EXPERIMENTAL EVALUATION OF UHPC PILES WITH A SPLICE AND PILE-TO-ABUTMENT CONNECTION PERFORMANCE

Sriram R. Aaleti, PhD
Post doctoral research associate, Department of Civil, Construction, and Environmental Engineering, Iowa State University, Ames, IA

Jessica Garder
Graduate research assistant, Department of Civil, Construction, and Environmental Engineering, Iowa State University, Ames, IA

Sri Sritharan, PhD
Wilson Engineering Professor and Associate Chair, Department of Civil, Construction, and Environmental Engineering, Iowa State University, Ames, IA

ABSTRACT

A tapered, H-shaped, precast UHPC pile was previously developed at Iowa State University (ISU) as a means for increasing the longevity of bridge foundations and reducing the maintenance cost in comparison with steel and concrete piles.
To advance the field implementation of the UHPC piles in bridges and with an emphasis on promoting accelerated construction, an ongoing study has investigated a) filed splicing of the UHPC piles b) a pile-to-abutment connection detail appropriate for both cast-in-place and precast cap and abutment using large-scale experimental testing. Full-scale pile-to-abutment connection subassemblies representing a portion of a typical bridge pile foundation used in Iowa were tested under combined vertical axial forces and cyclic lateral displacements representing the cyclic thermal movements expected in integral abutment bridges. The experimental investigations revealed that the pile-to-abutment connection will not sustain any damage before the failure of the piles. The test results, observations and conclusions will be summarized in this paper.

Keywords: Pile foundations, Ultra high performance concrete (UHPC), Precast piles, integral abutment, pile splices, full-scale testing

INTRODUCTION

A significant portion of the United States bridge infrastructure is rapidly approaching the end of its intended design life. Furthermore, a recent evaluation of the current condition of bridges by the American Society of Civil Engineers resulted in a 'C' grade, due to the structural deficiency or functional obsoleteness of one in four of the nation's bridges [1]. According to the recent National Bridge Inventory database, at the end of 2011, the estimated total number of bridges in the nation was 605,102, of which 67,526 (11.2%) were identified as structurally deficient, while 76,366 (12.6%) were listed as functionally obsolete [2]. This necessitates an urgent development of new techniques, materials, and systems for rehabilitation and replacement of these deteriorated structures using accelerated construction.

Additionally, the AASHTO strategic plan in 2005 [3] for bridge engineering identified extending the service life of bridges as one of the greatest challenges. Producing safer, economical bridges at a faster rate, with a minimum service life of 75 years and reduced maintenance costs, is a driving objective to satisfy the infrastructure needs of the country. Several State Departments of Transportation (DOTs) and the Federal Highway Administration (FHWA) are engaged in the development of broadly applicable bridge components which are economical, highly durable and utilized in rapid construction using high performance materials. The superior structural and durability characteristics of the Ultra High Performance Concrete (UHPC) make it an ideal solution to address multiple grand challenges related to the bridge applications. Previous use of UHPC for bridge applications (mostly in bridge girders) [4, 5] in the United States has proven to be efficient and economical.

Foundations in the routine bridge can contribute up to 30% of the overall bridge cost. Furthermore, increasing the longevity of bridges requires an increase in the durability of the foundation as well. Consequently, consistent with the goals of the AASHTO, a tapered, H-shaped, UHPC pile (see Figure 1a(i)) was previously developed at Iowa State University (ISU) as a means for increasing the longevity of bridge foundations and reducing the maintenance cost in comparison to exposed steel and concrete piles and piles in aggressive environments [6]. The cross-section details and structural behavior of the UHPC pile and a commonly used steel H-pile in Iowa (HP 10 x 57) are compared in Figure 1. The full-scale vertical and lateral load tests on UHPC piles revealed several benefits of the UHPC pile including reduced risk of damage during driving, drivability with a greater range of hammers and strokes, and use of the existing equipment for pile handling and driving [6]. To accelerate the field implementation of the UHPC piles in bridge foundations, large-scale experimental testing of connections for the field splicing of UHPC piles and the pile-to-abutment connections appropriate for both cast-in-place and precast cap and abutment were performed at Iowa State university (ISU). Full-scale pile-to-abutment connection subassemblies representing a portion of a typical Iowa bridge pile foundations were tested under combined vertical axial load and cyclic lateral displacements representing thermal movements expected in integral abutment bridges (IAB). The summary of this experimental study is presented in this paper.

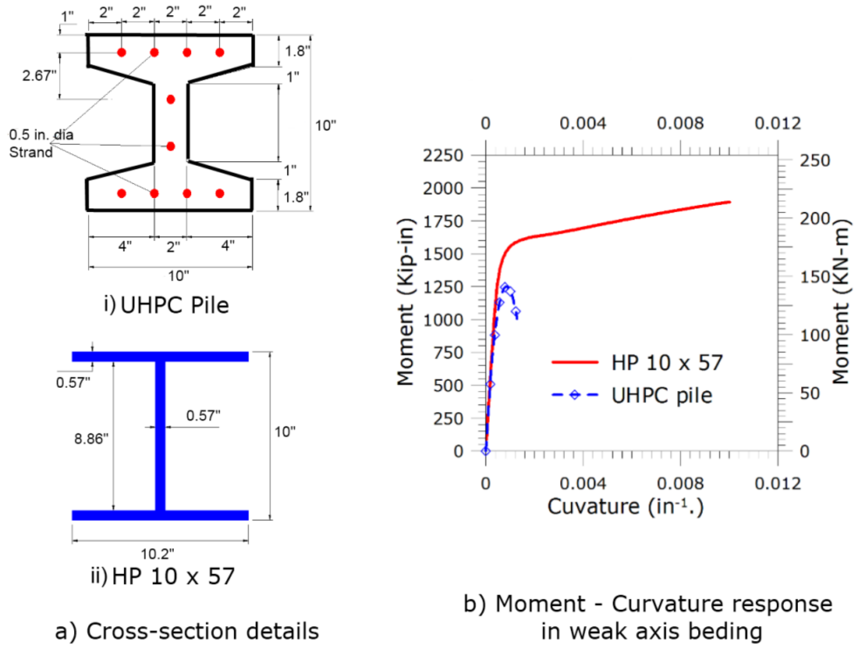


Figure 1 Comparison of details and section behavior of UHPC pile and steel HP 10x 57

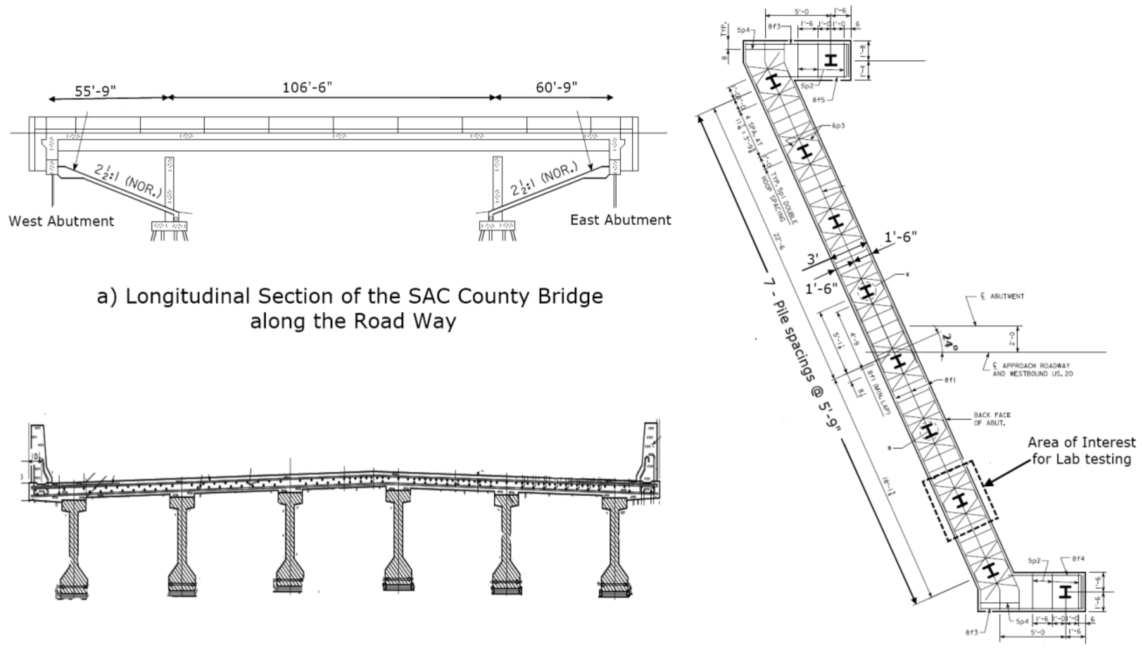
PROTOTYPE BRIDGE AND CONNECTION DETAILS

Integral Abutment Bridges (IAB)

Integral abutment bridges are widely used by several DOTs due to the reduced need for maintenance when compared to jointed bridges. These IABs consist a continuous deck and a movement system, composed primarily of stub abutments supported on a single-row of flexible piles. The seasonal and daily temperature changes impose cyclic horizontal displacements on the piles supporting the abutments. The design of IABs has mostly depended on local practices due to lack of knowledge on the behavior of IABs with respect to thermal movements and soil-structure interaction. So, in recent times several long-term monitoring studies on the IABs were performed by several researchers and a summary of key findings from these studies are presented in Garder (2012) [7]. The thermal movement of the IABs depends on the bridge length, bridge type (concrete or steel), soil properties and treatment of soil behind the abutments. Based on the available literature, it was found that an integral abutment in typical bridges moves on average by an inch (contraction or expansion) in longitudinal direction of the bridge. Also, Iowa DOT requires that the piles supporting integral abutment and their connections are designed for a maximum expected longitudinal thermal movement of 1.55 inches.

Prototype Bridge

A 223-ft long and 40-ft wide integral abutment bridge in Sac County, Iowa was selected for the field implementation of the proposed UHPC pile due to the bridge length and the site soil conditions. Also, at this length, the bridge is expected to subject the piles in each abutment to an average deformation of 1 in. during thermal expansion and contraction. The details of the bridge are shown in Figure 2. The bridge consists of three spans of lengths 55′-9", 106′-6", and 60′-9" from the west to the east. The abutments were designed according to the standard Iowa DOT details [8] with 80-100 ft long HP 10 x 57 steel piles. The soil at the Sac County bridge site consists of cohesive clay and silty clay. More details about the soil profile and prototype bridge are presented in Garder (2012) [7].



a) Longitudinal Section of the SAC County Bridge along the Road Way

b) Cross section of the SAC County Bridge

c) East Abutment Details

Figure 2 Details of the SAC County Bridge in Iowa

UHPC Pile Splice Details

Splicing of the piles is commonly done in practice due to the limitations in handling the long piles and the associated costs. There are several splicing details available in literature for precast concrete piles. However, with the optimized H-shape of the UHPC pile, there were no suitable splice connection details available for field splicing of the UHPC piles. Based on the literature on available splices, dry connections comprising of welding, bolting or quick-set grout, are typically preferred to extend the piles in the field during driving. The dry connection details helps in reducing construction delays. Also, it is a common practice to use welding when steel piles are spliced as this considered an efficient technique in the field. Consequently, a welded detail was developed for the splice of the UHPC piles. Figure 3 shows the steel embedment used at the ends of the UHPC piles, which facilitates welding between two H-shaped steel plates to establish the connection. The steel embedment consisted of a ½ in. thick, H-shaped A50 steel plate with four ¼ thick corner steel angles with shear studs. This splice was designed to have a minimum of 50% of the pile tension capacity and 100% of the pile moment and shear capacity.

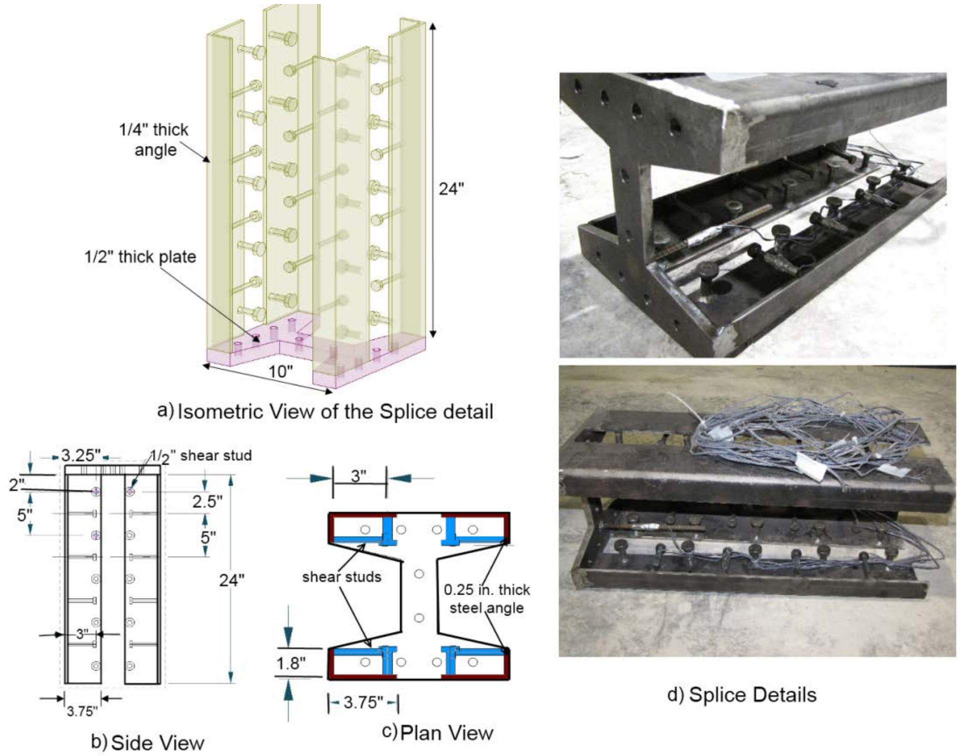


Figure 3 Splice details

UHPC Pile – to – Abutment Connection Details

The connection of the UHPC pile-to-abutment was established using the typical Iowa DOT standard details that are routinely used for steel pile-to-abutment connection [8]. This connection detail was preferred as this will minimize the changes needed to an already well-established construction method. Figure 4 shows the typical details used widely in Iowa for steel HP pile-to-abutment connection. The pile is embedded 2 ft into the abutment and a 21 in. diameter, #2-spiral with 3 in. pitch is provided along the embedded length for the confinement around the pile. Special bent bars (6p3 bars) (see Figure 4b) are provided at 3 in. from the bottom of the abutment to prevent any side punching shear failure of the abutment.

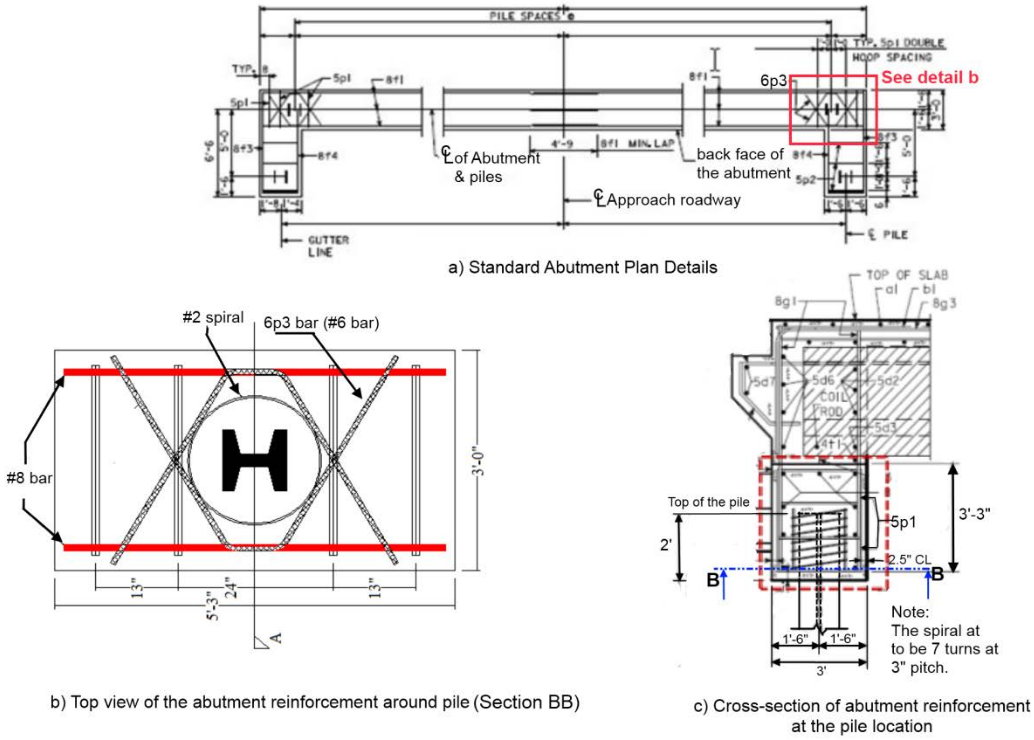


Figure 4 Standard pile-to-abutment connection details used in Iowa

EXPERIMENTAL PROGRAM

UHPC Splice Connection Tests and Observations

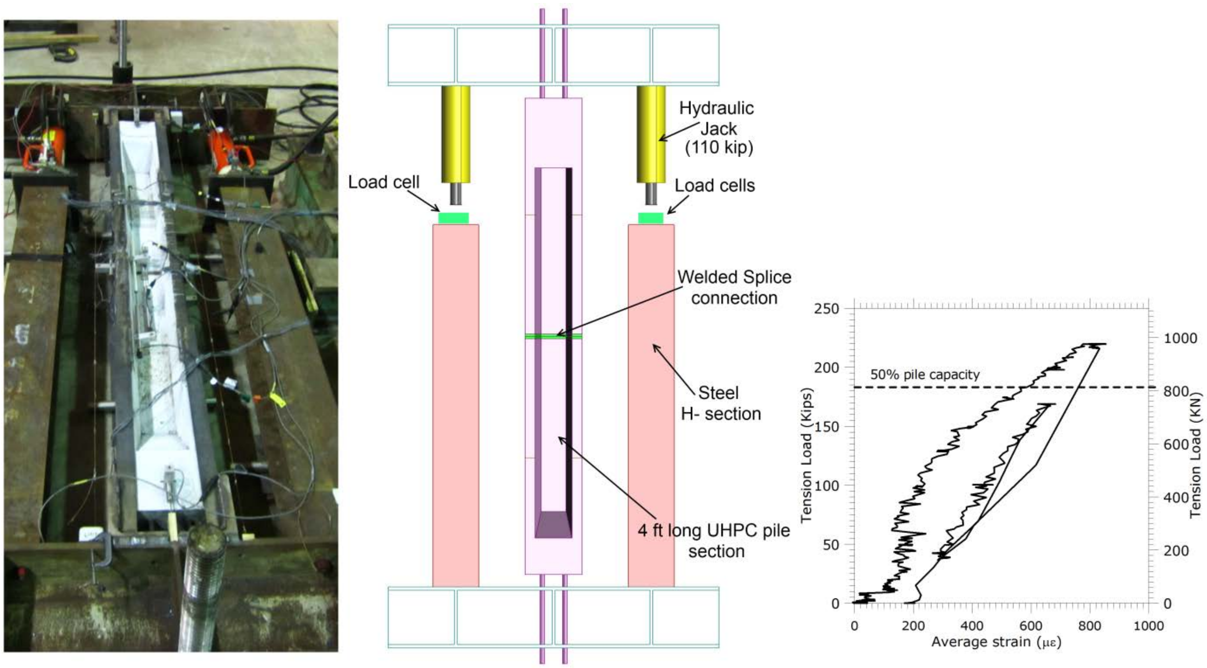
Full-scale laboratory tests have been completed to verify the expected behavior and to ensure adequate capacity of the UHPC splice connections. The laboratory investigation included the testing of the splice region under direct tension, as well as, critical shear and flexural stresses. A total of six different tests including, weak and strong axis bending tests, three shear load tests and a direct tension test were performed. The details of the load tests conducted are summarized in Table 1. Two test units were used for these tests. In each case, two 4 ft long UHPC pile segments with steel splice embedment (See Figure 3) were cast and spliced together using a 5/16 in. fillet weld going all around the perimeter of the end plates.

Table 1: details of tests for splice characterization

S.NO	Test type	# of tests conducted	purpose
1	Direct Tension	1	Evaluate the tension capacity
2	Shear	3	Estimate the shear force capacity
3	Flexure	2- weak and strong	Estimate the flexural capacity

Direct Tension Test

As shown in Figure 5 a, the direct tension test was performed on the test unit using a self-reacting test frame supported on rollers. Neoprene pads were provided underneath the rollers to minimize the friction force. Two 110 kip hydraulic jacks were used to apply the load onto the steel H-sections on the rollers, which in turn applied the direct tension force on the UHPC pile. Large number of instruments including the displacement gauges and strain gauges were used to measure the response of the UHPC pile with splice detail. The UHPC pile was subjected to a maximum load of 226 kips, equivalent to 60% of the pile tension capacity. The test was stopped as the maximum capacity of the hydraulic jacks was reached. There was no observed cracking in either the pile or the splice region. The strains in the splice region are well below the cracking strains at the maximum load of 226 kips, indicating the satisfactory performance of the splice connection detail in direct tension. The measured average strain in the splice region is shown in Figure 5c.



a) Direct Tension Test Setup b) Schematic of the Direct Tension Test Setup c) Average Strain in the Splice Region

Figure 5 Direct tension setup and observed splice behavior

Shear Tests

The shear capacity of the splice connection was evaluated using a simply supported configuration as shown in Figure 6a and Figure 6b. 8-ft long spliced pile was simply supported and was subjected to a point load using a 120 kip hydraulic jack. The load point was located at a distance of 8 in. from the splice. In order to capture the effect of different moment to shear ratio(s) on the splice performance, shear tests were done in three different configurations. These were obtained by varying the distance between the supports and the load point. These different configurations will simulate the expected moment and shear demands at the various locations along the pile length in the prototype bridge. The observed shear force vs. displacement under load point is shown in Figure 6c. Hairline shear cracks were observed at 48 kip shear force. However, the cracks were closed completely upon load removal. The splice region was subjected to maximum shear force of 66 kips in configuration-2, which is nearly double the typical shear force expected in the UHPC pile in the prototype bridge.

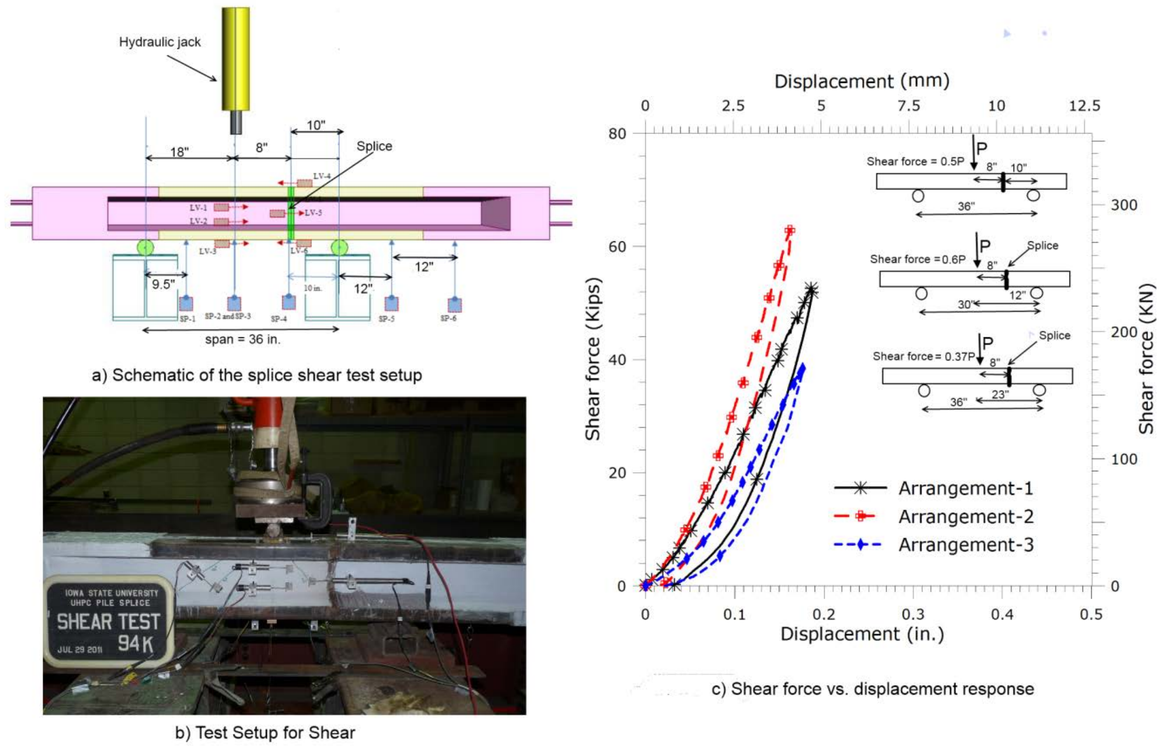


Figure 6 Shear test setup and observed shear force vs. displacement behavior.

Flexural Tests

The flexural capacity of the splice connection in both weak and strong axis directions were evaluated using a simply supported configuration as shown in Figure 7a. 8 ft long spliced pile was simply supported over 6 ft span and was subjected to a two point bending using a 120 kip hydraulic jack. The load points were located 2 in. on either side of the splice, subjecting the splice region to pure bending. The measured moment-curvature responses of the splice region in the weak and strong axis directions are shown in Figure 7c and Figure 7d respectively. In both the cases, the splice region failed at a load corresponding to 75% of the moment capacity of the UHPC pile in respective direction. The failure was initiated with the fracture of the weld between the corner angles and the ½ in. end plate. On further inspection of the failure surface, it was observed that the shop welding at the precast plant did not adhere to the requirements, which resulted in the shorter weld length between the corner angles and the plate, leading to the failure of the splice (See close up in Figure 7b). However, it is worth noting that the weld between the two pile pieces did not experience any damage, indicating that the connection will have sufficient strength to develop full pile moment capacity. Based on the observed damage mode, a full penetration weld between edge angles and the end plate is recommended for the splice detail.

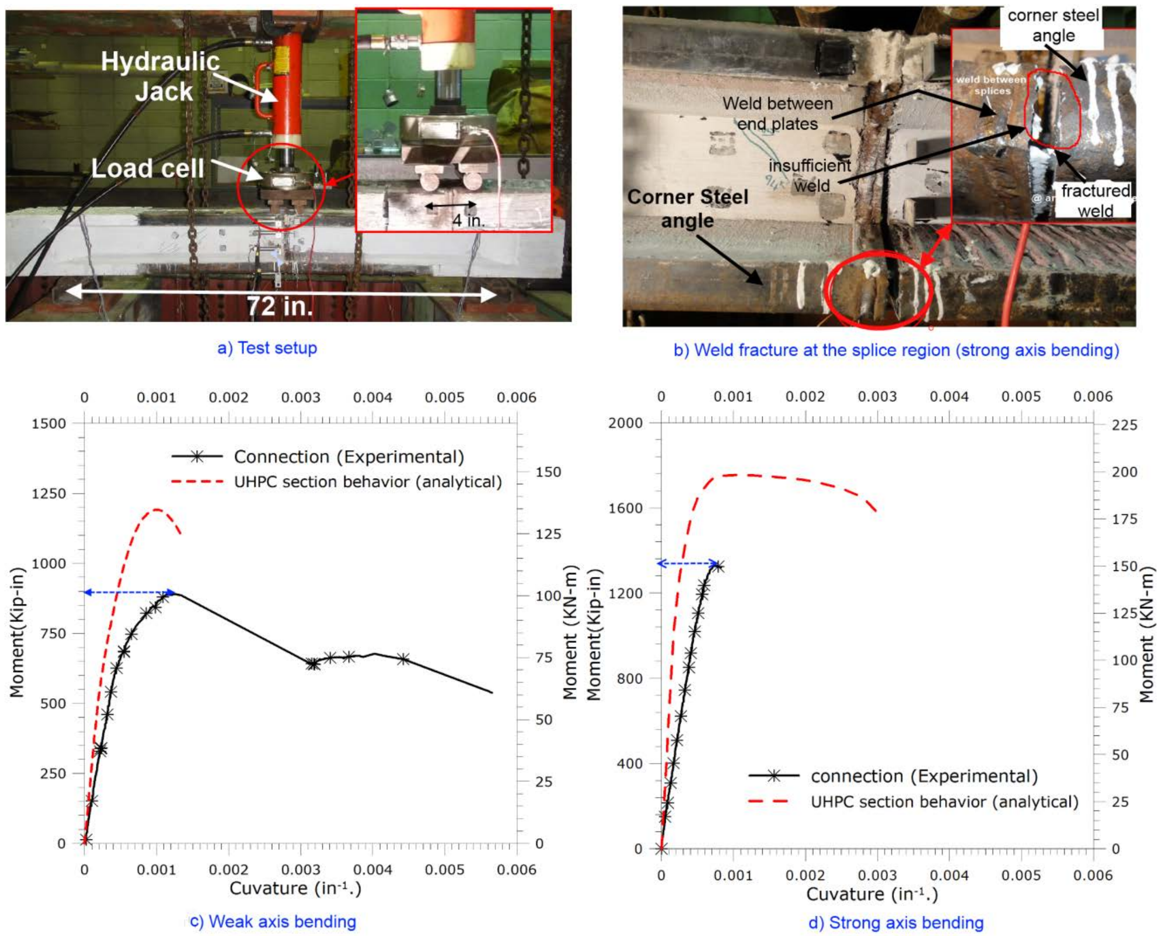


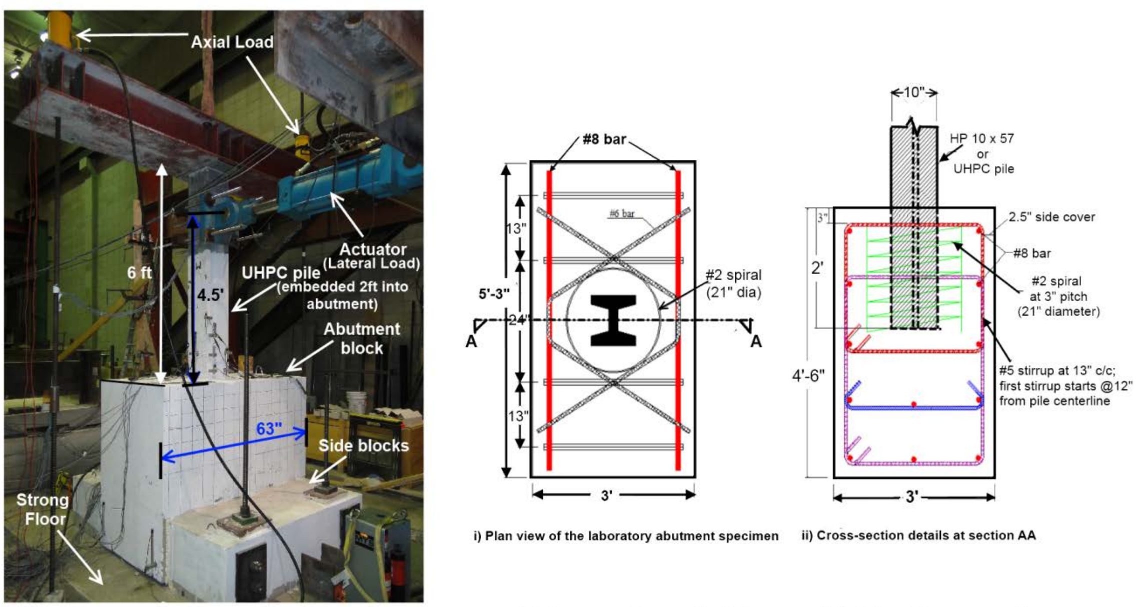
Figure 7 flexural Test setup and observed moment-curvature response of splice region in weak and strong axis directions

UHPC PILE-TO-ABUTMENT CONNECTION TESTS

Test Setup and load protocol

Three full-scale pile-to-abutment connection subassemblies representing a portion of a typical integral abutment pile foundation used in Iowa were tested. The three tests include a baseline steel pile oriented in weak axis direction and UHPC piles oriented in weak and strong axis directions. All the specimens were designed to simulate the pile foundations used in the prototype bridge shown in Figure 2. The experimental parameters include the pile orientation related to the roadway direction, amount of the axial load and the type of construction (precast to cast-in-situ).

All the pile-to-abutment connection tests were performed in an inverted position under combined axial and lateral loads as shown in Figure 8a. A detailed finite element analysis (FEA) model for the pile foundations at the Sac county bridge, including the soil-structure interaction, was developed to estimate the expected displacement demands in the piles and the pile-to-abutment connection [7]. Based on the FEA results, a 4.5-ft long cantilever pile segment was chosen for laboratory testing to simulate the expected longitudinal field thermal movements of the prototype bridge pile. According to the standard Iowa DOT practice, the typical details require the piles to be embedded into the abutment by 2 ft. So, for each test, an 8-foot long pile (including the 2 ft embedment in the abutment block) was used. The abutment block had standard dimensions of a bridge abutment with its length equal to typical center-to-center distance between two adjacent piles. The abutment block was suspended above the floor by post-tensioning two concrete blocks on both sides and attaching these ancillary blocks to the strong floor using high strength bars. Details of the pile-to-abutment connection details of the test specimens are shown in Figure 8b. Throughout the testing, the piles were subjected to either 100 kips or 200 kips of vertical load using two post-tensioning bars and hydraulic jacks. In addition, each pile was subjected to cyclic lateral displacements using a 110 kip actuator attached at a height of 4.5 ft from the top of the abutment block, to simulate the expected movement of a pile integrally connected to abutments. A large number of instruments including load cells, strain gauges and string potentiometers are used during testing to monitor the axial load, strain demands in concrete and prestressing strands and lateral deformations respectively.



a) Test setup

b) Cross-section and reinforcement detials of the connection

Figure 8 Test setup and the pile-to-abutment connection details

Based on the previous studies on the thermal movements and subsequent expansion and contraction that integral abutment bridges undergo, the piles in the prototype bridge are expected to move as much as 1 in. in the longitudinal direction, which corresponds to a 0.28 in. lateral displacement in the laboratory. Also, the maximum field pile displacement of 1.55 inches that is allowed by Iowa DOT corresponds to a lab displacement of 0.39 in. to 0.42 in. depending on the pile orientation and type. All the three UHPC piles were tested in three phases to understand the influence of vertical load on the behavior of the pile-to-abutment connection. The load protocol used for the three phases is shown in Table 2. In a similar manner, the HP 10 x 57 steel pile was also tested to failure in weak axis direction to provide the baseline performance of the connection.

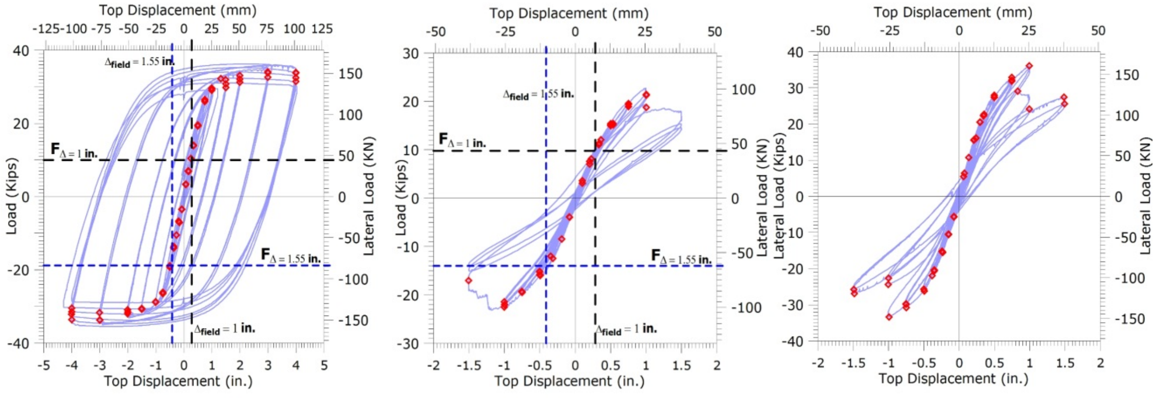
Table 2 load protocol for the pile-to-abutment connection test

Phase	Axial Load, kips	# Cycles per Step	Actuator Control	Load Step
I	100	2	Force	±4^k, ±8^k, ±12^k, ±16^k
II	200	2	Force	±3.5^k, ±7^k, ±10.5^k, ±12^k
III	100	3	Displacement	±0.5$''$, ±0.75$''$, ±1.0$''$, ±1.5$''$, ±2.0$''$, ±3.0$''$, ±4.0$''$

Test Observations and Results

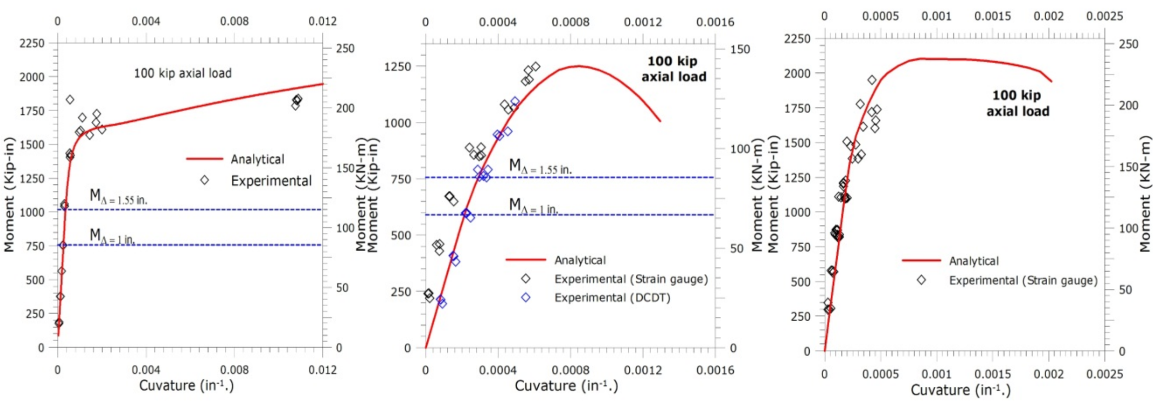
The force versus lateral displacement behavior for the steel (HP 10x57) and UHPC piles (weak and strong) specimens under constant 100 kip axial load are shown in Figure 9a, Figure 9b and Figure 9c respectively. Also, the comparison of predicted and measured moment-curvature responses of the piles is shown in Figure 10. The steel pile experienced yielding in the flange tips at 0.5 in. of lateral displacement and buckling of flanges in the critical moment region at 4 inches of lateral displacement (see Figure 11a). For the weak axis direction testing of the UHPC pile, two hairline cracks were observed at the lateral displacement of 0.28 in., corresponding to the filed displacement of one inch. However, these cracks were completely closed after the displacement of the pile returned to zero. The UHPC pile ultimately experienced compression failure at 1.5 in. of lateral displacement (see Figure 11b). Similarly, no cracking was observed in the UHPC pile oriented in the strong axis direction at the expected level of displacement. However, an unexpected vertical crack was developed in the web at 1 inch lateral displacement. The pile ultimately failed in compression at 1.5 inches of lateral displacement (see Figure 11c).

In all the three tests, there was no cracking observed in the abutment at the expected level of displacements. The maximum strain demand in the abutment primary reinforcement was below 80 micro strains. The strains in the confinement hoop reinforcement were below 60 micro strains at 0.28 in. displacement. The maximum strains measured in the abutment hoop reinforcement at the ultimate failure of the piles are still much smaller than the yield strains. Also, at the ultimate failure of UHPC piles, only a single hairline crack was observed in the abutment block, confirming the adequacy of the standard Iowa DOT's pile-to-abutment connection detail for usage of UHPC piles.



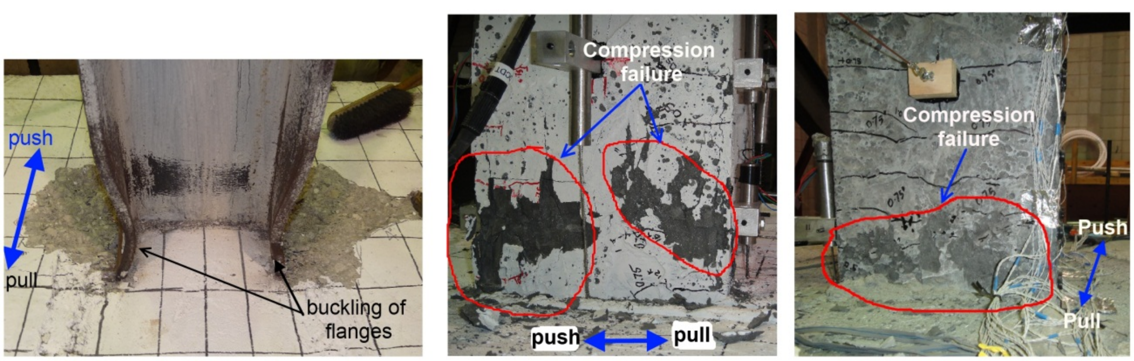
a) HP 10 x 57 (steel pile) b) UHPC pile (Weak axis) c) UHPC pile (Strong axis)

Figure 9 Measured force-displacement response of steel and UHPC piles



a) HP 10 x 57 b) UHPC pile (Weak axis) c) UHPC pile (Strong axis)

Figure 10 comparison of measured and calculated moment curvature response for steel and UHPC piles



a) HP 10 x 57 at 4 " displacement b) UHPC pile (Weak) at 1.5" displacement c) UHPC pile (strong) at 1.5" displacement

Figure 11 Observed damage to piles and abutment at failure

CONCLUSIONS

Based on the experimental testing of the UHPC splice detail and the pile-to-abutment connections, the following conclusions were made:

1. The full-scale tests on splice connection confirmed its satisfactory performance in tension and shear. The splice had reserve capacity in excess of 226 kips in tension (60% of pile tension capacity) and 66 kips in shear. The shear capacity is nearly 2-2.5 times the expected shear force.
2. The splice failed prematurely in flexure at 70% of pile moment capacity due to the poor shop weld quality between the steel corner angles and end plate in the prefabricated pile splice assembly. Therefore, strict quality control measures are needed for the shop welding to assure the performance of the splice detail.
3. The UHPC pile-to-abutment connection was also very successful. Two hairline cracks were observed in UHPC piles at 0.28 inches of lateral displacement which corresponds to 1 in. field displacement of prototype bridge piles. However, all cracks were closed upon load removal. Hence, at 1 inch abutment displacement, hairline cracks are expected to appear in the prototype bridge piles over 12-18 inches length from the abutment connection.
4. No changes required for the standard Iowa DOT abutment connection to accommodate the UHPC pile in either weak or strong axis orientation.

ACKNOWLEDGEMENT

The authors would like to thank the Iowa Highway Research Board for sponsoring this research project. We would like to thank John Heimann from the Coreslab Structures of Omaha for helping and organizing the casting of the precast UHPC piles for laboratory testing in a timely manner. The authors would also like to thank Lafarge North America for donating the UHPC material required for the project. Finally, the assistance provided by Doug Wood, Structural Lab Manager and Owen Steffens, Lab research technician at Iowa State University, in completing the tests is greatly appreciated.

REFERENCES

1. American Society of Civil Engineers: Report Card for America’s Infrastructure: Facts about bridges, Reston, VA, USA, 2009.
2. Office of Engineering. Federal Highway Administration. U.S. department of Transportation. http://www.fhwa.dot.gov/bridge/deficient.cfm. Accessed 15th, May, 2011.
3. American Association of State Highway and Transportation Officials (AASHTO), “Grand Challenges: A Strategic Plan for Bridge Engineering,” *AASHTO Subcommittee on Bridges and Structures*, June 2005.
4. Aaleti, S., Sritharan, S., Bierwagen, D., and Wipf, T., J. (2011). “Experimental Evaluation of Structural Behavior of Precast UHPC Waffle Bridge Deck Panels and Connections”, Transportation Research Record: Journal of the Transportation Research Board
5. Keierleber, B., Bierwagen, D., Wipf, T., and Abu-Hawash, A., “Design of Buchanan County, Iowa Bridge Using Ultra-High Performance Concrete and Pi-Girder Cross

Section," In: Proc. Precast/Prestressed Concrete Institute National Bridge Conference, Orlando, Florida, 2008.

6. Vande Voort, T.L., Suleiman, M.T., and Sritharan, S. "Design and Performance Verification of UHPC Piles for Deep Foundations," Final Report, Ames, IA: Iowa State University – Center for Transportation Research and Education, November 2008.*on Bridges and Structures*, June 2005.
7. Garder, J., (2012), "Use of UHPC Piles in Integral Abutment Bridges", M.S thesis, Department of Civil, Construction & Environmental Engineering, Iowa State University, Ames, IA.
8. Iowa DOT. (2011). Iowa LRFD Bridge Design Manual, Retrieved February 2012, from Iowa DOT Design Policies: www.iowadot.gov/bridge/manuallrfd.htm.