Field Testing of Precast UHPC Piles and Long-term Performance Monitoring

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ABSTRACT

In order to make the Ultra High Performance Concrete (UHPC) pile a viable foundation option in practice, the long-term performance monitoring of a UHPC production pile was planned in Iowa. As a precursor to this effort, two UHPC piles were field tested in order to ensure that the production pile will achieve the desired behavior and capacities.

First, a vertical load test was performed on a 46-ft UHPC test pile one week after being driven into the ground at the same site where the UHPC production pile was subsequently implemented into a 223-ft long integral bridge with a 24º skew. Before failure, the test pile resisted 1.5 times the predicted capacity based on the Iowa Bluebook method of design for concrete piles, verifying appropriateness of a 16% shortened UHPC pile length compared to the specified HP 10×57 production piles for the integral bridge. Additionally, a lateral load test was conducted on the second test pile with a newly designed splice detail, which confirmed the adequacy of the splice detail and the lateral load resistance. This paper summarizes the vertical and lateral load tests and presents the details about the instrumented UHPC production pile.

Keywords: UHPC Pile, Lateral Load Test, Vertical Load Test; field; implementation

INTRODUCTION

In 2005, the American Association of State Highway Transportation Officials (AASHTO) identified grand challenges that should be addressed through research advancements. The focus of two of these challenges is to extend service life of bridges, as well as optimize structural systems. Currently, AASHTO calls for a 75-year service life for bridges and highway structures[1]. In recent years, some bridges in the United States have been designed with a 100 to 150-year service life[2]. The characteristics of UHPC materials exhibit desirable qualities for increasing the service life of new bridges.

According to a special report by the Bureau of Transportation Statistics in 2006, approximately 12 percent of the Nation's bridge inventory was estimated to be structurally deficient and approximately 14 percent were functionally obsolete[3]. A major portion of bridge construction costs lies in the foundation with the average cost of a bridge substructure totaling approximately 30% of the total bridge cost[4]. Consequently, when extending the service life of a bridge, it is also important to increase the longevity of its foundation. Due to the cost and difficulty of maintaining bridge substructures, creative solutions are needed to extend the service life of structural systems by utilizing new and existing materials with advanced durability properties. The high strength available when using Ultra High Performance Concrete (UHPC) allows for reduced cross-section design and more efficient use of the material. In addition, the durability of UHPC also indicates the possibility of dramatically reducing or even eliminating the deterioration found in conventional pile options used for bridge foundations.

In a previous project, a UHPC pile section was designed and optimized[5]. Fig. 1 compares the cross-section of a steel HP 10×57 pile and a normal concrete pile to the UHPC pile, The UHPC pile was designed to: 1) overcome frequent damage that occurs to concrete piles during driving by utilizing the high strength of the UHPC material; and 2) provide vertical load carrying capacity that is equal to or greater than that of an HP 10×57 pile with the same outer cross-sectional dimensions resulting from the increased end bearing and skin friction components.

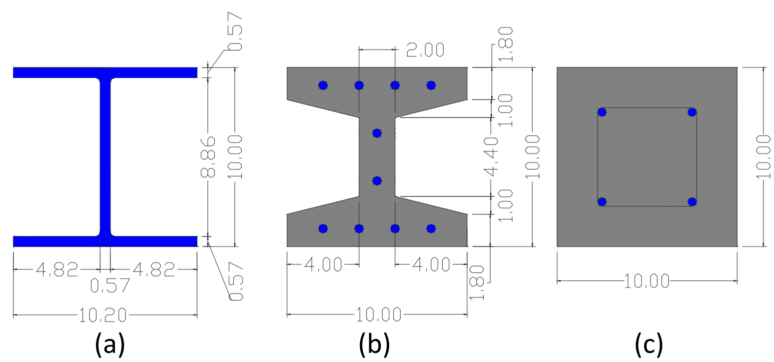

Fig. 1 Cross-Section of a) Steel HP 10×57 Pile; b) UHPC Pile; and c) 10×10-in. Normal Concrete Pile (all dimensions are in inches)

Following the successful laboratory testing of the pile-to-abutment connection detail[6], two test piles, P3 and P4, were fabricated for field testing, along with a UHPC production pile, UW1, to take the place of one HP 10×57 pile in a new bridge constructed in Sac County Iowa. A vertical load test was performed on one of the test piles to verify the vertical capacity of the UHPC pile. This test was followed by a lateral load test between the two

UHPC test piles in order to verify the performance of a splice detail in the field and to characterize the weak-axis lateral load behavior of the UHPC pile.

TEST SITE DESCRIPTION

A suitable new or replacement bridge for installing the UHPC production pile and instrumented HP 10×57 piles was selected using the following criteria: 1) integral abutment bridge; 2) length greater than 200-ft; and 3) stiff clay soil. The Sac County Bridge Project was the final choice to integrate a UHPC pile into a prototype bridge because of the bridge's ideal geometry, soil conditions and construction timeline that met the criteria sought by the research team. Of the two bridges at this site, the westbound bridge was chosen as the prototype bridge and is located just north of Early, Iowa, at the intersection of U.S. 20 over U.S. 71.

The prototype bridge is 223-ft in length and 40-ft wide with a 24 degree skew. The bridge consists of three spans with span lengths of 55′-9", 106′-6", and 60′-9" from west to east. HP 10×57 steel piles were designed to support the two abutments and the two bridge piers. The soil at the Sac County Bridge site consists of clay and silty clay. According to the Iowa Department of Transportation (DOT) soil report, the water table is located approximately 20.5 feet below the ground surface.

The site for testing P3 and P4 was located near the west abutment of the westbound bridge where the UHPC production pile would be located to verify the capacity of the shortened UHPC pile with respect to the production steel HP 10×57 piles. Fig. 2a illustrates the approximate locations of the UHPC test piles and UHPC production pile with respect to each other. To identify the location of the UHPC production pile and instrumented steel HP 10×57 production piles, both abutments of the westbound bridge are shown in Fig. 2b.

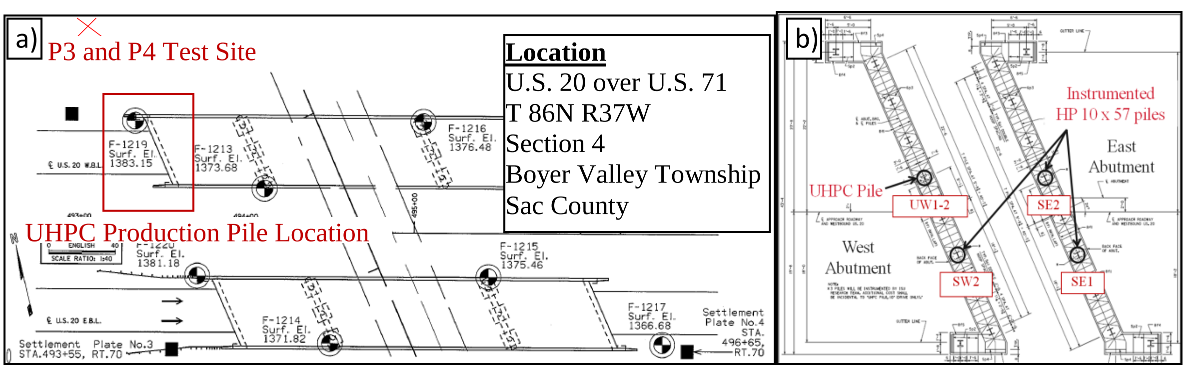

Fig. 2 Location of a) Field Testing; and b) Instrumented Production Piles

FIELD TESTING OF P3 AND P4

Based on the vertical load test previously completed by Vande Voort et al.[5], the ultimate capacity of the UHPC pile was found to be 86 percent higher than that of the HP 10×57 pile having the same length due to the increased toe area and perimeter. As a result, a steel pile could be replaced with a shorter UHPC pile to achieve the same vertical load capacity, which was the intent for the production pile planned for the Sac County Bridge project. To ensure that a reduction in length of the UHPC production pile would perform as well as the HP 10×57 production pile, a vertical load test was performed on test pile P3. A second UHPC test pile (P4) was installed with a splice to confirm its performance during driving which was followed by a lateral load test to verify the laboratory testing performed on the proposed splicing detail[6] as well as to characterize the weak-axis bending behavior of the UHPC pile. The splice for the UHPC pile was established using a welded detail by incorporating the splice attachment shown in Fig. 3 at the splice end of each pile segment before the prestressing strands were placed and stressed.

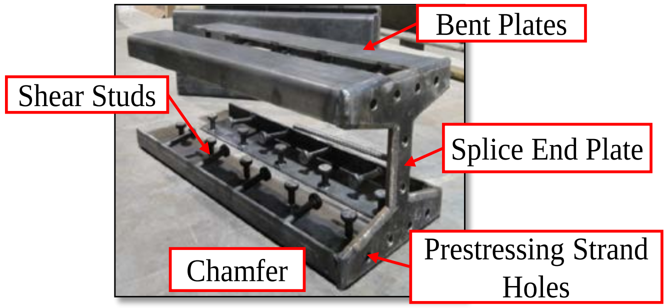

Fig. 3 Embedded UHPC Pile Splice Attachment

DESIGN AND INSTRUMENTATION OF TEST PILES

The design lengths of the vertical load test pile and two reaction piles were calculated using the current Iowa DOT Bridge Design Manual[7]. In preparation for the vertical load test, P3 was designed for a 100 kips design load, which required a 46-ft long pile with 42 feet embedded into the ground. The reaction piles were given the names Reaction Pile South (RPS) and Reaction Pile North (RPN). The reaction piles were designed to resist axial tension, with a total reaction frame capacity of 340 kips. Both reaction piles were 80 feet in length with 73 feet embedded into the soil.

Embedded concrete strain gages were used to measure the strains along the length of the UHPC test piles and were installed at Coreslab Structures, Inc. in Bellevue, Nebraska. A total of twenty strain gages were installed in P3 and six strain gages were installed in P4. As shown in Fig. 4, 2×3-in. steel plates were embedded into the web of P4 to provide a surface for welding a 1.5-in diameter steel pipe in order to enable the installation of a ShapeAccelArray (SAA) after driving.

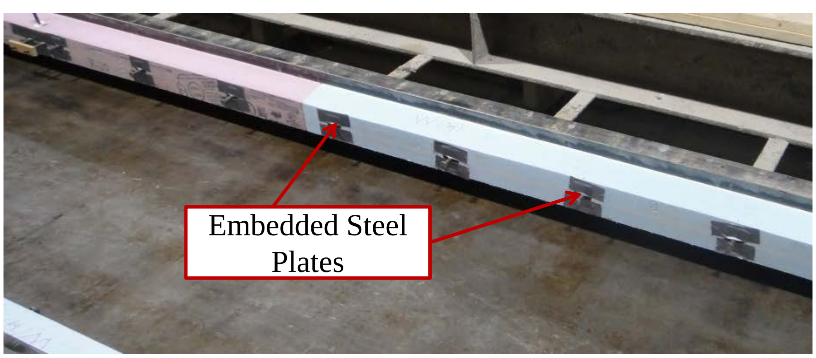

Fig. 4 Embedded Steel Plates along P4 before Pouring

During driving, Pile Driving Analyzer (PDA) equipment was used to measure the driving stresses of the test piles and also to predict the capacity of the piles. A pair of PDA strain gages and a pair of accelerometers were installed by inserting a bolt through the holes in the web and on the flange 30-in below the test pile head. The accelerometers were installed on the opposite flanges of the pile, due to the limited space on the web of the UHPC pile resulting from the tapered flanges. To ensure the accelerometers remained flat and tightly bolted to the pile, inclined steel brackets were used between the accelerometer and pile. The readings were wirelessly transmitted to and recorded by the PDA unit.

INSTALLATION OF TEST PILES

Before driving began, two 15 foot long piles were welded together end-to-end while placed horizontally on the ground as shown in Fig. 5. Once the splice was complete, the steel pipe for the SAA was welded to the web of P4 so that it could be driven with the test pile.

Fig. 5 Splicing UHPC Test Pile Horizontally on the Ground

The installation of the UHPC test piles was similar to that of the steel reaction piles. The low soil resistance at the beginning of driving required the ram to be raised manually several times before the DELMAG 19-32 hammer was able to develop enough combustion pressure to run continuously.

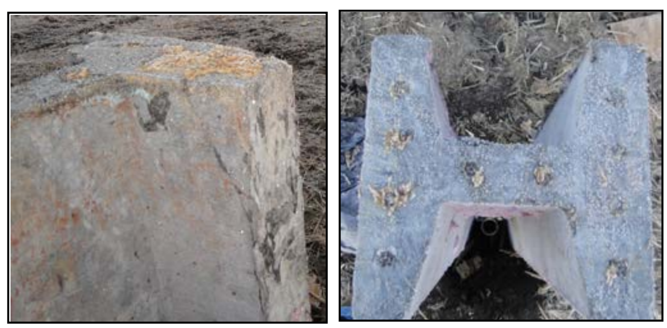

Fig. 6 a) Slight Damage to P3 at End of Driving (EOD); and b) No Visible Damage to P4 at EOD

A 4-in. plywood pile cushion was used for the UHPC test piles, but both test piles punched through the pile cushion shortly after driving had begun. Instead of replacing the damaged cushion, the pile was driven with essentially no cushion. Slight cracking was observed on the corners of the 46-ft pile and no visible damage to the 30-ft pile as shown in Fig. 6a and Fig. 6b, respectively. It was suspected that the pile head was not perfectly centered under the helmet, causing slight cracking to the top of pile P3.

VERTICAL LOAD TEST

Test Setup and Procedures

After the test piles and reaction piles were installed, the top 12 inches of the reaction piles were cut off and two 40-in. long HP 10 x 57 pieces were welded to each flange of the reaction piles. The main reaction beam was lifted and placed on the protruding flanges of the side pile pieces. Four 3-in. diameter rods were lowered through the holes in the height adjusters and clamping beams, the spaces between each side pile piece web and the corresponding anchor pile web. Finally, sleeved rod nuts were tightened against the bottom plate directly underneath each side pile piece. The completed load frame is shown in Fig. 7.

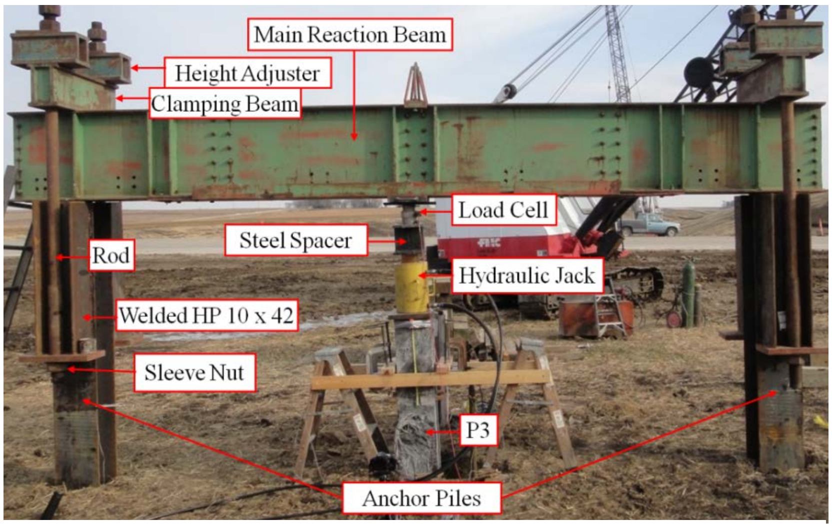

Fig. 7 Complete Vertical Load Test Setup

The vertical load test was completed following "Procedure A: Quick Test" as outlined in ASTM D 1143/D 1143 M – 07[8]. Accordingly, the test pile was loaded in five percent increments up to the anticipated failure load. The load was kept relatively constant during each load step until deflection readings had stabilized, which specified a minimum of 5 to 15 minutes for each step. Vertical deflection, strain, and load measurements were recorded electronically every second. The Davisson failure criterion[9] was used to determine the ultimate capacity of the pile.

Observations and Results

The load-displacement behavior of P3 is presented in Fig. 8. P3 was loaded to a maximum value of 297 kips and a maximum downward displacement of 0.71 inches. The Davisson Failure Criterion Line[9] was calculated using Equation (1), which corresponds to the load at the point where the Davisson Failure Criterion crosses the measured load-displacement curve. The ultimate measured capacity of P3 was determined to be 297 kips, which was 49 percent higher than the predicted ultimate capacity of 200 kips.

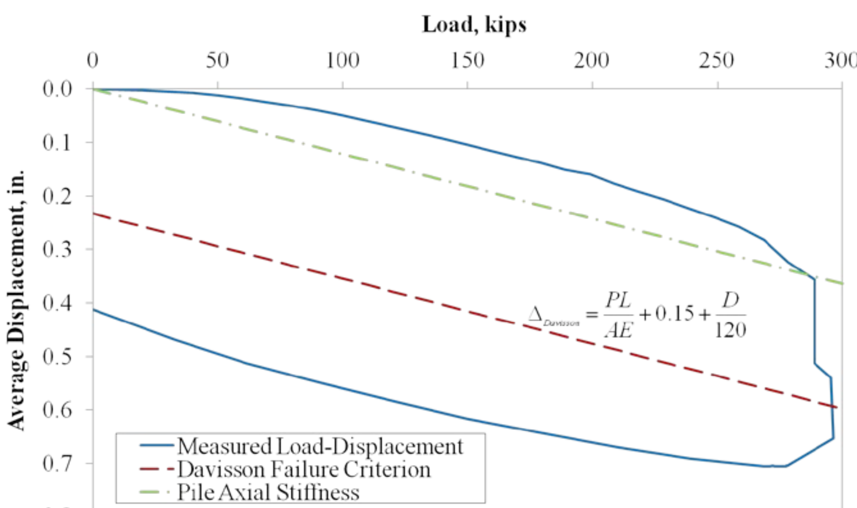

Fig. 8 Force-Displacement Curve of P3 during the Vertical Load Test

$$\Delta_{Davisson} = \frac{PL}{AE} + 0.15 + \frac{D}{120} \tag{1}$$

where: P = axial load, kips
L = length of pile, in.
A = cross-sectional area, in^2
E = modulus of elasticity, ksi
D = diameter of pile, in.

The strain gages embedded along P3 provided information about the skin friction along the pile. Fig. 10 shows the average calculated load transfer along the length of the pile from the measured strains. Even though the maximum vertical load applied to the test pile was 297.25 kips, the measured axial load from the strain gages 4 feet from the top of the pile head was only 220 kips as shown in Fig. 10.

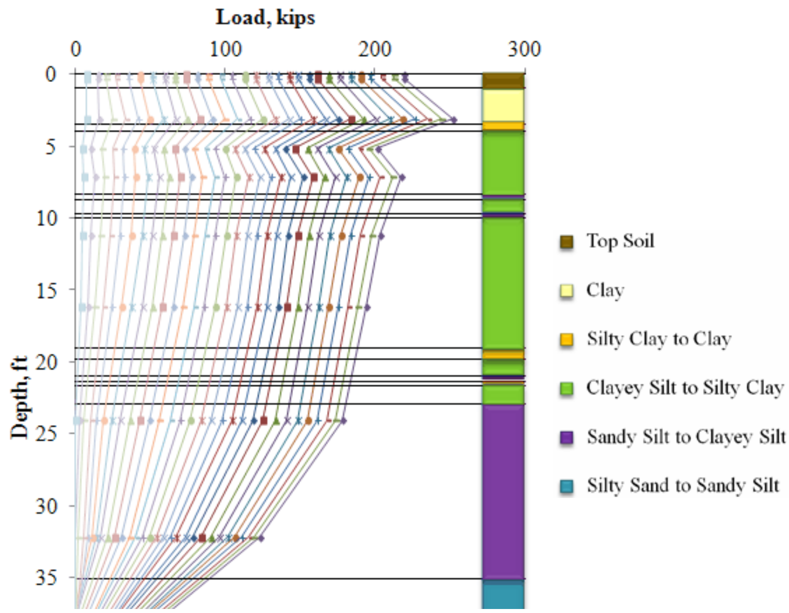

Fig. 9 Load Transfer Response of P3 during the Vertical Load Test

One of the reasons that the load transfer curve does not match the measured applied load could be due to the way in which the gages were installed during the prefabrication process. The embedded strain gages were suspended between two prestressing strands. When UHPC was poured, the gages could have tilted in the y-direction or shifted in the x-direction changing the angle of the gage as well as the distance from the neutral axis.

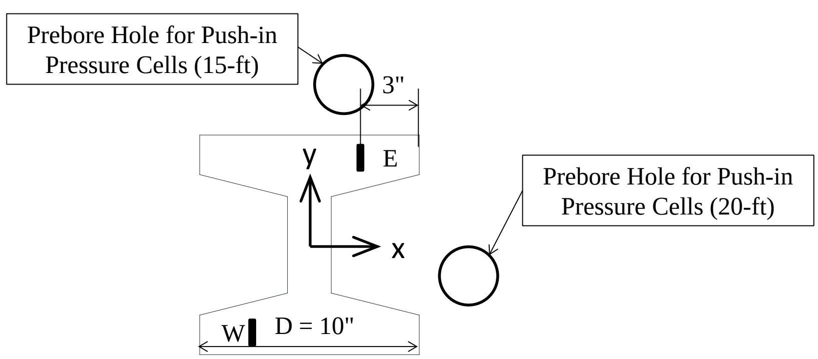

Fig. 10 Location of Push-In Pressure Cells Relative to P3

Furthermore, P3 was installed very close to 4-in diameter boreholes where the push-in pressure cells were installed as noted in Fig. 10. The depth of one of the push-in pressure cells is 15 feet and the other 20 feet from the ground surface. A void around P3 was formed during installation which was measured to be 5 feet deep from the ground surface.

After driving of pile P3, it was noted that the pile had noticeable inclination in both the x-axis and y-axis directions. Fig. 11 shows the tilt of P3 in the strong-axis and weak-axis directions. The tilting angle causes two force components, vertical (P_v) and horizontal (P_h), which induces a moment on the pile. Additionally, the hydraulic actuator was not placed exactly on the center of the pile during load testing. This causes the vertical force to be applied with an eccentricity in both directions. These issues are being investigated to understand the measured strains with respect to the applied vertical load.

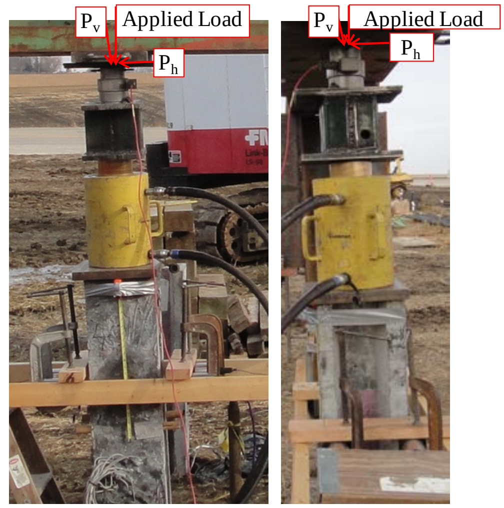

Fig. 11 Tilt of P3 after Driving in the a) Weak-Axis Direction; and b) Strong-Axis Direction

LATERAL LOAD TEST

Test Setup and Procedures

A 100 kip actuator was used to apply the lateral load to P3 and P4 simultaneously. The actuator was clamped 14.5 inches below the pile head of P3, and a steel spacer was clamped 8 inches from the pile head of P4. A 300-kip load cell was used to measure the applied load, which was positioned in line with the actuator and steel spacer. The completed test setup is shown in Fig. 12. The SAA was inserted into the steel pipe that was welded to the embedded plates of P4. The SAA ran along the east side of 30-ft. test pile for the top 20 feet. Three-dimensional displacements and rotations were recorded during testing.

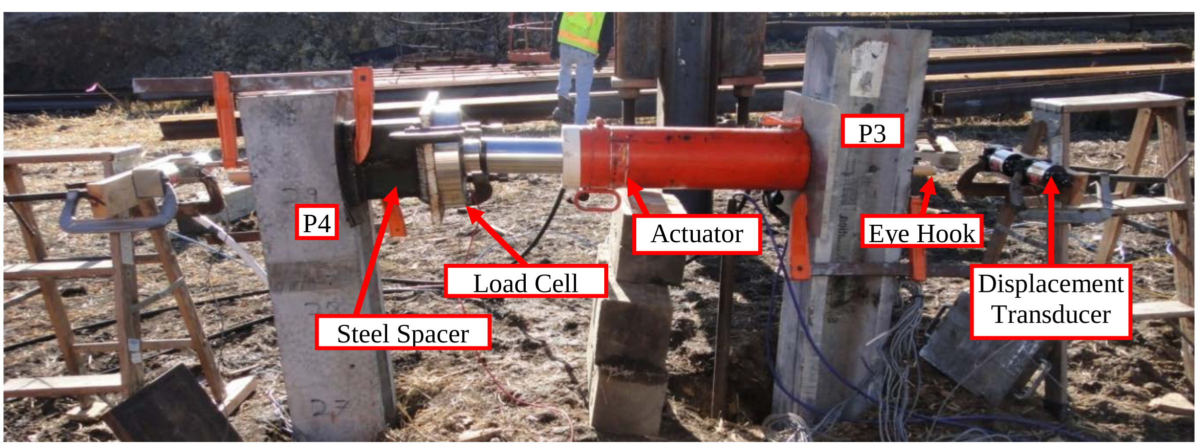

Fig. 12 Complete Lateral Load Test Setup (locate below the figure)

The lateral load test was completed following "Procedure A: Standard Loading" of ASTM 3966-07[10]. The procedure recommends applying a design load of 200% of the proposed pile lateral design load unless failure occurs first. A design lateral load of 10 kips was used for the test with a maximum lateral load of 20.6 kips.

Observations and Test Results

P3 was tested in strong-axis bending during the lateral load test. The lateral force-displacement curve is given in Fig. 13. The maximum load that P3 was subjected to is 20.6 kips corresponds to 1.7 inches of lateral displacement with a total residual displacement of 0.03 inches after completing all load cycles.

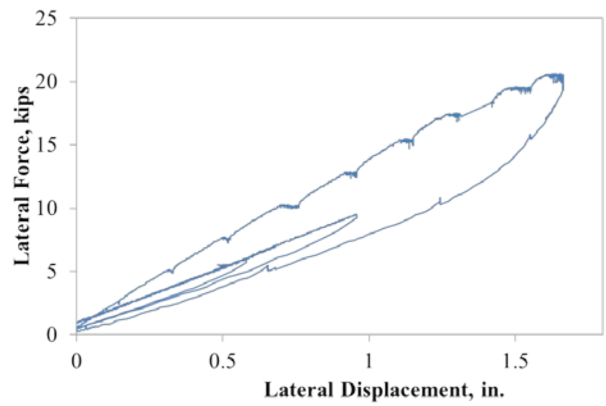

Fig. 13 Force-Displacement Curve P3 during the Lateral Load Test

As previously mentioned, P4 was tested in weak-axis bending. Fig. 14 shows the lateral force-displacement curve for P4. The maximum measured load was 20.6 kips and the maximum lateral displacement was 10 inches. There was noticeable heaving of the soil on the east side of P4 during the lateral load test. P4 had a 2.35-in. residual displacement after completing all load cycles.

The splice on P4, located 15 feet from the pile head, performed very well during installation and testing. No visible damage from driving or the lateral load test was found on or near the splice after excavation. The splice was subjected to compressive stresses of 5.7 ksi and a tensile stress of 0.1 ksi during driving. The final elevation of the splice was 12 feet below the ground surface. Based on the field measurements, the splice was subjected to 2.6 kips of shear, 52.4 kip-in of bending moment, and 0.1-in of lateral displacement.

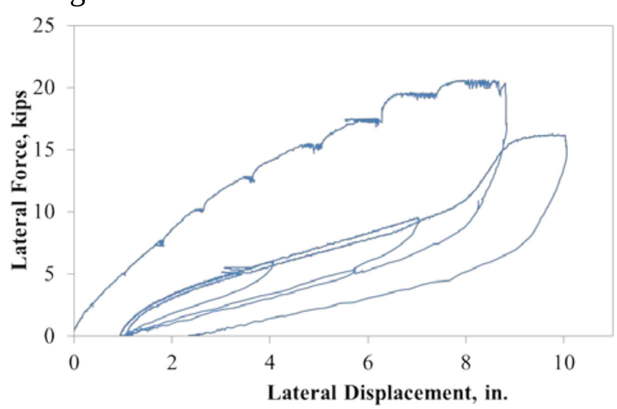

Fig. 14 Force-Displacement Curve of P4 during the Lateral Load Test

Compared to the laboratory test[6], in which the splice was subjected to significantly high shear and bending actions, the splice attachement proved to be very robust with a shear capacity in excess of 45 kips, the maximum shear demand during the lateral load field test was not expected to be significantly higher than 20.6 kips or 50 percent under weak axis bending. Thus, the performance of the splice in the field is expected to adequately meet the required shear and moment demands of the UHPC piles under weak axis bending.

INSTALLATION OF UHPC PRODUCTION PILE

After the field testing had been completed, the UHPC production pile (UW1-2) was installed into a prototype bridge with the overall goal of determining the suitability of UHPC piles in integral bridge foundations. This task was accomplished as part of this project by replacing a steel HP 10 x 57 pile having a design capacity of 100 kips, with an equivalent, shorter length UHPC pile during the construction of a new bridge.

DESIGN AND INSTRUMENTATION OF PRODUCTION PILE

The steel HP 10 x 57 piles for the prototype bridge were designed for 100 kips of vertical load using the Iowa DOT Blue Book Method[7]. As previously noted, the UHPC production pile (UW1) was used to replace one of the HP 10 x 57 piles, and thus UW1 was also designed for a 100 kip vertical load.

The instrumented HP 10 x 57 pile on the west abutment (SW2) had a total length of 65-ft with 62-ft embedded below the ground surface. Due to varying soil profiles between the west and the east abutments, the two instrumented HP 10 x 57 piles on the east abutment, SE1 and SE2, had a design length of 85-ft with an embedment of 82-ft. UW1 was designed with a total length of 56-ft and a 53-ft embedment below ground surface for a 100 kip design load—a 15% reduction in the pile embedment length.

The instrumentation used for the first UHPC production pile (UW1-1) was the same embedded concrete gages that were used for the test piles. This first pile UW1-1 was inadvertently damaged due to poor handling, which led to the preparation of a second identical production pile (UW1-2). For the instrumented steel piles, weldable strain gages were used along the length of the pile and were protected by a steel angle welded to the pile. All of the production piles had two gages at each level that were placed diagonally to measure the curvature of the pile during the expansion and contraction of the integral bridge due to thermal effects.

INSTALLATION OF PRODUCTION PILE

The steel piles were lifted into position by using the pickup point shown in Fig. 15. The pile was lifted to a vertical position and set into the 10-ft deep prebore hole. The crane was unhooked from the steel pile to pick up the hammer leads and position them on the top of the steel pile. When the leads, hammer and pile were in place, the ram of the hammer was lifted manually by the crane and dropped.

Fig. 15 Pickup Point for Steel Piles

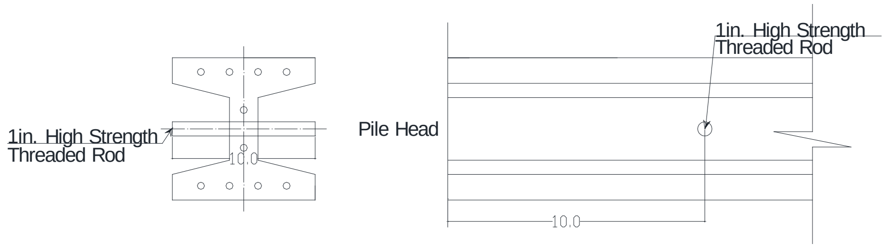

Fig. 16 Illustration of the New Pickup Point for UW1-2

The new pickup point for the UHPC pile was designed to sustain a similar procedure as the steel pile, as drawn in Fig. 16. During construction, the pile was picked up using the pickup point at the pile head and the inserted prestressing strand hook at the toe of the pile. Once the pile was lifted off the ground, the crane operator rotated the pile to the vertical position in the air as shown in Fig. 17, which was very similar to that of a steel H-pile.


Fig. 17 Stages of the Pickup of UW1-2

A 4-in. plywood pile cushion was used to protect the UHPC pile head, but UW1-2 punched through the pile cushion shortly after driving had begun. Instead of replacing the cushion with a new one, the pile was driven with essentially no cushion. There was slight cracking to the pile head corners of UW1-2 as shown in Fig. 18. This insignificant damage could also be due to the pile head being not perfectly centered under the helmet. It is also important to note that the UW1-2 was slightly tilted after driving and on the west side of the prebore hole as shown in Fig. 18.


Fig. 18 Slight Damage to UW1-2 at EOD

CONCLUSIONS

For the vertical load test, the UHPC test pile reached an ultimate capacity of 297 kips which is 49 percent greater than the estimated nominal capacity of 200 kips. Both lateral test piles were subjected to a maximum lateral load of 20.6 kips with the largest lateral displacement of 10 inches for the pile that experienced weak-axis bending. The splice on P4, 15 feet from the pile head, performed well during installation and testing, with no distress to the splice or the pile connected to the splice attachment. Based on laboratory and field testing, the performance of the splice in the field can be expected to meet the required shear, moment and tensile demands. An overall conclusion of the research outcomes reported herein is that the UHPC pile can successfully be implemented in integral abutment bridges to support both the abutments and pier foundations.

ACKNOWLEGMENTS

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