Fabrication and Experimental Testing of Prestressed UHPC H-Piles under Flexural and Shear Loading

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Abstract

Ultra-high Performance Concrete (UHPC) is a high-strength, robust material that is well-suited for a wide range of structural applications. Driven piles as a replacement for normal steel HP sections is one such application. As part of an ongoing research study, three 12-in., 14-in., and 16-in. deep UHPC H-shaped cross-sections were designed to be comparable in weight and performance to traditional steel H-piles. The 12-in., 14-in., and 16-in. deep UHPC pile sections were designed using first principles while considering the tensile capacity of UHPC, resulting in 8, 10, 16 - 0.6 in. diameter prestressing strands in the cross-section respectively.

Thirteen full-scale pile specimens ranging in length from 6.5-ft. to 24-ft. were cast at two precast facilities, with two different UHPC mixes. Pile specimens were instrumented with multiple internal strain gauges and monitored during curing, detensioning, and post-detensioning to capture transfer length for prestressing strands and short-term losses. To describe the structural performance of the piling sections, they were tested to failure under various combinations of flexural and shear loading. The findings and lessons learned from fabrication and large-scale flexural and shear testing of the pile specimens are presented in this paper.

Keywords: UHPC piles, precast/prestressed piles, full-scale testing, flexure/shear behavior

1. Introduction

In evaluating new techniques and materials for use in construction, two key details that must be examined are short-term installation viability and long-term durability. Current deep foundation piles experience problems in both of these areas. During installation, both steel and normal concrete prestressed piles are prone to damage during driving, especially in hard soil conditions. At the pile head, steel piles can experience local buckling, and normal concrete prestressed piles can experience tensile cracking. Long-term, steel piles have a low environmental resistance, especially vulnerable to corrosion. Normal concrete prestressed piles, though possessing better environmental resistance than their steel counterparts, are still susceptible to reinforcement corrosion, especially in harsh marine environments or climates where freeze-thaw cycles are a concern. The durability issues with current piles are paramount, as repair of these systems are difficult to perform and costly.

UHPC offers advantages that can potentially mitigate the problems experienced by steel and prestressed normal concrete piles. The high sustained-tensile capacity of UHPC can increase driving capacity, especially with the addition of prestressing. UHPC also possesses a dense particle matrix that provides more environmental resistance than normal concrete. Due to UHPC's self-levelling nature, a UHPC prestressed pile section's shape can be optimized to remain comparable to their steel counterparts in weight and still be driven using the same driving equipment. Although the material cost associated with UHPC is higher than steel or normal concrete, the immediate increase in cost can be offset reducing the number repairs necessary later in the bridge life span.

Currently, research on the production and structural characterization of UHPC piles is limited. Researchers at Iowa State University developed a 10-in. (25.4-cm) UHPC prestressed pile comparable to an HP 10x57 (Vandevoort, 2008), and investigated its performance experimentally during the driving process and under the application of lateral loads. They concluded that the UHPC section performed satisfactorily at similar or higher loads than the capacity of its steel equivalent pile section. This paper presents the results from fabrication of 12, 14, and 16-in. (30.5, 35.6, and 40.60-cm) UHPC prestressed piles and destructive testing of pile sections under flexural and shear loading.

2. Section Details and Fabrication

2.1. Section Development and Details

The main objective of this project was to develop UHPC prestressed pile sections for use as an alternative to standard 12, 14, and 16-in. (30.5, 35.6, and 40.6-cm) steel piles. Current local practices employ HP12x53, HP14x89 and HP 16 x 121 steel sections as deep foundation elements. Design goals were established from the beginning with the intention of ensuring that UHPC piles would be an acceptable alternative to steel piles from a construction, structural, installation, and cost perspective. Some key goals considered were as follows:

- Similar structural capacity of equivalent steel piles or better
- Elimination of mild steel shear reinforcement
- Maintaining weight of the pile within 30 lb/ft (4.1 kg/m) of an equivalent steel pile
- Keeping the overall pile dimensions similar to equivalent steel piles to use same pile driving equipment
- Increase the driving force capacity without sustaining damage

Eliminating mild shear reinforcement would take advantage of the tensile strength of UHPC while reducing the labor requirements and the cost. Maintaining a similar weight ensures that the transportation costs and handling requirements in the field for UHPC piles stay similar to that of steel piles. The final two goals aim to mitigate the main issue with steel piles during installation: damage during the driving process.

Before completing final section design, an initial material study was conducted to obtain general design mechanical property values. Compressive strength was measured using standard 3 by 6 cylinders according to ASTM C39, as modified by C1856 for UHPC. Peak tensile strength was measured through direct tension testing of 2-in. (5.1-cm) square prisms. The preliminary material properties along with the design values used for the UHPCs, are shown in Table 1. Throughout the project, two different UHPCs were used. These will be identified as UHPC 1, used for 12 and 14-in. deep piles, and UHPC 2 used for 16-in piles. For conservative design purposes, a reduced compressive strength was used.

Table 1 Measured and design UHPC material properties

Property	Preliminary Testing	Design Value	UHPC 1 (12 and 14-in. piles)	UHPC 2 (16-in. piles)
Compressive strength at release (f'_{ci})	13 ksi	9 ksi	13.9 ksi	12.6 ksi
28-day compressive strength (f'_c)	20.6 ksi	19.5 ksi	21.5 ksi	18.4 ksi
Peak tensile strength (f'_t)	1.25 ksi	1.25 ksi	1.4 ksi	1.2 ksi

1 ksi = 6.895 MPa; 1 in. = 2.54 cm

Piles section designs (see Figure 1) were completed taking influence from the H-pile section developed previously (Vandevoort, 2008), using a strain compatibility approach with measured material properties. An H-shape was chosen to optimize the weight and cross-sectional area for these piles, as opposed to a solid or hollow section. Moment-curvature and interaction diagrams for both strong and weak-axis bending were developed as tools in section optimization. All sections were prestressed with 0.6-in. strands to have a compressive stress around 4.25 ksi (29.3 MPa), to allow for harder driving and increase the shear capacity, eliminating the need for mild steel reinforcement.

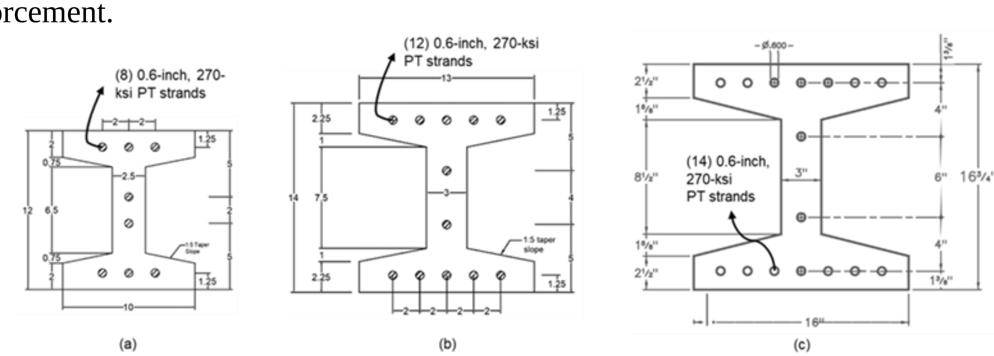


Figure 1 UHPC Sections: (a) UH12x71, (b) UH14x105, (c) UH16x151

The UHPC pile sections were named using a similar convention to steel piles. Names begin with UH, standing for UHPC H-pile, followed by the section depth in inches and weight in pounds per linear foot. Hence the UH12x71 is a UHPC H-pile with a depth of 12-in. weighing 71 lb/ft (9.8 kg/m). The pertinent properties are compared to their steel counterparts in Table 2.

Table 2 Weight and cross-sectional areas of UHPC and steel HP piles

	HP12x53	UH12x71	HP14x89	UH14x105	HP 16x121	UH16x151
Weight (lb/ft)	53	71	89	105	121	151
Area (in^2)	15.5	65.6	26.3	97	29.9	141.4

1 lb/ft = 1.488 kg/m; 1 in^2 = 6.542 cm^2

2.2 Pile Fabrication

The 12-in. and 14-in. piles were fabricated at a precast producer located in Birmingham, Alabama, USA and the 16-in. piles were fabricated at a precast facility in Tampa, FL, USA. Prior to casting of UHPC piles, foil strain gauges were applied to the prestressing strands at various locations. Embedded concrete gauges were also placed across the depth and along the length of the pile. The location of gauges varied based on the intended type of testing for each pile specimen.

Strain gauges were also placed at the ends of each pile at 15-in. (38.1-cm), to confirm that the prestressing is fully transferred by that distance. In addition to monitoring during testing, these strain gauges were monitored immediately after casting until detensioning to capture the early shrinkage and losses from detensioning.

A total of 133-ft. (40.5-m) of pile were cast in the strong axis direction at the Birmingham plant using wooden formwork. UHPC was mixed in a standalone high-shear mixer with representatives from the UHPC supplier present to lead the mixing process (see Figure 2). UHPC flow was measured as per ASTM C1437 and UHPC was poured into a bucket to place into the wooden forms. UHPC was able to flow around 0.6-in. strands in webs as narrow as 2.5-in. (6.4-cm). Some attempt was made at finishing the top surface of the piles with spiked rollers, but this was not done very well, as some piles exhibited voids and "elephant skin" on their top surfaces. After casting was complete for all piles, tarp was pulled over the prestressing bed and the piles were allowed to cure in ambient temperature. In response to unexpectedly cold nights after casting, propane heaters were placed at each end of the bed to maintain temperatures around 75 F (24 C) around the piles until detensioning. The internal strain gauges were monitored periodically during this time.

Figure 2 Pile fabrication in Birmingham (left) and Tampa (right)

In general, the process for casting the 16 in. piles at the Tampa Plant was the same as that of 12 and 14-in. piles, with some key differences. Steel forms were used instead of wooden forms; UHPC was mixed in overhead batch plant and dispensed from a Tuckerbilt truck, seen in Figure 2. Short bursts of vibration were applied to the prestressing bed during casting. As the surface was finished for these piles, a tarp was pulled over the forms and the piles cured in ambient temperatures. Inspection of the top-surface of these piles showed less elephant skin and little to no voids on the top surface. Overall, 140-ft. (42.7-m) of pile was cast, including lengths of 24-ft. (7.3-m), 16-ft. (4.9-m), and 6-ft. (1.8-m). In both Birmingham and Tampa, the piles were detensioned two days after casting. Additionally, quality assurance specimens were cast and tested to verify the material properties, which are provided in Table 1.

3. Experimental Testing Setup

A total of six flexure tests were conducted in simply-supported four-point loading configuration, two for each pile size, one in the strong-axis and one in the weak-axis direction. Extensive instrumentation, including load cells, pressure sensors, internal and external strain gauges, string potentiometers, and non-contact 3D-displacement measurement LEDs were used to capture load, strains and displacements. A standard hydraulic jack was used to apply the load to a spreader beam. The test setup used for flexural testing is shown in Figure 3.

The pile spans varied depending on the pile size and direction of testing. The spans for strong axis flexural testing were 11.5-ft., 19.5-ft., and 23.5-ft. (3.5-m, 5.9-m, and 7.2-m) for UH12x71, UH14x105, and UH16x151 respectively. Whereas, for weak axis flexural testing, 11.5-ft., 11.5-ft. and 15.5-ft. The two load points were 24-in. (0.6-m) apart and 32-in. (0.8-m) apart for the UH12x71 and UH14x105 specimens and UH16x151 respectively. External surface gauges were placed at mid-span, on the top, bottom surfaces, and web region.

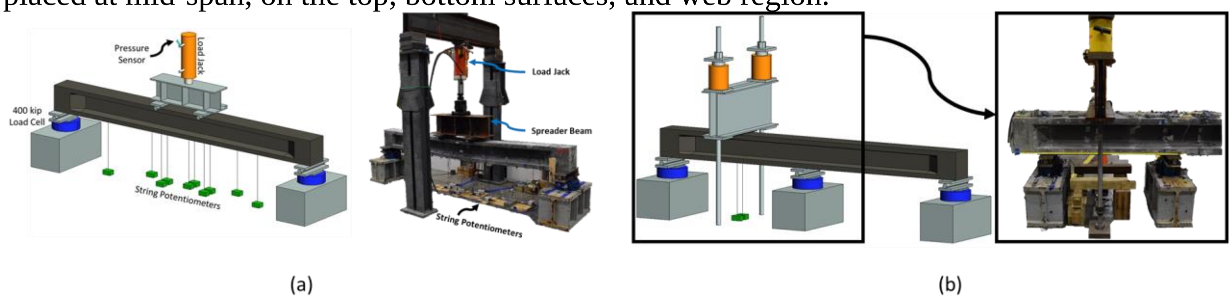


Figure 3 Experimental schematic and lab test setup for a) flexural testing and b) shear testing

After concluding flexure testing, the undamaged portions of flexure piles were retested in shear. Three UH12x71 and three UH14x105 shear tests were conducted with various support lengths as detailed in Table 3. Piles were supported in three locations: one on each end, then one just outside of the damage region. A point load was applied in between two of the supports, as in Figure 3, using two post-tensioning bars and hydraulic jacks. The spans for loading were chosen to avoid flexural damage regions and reach the anticipated shear capacity before flexural failure would occur for each pile section. Given the high amount of prestressing in these piles, it was difficult to use long spans and still attain a shear failure. Load cells at the supports and pressure sensors on each jack captured applied forces. Two string potentiometers captured displacement under the load, and LEDs were used to capture displacements throughout the load span.

Table 3 Shear testing spans and peak loads

Specimen Name	Total Load Span	Critical Distance to Load Point	Peak Shear Load
UH12FS_V1	48-in.	18.5-in.	100.4
UH12FW_V1	54-in.	23.75-in.	99.2
UH12FW_V2	54-in.	23.75-in.	95.5
UH14FS_V1	92-in.	52-in.	158.4
UH14FS_V2	72-in.	24-in.	190.3
UH14FW_V	57-in.	24.25-in.	182.7

1 inch = 2.54 cm; 1 kip = 4.448 kN

4. Testing Observations and Results

4.1 Early Age Losses

The measured strain in the pile sections during detensioning process is shown in Figure 4. Based on the measured strain gauge data, elastic shortening losses were calculated to be 23.1 ksi for the UH12 and UH14 piles and 24.9 ksi for UH16 piles. Using first-principles techniques with measured material properties, the expected elastic shortening losses for the UH 12, UH 14, and UH16 were 24.4 ksi, 24.4 ksi, and 27.3 ksi respectively. This supports that the current elastic shortening losses calculation method is appropriate for these prestressed UHPC piles. In addition, as seen in Figure 4, the strain gauges placed at 15-in. from ends of the pile and the gauges at mid-span of the pile show nearly same changes in strains during the detensioning process. This indicates that prestressing was able to transfer with in a length of 15-in. and supporting that the transfer length is at the maximum $24d_b$, where d_b is the diameter of the strand.

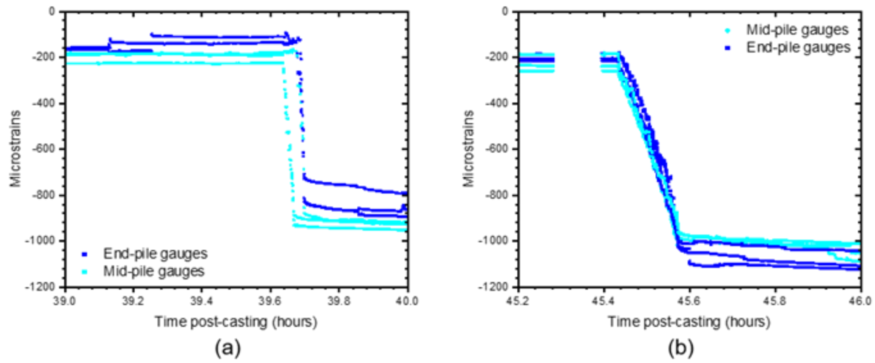


Figure 4 Strain gauge readings in piles during detensioning for a) 12 and 14-in. piles and b) 16-in. piles

4.2 Flexure Testing

Generally, during flexural testing, tension microcracks were observed and were only visible when acetone was applied to the UHPC surface. The load at which microcracking was first observed is presented in Table 4. The piles in weak axis bending failed in a compression-controlled manner, with no tensile cracks localizing before crushing of UHPC in the compression region. This was consistent for all pile sizes and measured maximum load and applied moment are shown in Table 4. The failure condition of all the piles under flexural loading are shown in **Error! Reference source not found.**.

Table 4 Flexure testing test results

Bending Direction	Pile	Max Load (kips)	Max Moment (kip-ft)	Failure Mode	Microcracking Load in flexure (kips)	Microcracking Load in shear (kips)
Strong-Axis	UH12x71	92.6	218.0	Compression	35	70
	UH14x105	90.9	386.4	Compression	25	80
	UH16x151	123.1	641.4	Shear	45	90
Weak-Axis	UH12x71	42.3	98.6	Compression	30	--
	UH14x105	89.3	211.1	Compression	25	--
	UH16x151	103.1	328.7	Compression	30	--

1 kip = 4.448 kN; 1 kip-ft = 1.356 kN-m

Strong-axis flexure saw similar trends with some variation. Once the compression crushing started, a single flexural crack localized in the constant bending region. Shear microcracking was also observed outside of the load application region for all pile sizes, with a small visible shear crack forming during testing of the UH12x71 strong-axis pile specimen. More widespread shear microcracks were observed during the UH14x105 test, but both the 12 and 14-in. piles experienced a compression-controlled failure. UH16x151 sustained a sudden shear failure, in which shear cracking ripped through the top flange, web, and web-bottom flange interface. This crack persisted almost the entirety of the 9-ft. (2.7-m) distance from the load point to the support.

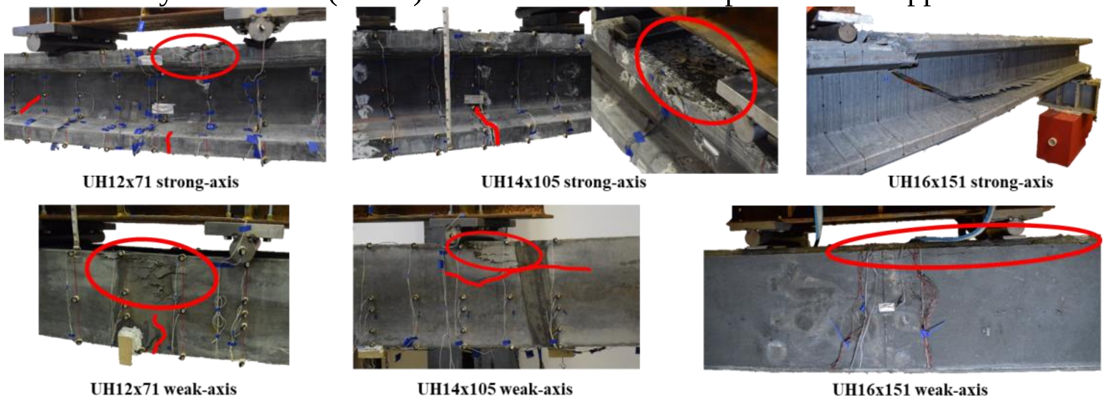


Figure 5 Condition of UHPC piles after flexural testing

Experimental curvature in the constant bending region was calculated using the data from the internal and external strain gauges, as well as average strains calculated using the non-contact LED measurements. For each pile section, theoretical moment-curvature was calculated using the strain compatibility approach and measured UHPC stress-strain behavior. The comparison between the measured and calculated moment-curvature response for each pile specimen for both strong and weak axis direction bending is shown Figure 6.

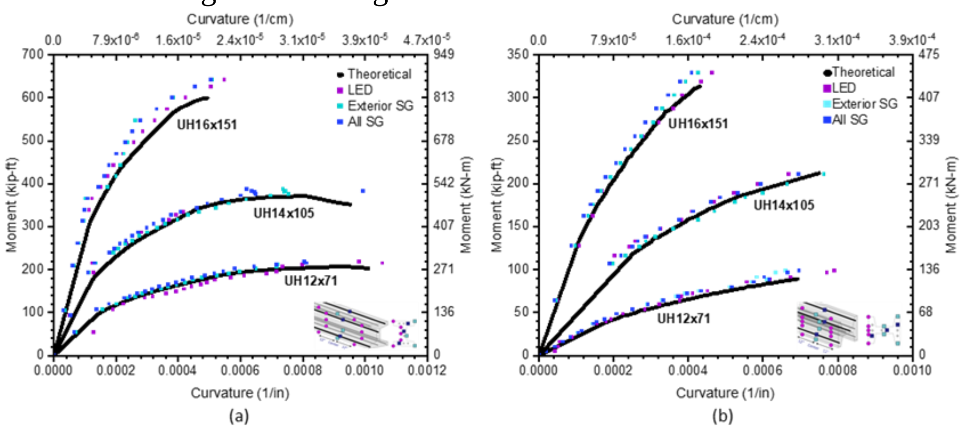
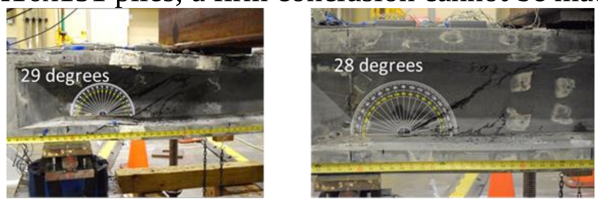


Figure 6 Moment-curvature comparisons for a) strong-axis and b) weak-axis bending

In all cases, the theoretical moment-curvature was within 10% the experimental results. The moment-curvature curve for UH16x151 is plateauing at the time of shear failure, which suggests that the pile was close to its flexural capacity.

4.3 Shear Testing

Data from shear testing is still being analyzed; however, the test observations and preliminary data are presented here. In all cases, we were able to induce shear failure in the specimen. As the load increased, microcracking in shear became visible with the application of acetone, and specimens eventually failed with one to two localized shear cracks. After shear crack localization, as pressure continued to be applied, that crack would widen, and load would decrease. On average, the angle of shear cracking was 28 degrees. Table 3 shows the experimental max shear force for each pile. For the 12 and 14-inch piles, the experimental results are consistently grouped together within each pile size, with the 14-inch piles exhibiting higher shear capacities. The shear failure during the UH16x151 strong-axis flexure test is also worth mentioning, but because only one shear failure has been observed for UH16x151 piles, a firm conclusion cannot be made from this.



(a) (b)

Figure 7 Condition of UHPC piles after shear testing with crack angles for a) 12-in. pile and b) 14-in. pile

5. Conclusions

The casting and experimental testing of UHPC prestressed H-Piles in flexure and shear has led to the following conclusions:

- The fabrication of UHPC H-piles is feasible and adaptable to a variety of full-scale environments, including different plant locations, UHPC mix and mix dispensing,
- A transfer length of $24d_b$ can be used for 0.6-in. strands in UHPC H-piles
- First principles analysis is adequate in characterizing the elastic shrinkage losses, flexural capacity, and moment-curvature response of UHPC H-piles as long as accurate UHPC tensile behavior is considered.
- Flexural compression failure is likely to happen before shear failure even without mild steel reinforcement for the 12 and 14-in. piles due to the high amount of prestressing.

6. Acknowledgements

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7. References

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