

Experimental and Analytical Investigation of UHPC Pile-to-Abutment Connections

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Abstract: A significant portion of the United States bridge infrastructure is rapidly approaching the end of its intended design life, demanding development of new structural members that are durable, faster to construct and increase the longevity of bridges. In response, using Ultra-high performance concrete (UHPC) and prefabrication methods, a tapered, H-shaped, precast UHPC pile was developed at Iowa State University (ISU). The UHPC pile increases the longevity of bridge foundations while reducing their maintenance cost in comparison to steel and concrete piles. This paper will focus on experimental and analytical studies done to facilitate the field implementation of the UHPC pile. A total of four full-scale pile-to-abutment connection subassemblies were tested under combined vertical axial forces and cyclic lateral displacements representing the expected thermal movements in integral abutment bridges. Several variables such as axial load, pile orientation and construction method were investigated. The experimental investigations revealed that the UHPC piles can be installed with connection details similar to those used for steel H-piles in both cast-in-place and precast abutments. Also, an analytical model was developed in OpenSEES to predict the observed lateral load behavior. The test results, observations, measured and calculated response and conclusions are presented in the paper.

Keywords: UHPC, pile foundations, precast piles, integral abutment, pile splices, full-scale testing

1. 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 obsolescence of one in four of the nation's bridges [ASCE 2013]. According to the recent National Bridge Inventory database, one in nine of the nation's bridges are rated as structurally deficient, while the average age of the nation's bridges is currently 42 years. 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 [AASHTO, 2005] 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 service life of 100 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) [Aaleti et al., 2011 and Keierleber et al., 2008] in the United States has proven to be efficient and economical.

Foundations in routine bridges 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 prestressed pile (see Figure 1a) 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 [Vande Voort et al., 2008]. 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 1a.

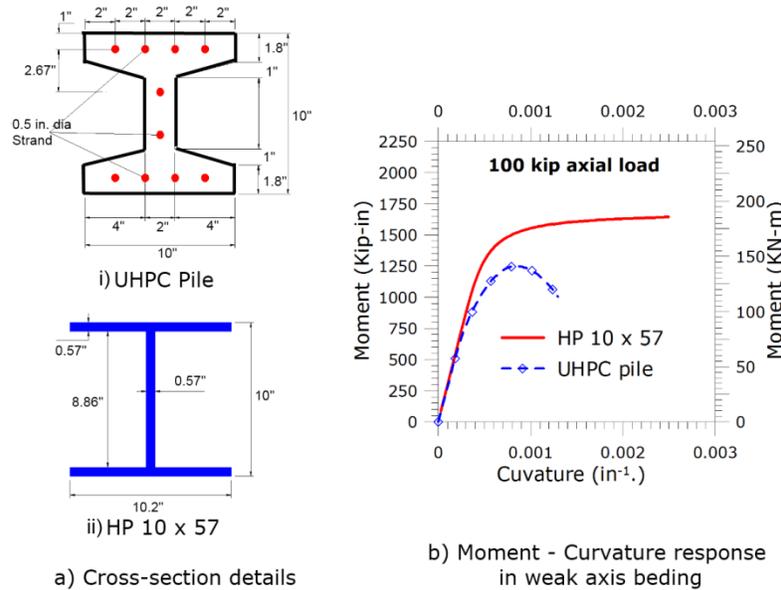


Figure 1: Comparison between UHPC prestressed pile and standard steel HP 10 x 57 pile.

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 [Vande Voort et al., 2008]. 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.

2. Prototype Bridge and Connection Details

2.1 Integral Abutment Bridges (IAB)

Integral abutment bridges are widely used by several DOTs in the U.S due to the reduced need for maintenance when compared to jointed bridges. These IABs consist of 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 higher stiffness of the traditional concrete piles compared to steel piles, limits their frequent usage in IABs. 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). 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 (39.4mm).

2.2 Prototype Bridge

A 223-ft (68 m) long and 40-ft (12.2m) 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. (25 mm) 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" (17m), 106'-6" (32.5m), and 60'-9" (18.52m) from the west to the east. The abutments were designed according to the standard Iowa DOT details [8] with 80-100 ft (24-30m) 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).

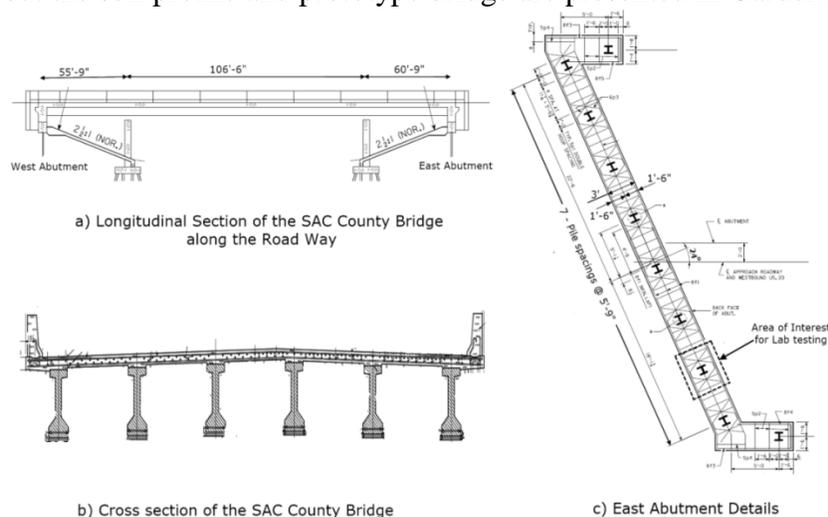


Figure 2: Prototype bridge details

2.3 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 [IowaDOT, 2011]. This connection detail was preferred as this will minimize the changes needed to an already well-established construction method. Figure 3 shows the typical details used widely in Iowa for steel HP pile-to-abutment connection. The pile is embedded 2 ft (0.61 m) into the abutment and a 21 in. (0.53 m) diameter, #2-spiral with 3 in. (75 mm) pitch is provided along the embedded length for the confinement around the pile. Special bent bars (6p3 bars) (see Figure 3b) are provided at 3 in. (75 mm) from the bottom of the abutment to prevent any side punching shear failure of the abutment.

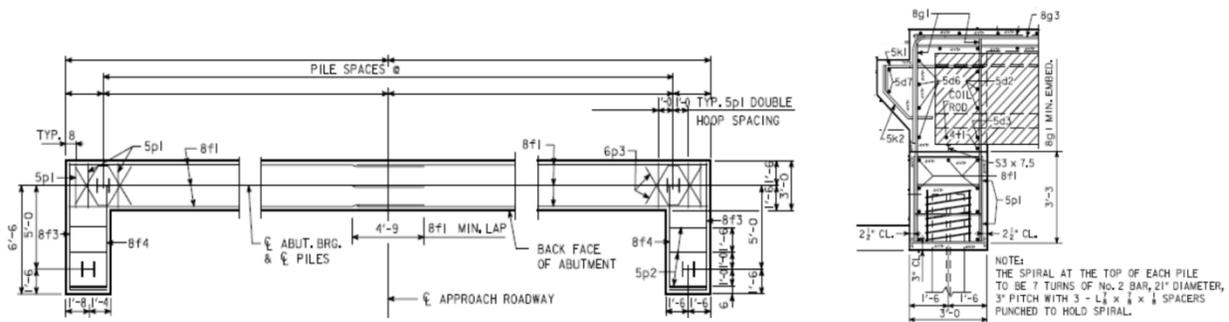


Figure 3: Standard details of pile-to-abutment connection used by IowaDOT

3. Experimental Work

A total of four full-scale pile-to-abutment connection subassemblies representing a portion of a typical integral abutment pile foundation used in Iowa were tested. The four tests include a baseline steel pile oriented in weak axis direction and UHPC piles oriented in weak, strong axis and at a 30° skew angle 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 abutment to cast-in-situ abutment).

3.1 Test Setup and load protocol

All the pile-to-abutment connection tests were performed in an inverted position under combined axial and lateral loads as shown in Figure 4a. 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 [Garder, 2012]. Based on the FEA results, a 4.5-ft (1.37 m) 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 (0.61 m). So, for each test, an 8-foot (2.44 m) 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. The pile-to-abutment connection details of the test specimens are shown in Figure 4b. The piles were subjected to either 100 kips or 200 kips (445 kN or 900 kN) of axial load using two post-tensioning bars and hydraulic jacks. In addition, to simulate the expected movement of a pile integrally connected to abutments, each pile specimen was subjected to cyclic lateral displacements using a 110 kip (490 kN) actuator. The actuator was attached at a height of 4.5 ft (1.37 m) from the top of the abutment block. A large number of instruments including load cells, embedded strain gauges, string potentiometers and LED's are used during testing to monitor the axial load, strain demands in concrete and prestressing strands and lateral deformations respectively.

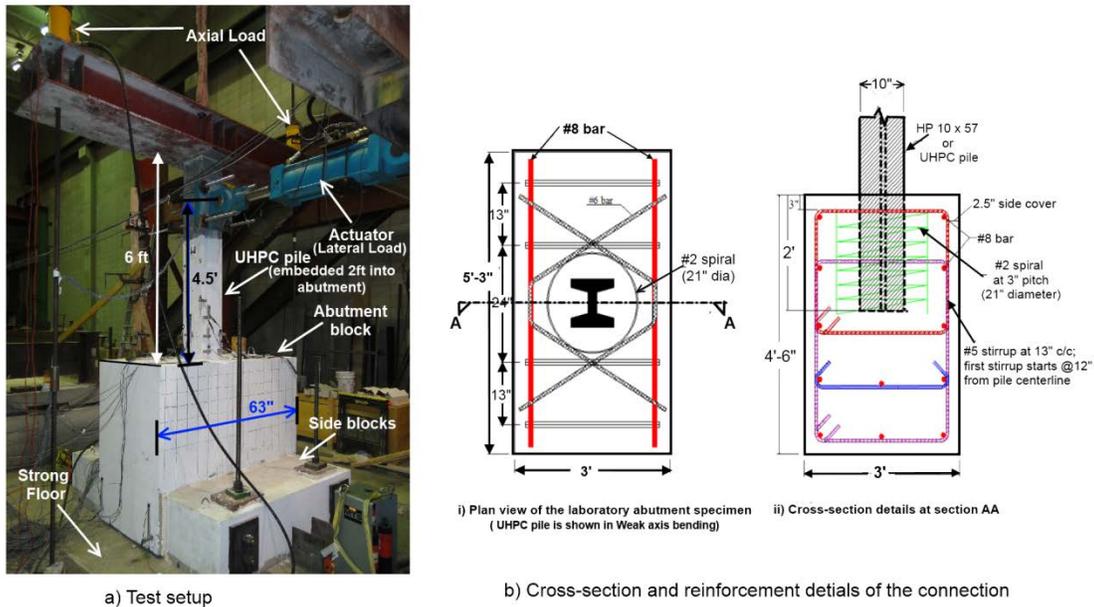


Figure 4: Details of the pile-to-abutment connection tests

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. (25 mm) in the longitudinal direction, which corresponds to a 0.28 in. (7 mm) lateral displacement in the laboratory. Also, the maximum field pile displacement of 1.55 inches (39 mm) that is allowed by Iowa DOT corresponds to a lab displacement of 0.39 in. to 0.42 in. (9.8 mm to 10.5 mm) depending on the pile orientation and type. All the three UHPC piles and reference steel pile 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 1.

Table 1: Load protocol used for the pile-to-abutment connection tests (1 Kip = 4.45 kN; 1 in. = 25 mm)

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

3.2 Test Observations and Results

The force versus lateral displacement behavior for the steel (HP 10x57) and UHPC piles (weak and strong) specimens under 100 kip (445 kN) and 200 kip (890 kN) axial load are shown in Figure 5. The increased axial load had minimal effect on the initial lateral stiffness of the pile and is evident in the Figures 5b, 5c and 5d. Within the expected pile field displacements range (shown by dashed lines in Figures 5a and 5b), the steel pile and UHPC pile in weak axis bending had nearly same demand on the abutment connection. There was no cracking observed in the abutment connection region.

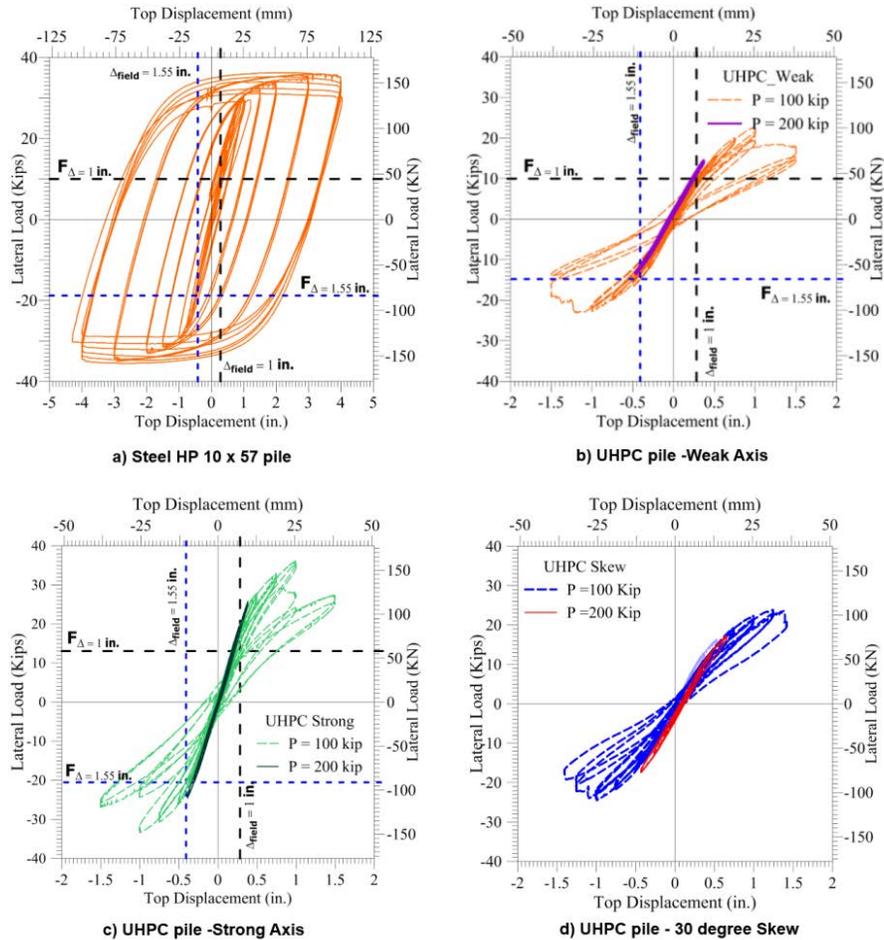


Figure 5: Force - displacement response of Steel and UHPC piles under cyclic loading

The steel pile experienced yielding in the flange tips at 0.5 in. (12.7 mm) of lateral displacement and eventually experiencing flange buckling in the critical moment region at 4 inches (101.6 mm) of lateral displacement (see Figure 6a). For the weak axis direction testing of the UHPC pile, two hairline cracks were observed at the lateral displacement of 0.28 in. (7 mm), corresponding to the filed displacement of one inch (25 mm). 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. (37 mm) of lateral displacement (see Figure 6b).

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 (25 mm) lateral displacement (Figure 6c). The pile ultimately failed in compression at 1.5 inches (37 mm) of lateral displacement (see Figure 6c). The UHPC pile under skew direction loading failed in compression at 1.4 in. (35.6 mm) of lateral displacement (Figure 6d). In all the four tests, there was no cracking observed in the abutment or connection region at the expected level of displacements. In the UHPC pile in skew direction, there was crack observed in the abutment at 1.25 in. (31.8 mm) of displacement, which corresponds to more than 3 inches (76 mm) of field displacement, nearly 200% more than expected displacement in the prototype bridge. 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. (7mm) 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.

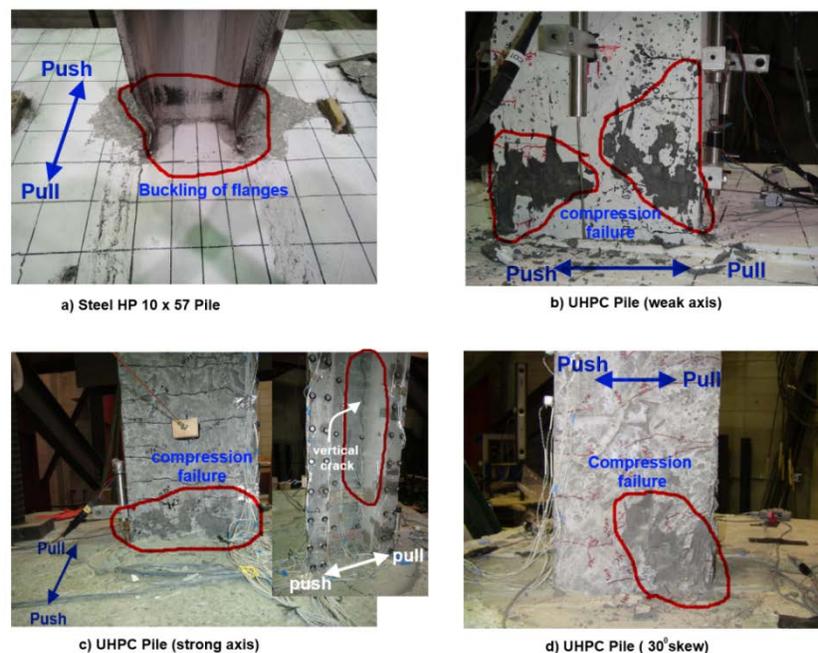


Figure 6: Observed damage in piles at failure.

4. Analytical Modeling

The analytical models of the steel and the UHPC piles in different orientations were developed using fiber based beam-column elements available in OpenSees (OpenSees 2016). The abutment block of each wall was rigidly connected to support side blocks and the lateral movement and rotation of the abutment block with respect to the strong floor were found to be negligible during testing. Therefore, the abutment was represented with a node in the analytical model and its degrees of freedom were restrained in all directions. Also during testing, it was observed that, the pile experienced slip within the foundation due to anchorage condition and development of

inelastic strains. Consequently, the concentrated rotation at the pile-abutment interface is modeled using a zero-length fiber-based element placed at the interface between the pile and abutment (see Figure 7a). This element was modeled with the same cross-section as the pile section (see Figure 7a).

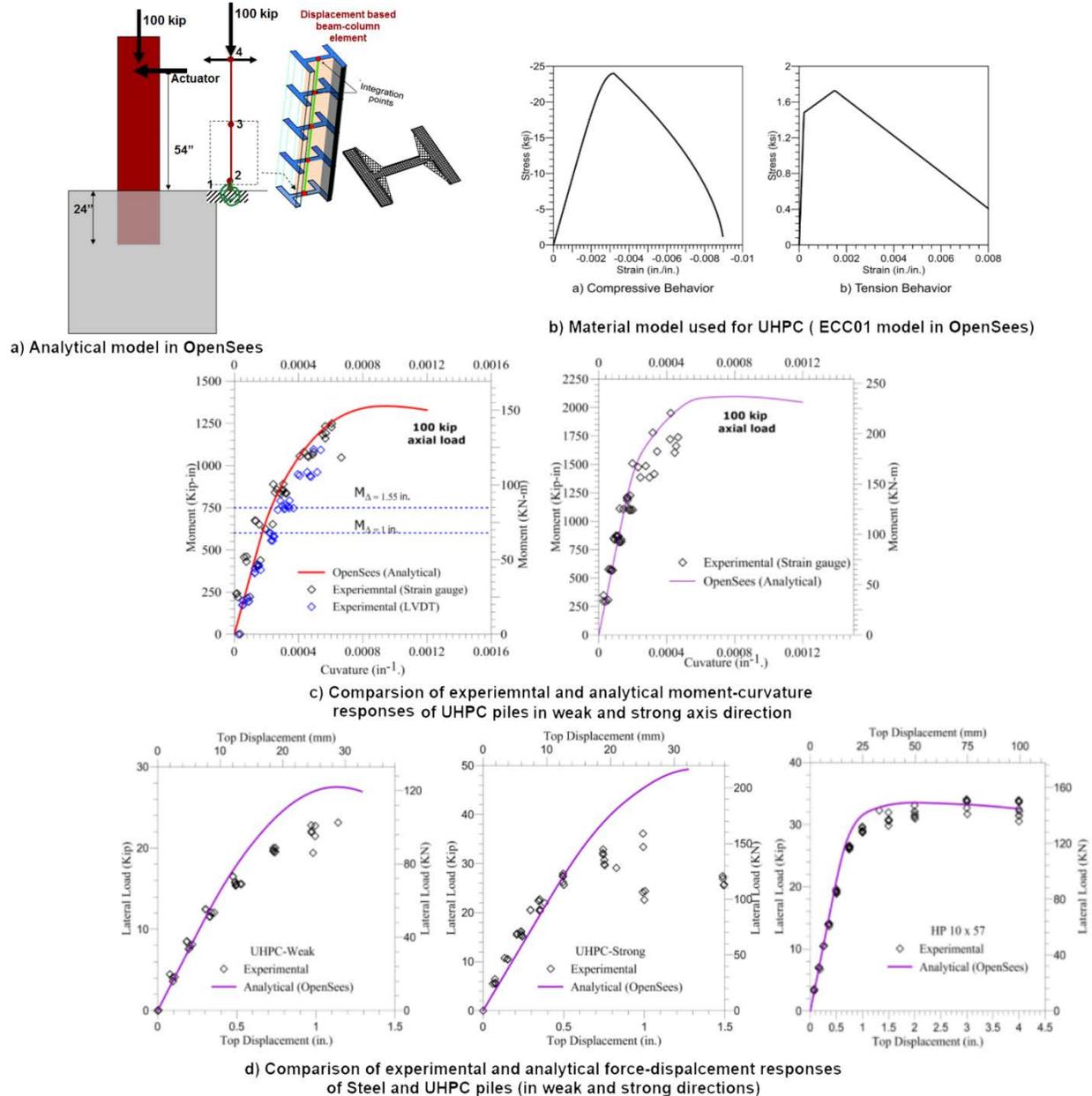


Figure 7: Fiber based analytical model and comparison of experimental and analytical results

For the steel pile, the material behavior was modeled using the bilinear stress-strain model (Steel 02 model in OpenSees) and the zero length section behavior were modeled using a strain penetration material model proposed by Zhao and Sritharan (2007). The strain penetration material model parameters were calibrated using the experimental results. The UHPC stress-strain behavior in the UHPC pile sections was represented using ECC01 material model (see

Figure 7b). The predicted moment-curvature and force-displacement responses UHPC and steel pile are compared with experimental values in Figures 7c and 7d, respectively. The analytical models were able to capture the UHPC pile section responses very accurately. However, the force-displacement response is over predicted by the analytical model. This can be attributed to not considering the shear deformations and damage due to cyclic reversal of loading in the analytical models.

5. Conclusions

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

- The UHPC pile-to-abutment connection was very successful. Two hairline cracks were observed in UHPC piles at 0.28 inches (7 mm) of lateral displacement which corresponds to 1 in. (25 mm) field displacement of prototype bridge piles. However, all cracks were closed upon load removal. Hence, at 1 inch (25 mm) abutment displacement, hairline cracks are expected to appear in the prototype bridge piles over 12-18 inches (0.3 m-0.45 m) length from the abutment connection.
- No changes are required for the standard Iowa DOT abutment connection to accommodate the UHPC pile in either weak, 30⁰ skew or strong axis orientation.
- The fiber based analytical model in OpenSees accurately captured the measured moment-curvature responses of UHPC pile sections under weak and strong axis bending. However, the force-displacement response of the UHPC pile was over predicted by the analytical model. Further modifications to material analytical models are needed to account for the connection flexibility, shear deformations and cyclic damage at the pile-to-abutment interface.

6. References

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7. Acknowledgements

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.