6: Experimental program

5 Construction of Precast 1 and Testing

The design for the jacket of Precast 1 was accepted by ITD and construction began by ISU in July of 2022. The first step is to roughen the surface for the pour, as well as drill the concrete to allow for the tension dowels to be epoxied in (Figure 7-a). The next step is to assemble the cage (Figure 7-b). Lastly, the form is assembled and the UHPC is poured (Figure 7-c). Note that the jacket is poured while the pier is under a 30-kip (133kN) axial load to simulate the structure of a bridge.

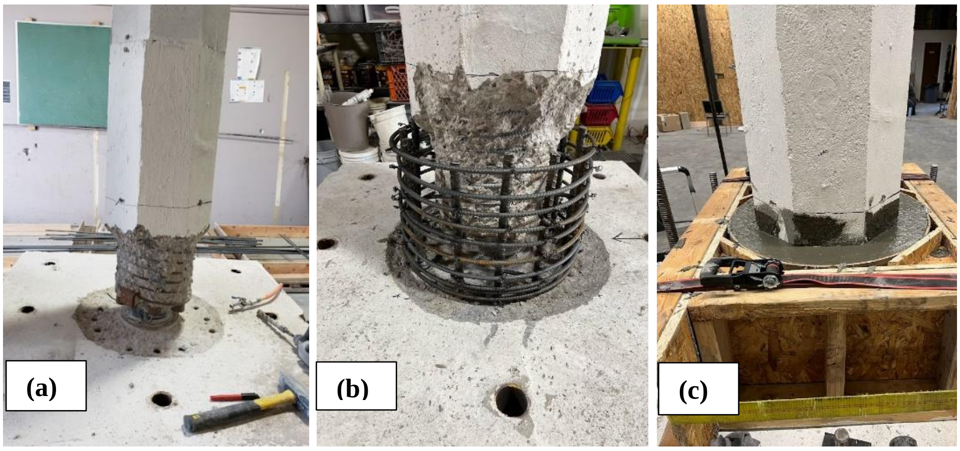


Fig. 7: Construction of Precast 1

After the pier is poured and cured, Precast 1 is instrumented and moved into the lab to get ready for testing. The test setup can be seen in Figure 8. The test is accomplished by programming the hydraulic actuator to run a loading protocol similar to the bent loading protocol, which has been scaled down for one pier. The loading protocol is a quasi-static cyclic loading protocol. During testing, the pier is monitored for cracks and spalling. Photos, videos, and documentation were taken as necessary.

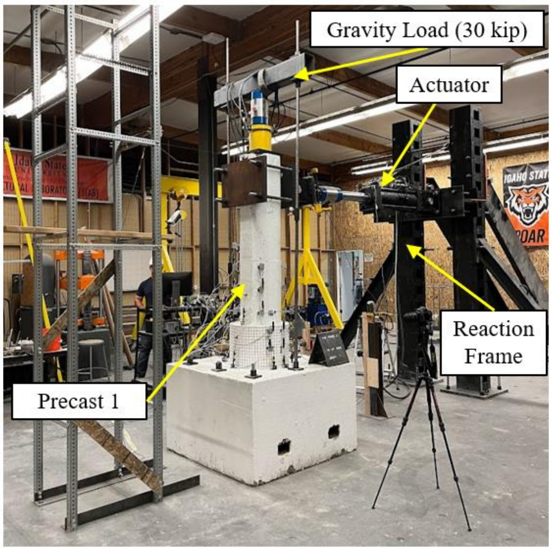


Fig. 8: Test set-up

6 Results for Precast 1

The results for Precast 1 can be seen in Figure 9. The jacket performed as expected and was successful in pushing the plastic hinge up the face of the column. The jacket saw no uplift from the footing and no separation from the column.

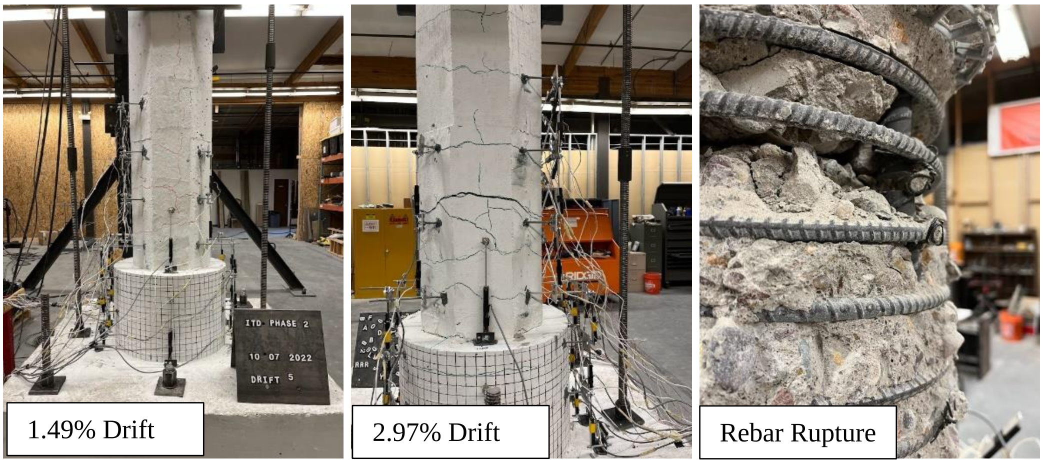


Fig. 9: Photos from Precast 1 Testing

The hysteresis of Precast 1 can be seen in Figure 10. The ultimate force for Precast 1 is 30.76 kip (137 kN) at 2.6% drift. Data from Precast 1 is still being analyzed and processed and will be presented in the future.

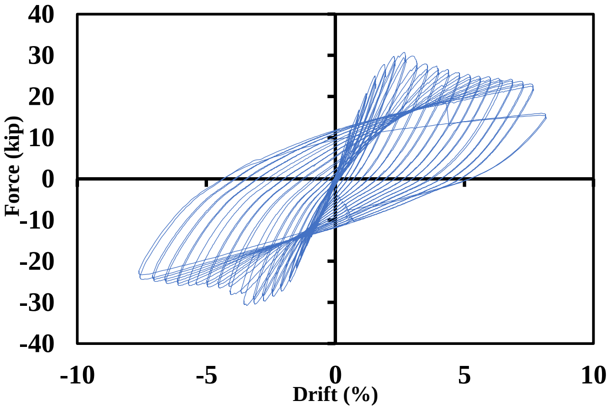


Fig. 10: Precast 1 Force vs Displacement (1 kip = 1.45 kN)

7 Construction of Precast 2 and Testing

After the success of Precast 1, Precast 2 was constructed. The design for Precast 2 was a 4 in. jacket with no steel reinforcing. The construction process follows the same steps as that of Precast 1, except for the concrete drilling. After Precast 2 is constructed, it was tested in the same manner as Precast 1. The testing used the same test setup and instrumentation. The same loading protocol was used for Precast 2. During testing documentation, photos, and videos were taken as necessary.

8 Results for Precast 2

The results for Precast 2 can be seen in Figure 11. The jacket succeeded in pushing the plastic hinge up the face of the column. Due to no tension dowels being used, the jacket and footing interface separated, creating rocking during testing. Despite the rocking, the column was still able to deform above the jacket. Due to the rocking, testing of Precast 2 ran longer by 4 cycles. The force vs drift hysteresis for Precast 2 can be seen in Figure 12. The rapid decline around at 6.64% drift is due to the rebar rupture.

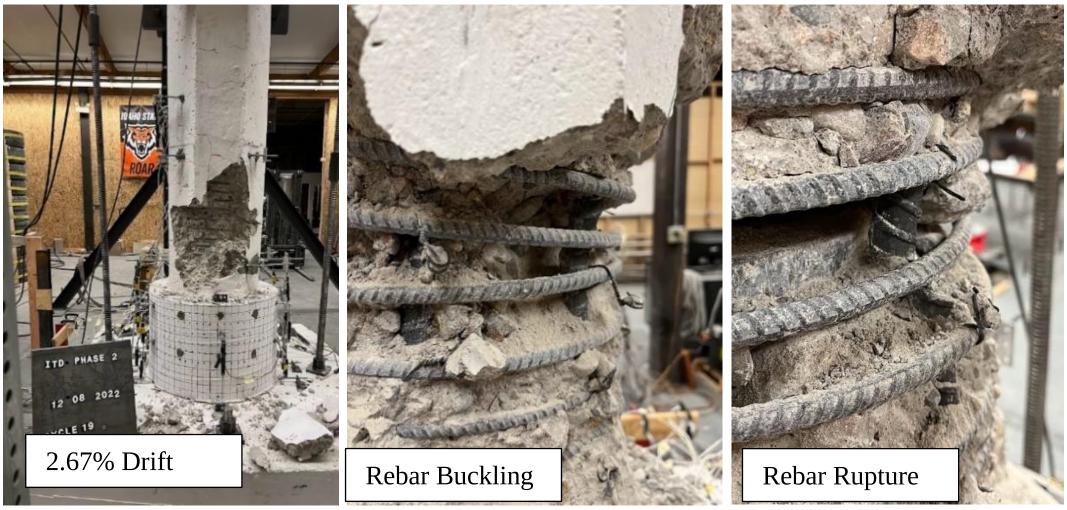


Fig. 11: Photos from Precast 2 Testing

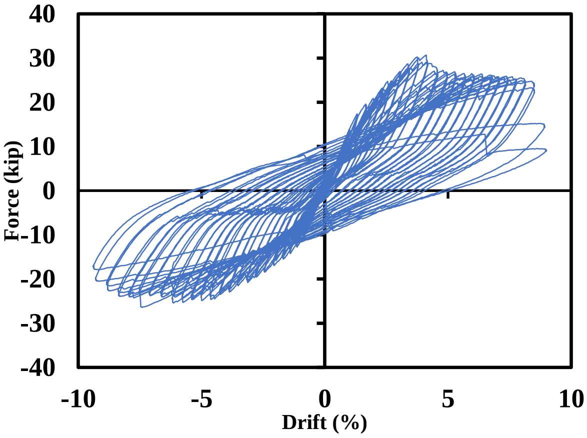


Fig. 12: Force vs Drift for Precast 2 (1 kip = 1.45 kN)

9 Conclusion

This project covers seismic retrofit of pipe-socket connected piers. The project investigated the suitability of UHPC jacketing methods. For Precast 1, a 4" UHPC jacket is used with light caging. Precast 2 incorporated a 4" UHPC jacket with no caging. Both methods for retrofit were successful. Precast 1 pushed the plastic hinge up the column face with no separation from the footing. Precast 2 succeeded in pushing the plastic hinge up the face of the column with separation from the footing and partial failure due to rocking. Precast 2 has just been tested in the ISU SLAB in December of 2022. More results are to become available as they are processed for comparison with the original pier and the two retrofit options. From observation, it is clear that the UHPC jacket method is a suitable method to retrofit the pipe-socket connection.

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