A PRECAST UHPC PILE FOR SUBSTRUCTURAL APPLICATIONS

Thomas L. Vande Voort, Iowa State University, IA
Sri Sritharan, PhD, Iowa State University, IA
Muhannad Suleiman, PhD, Iowa State University, IA

ABSTRACT

Ultra High Performance Concrete (UHPC) with strengths of up to 30,000 psi (207 MPa) and excellent durability has been used in several different applications but not in geotechnical and substructural applications. This paper explores the possibility of using UHPC in precast, prestressed piles. Various solid and hollow pile cross-sections were considered. An H-shaped UHPC section with tapered flanges was selected for economical reasons and was further investigated. The 10-in. (250 mm) deep H-shaped UHPC pile with weight similar to a 10-in. (250 mm) deep steel HP pile has been designed with axial capacity exceeding that of the steel pile while maintaining sufficient moment capacity. UHPC allows application of high prestressing and reduced spacing between strands, while the superior durability enables a reduction to the cover concrete. Driving analysis shows that the UHPC H-pile can also be driven with more ease than conventional precast/prestressed piles, and cracking of the UHPC pile during driving can be completely eliminated. UHPC piles will have much improved durability characteristics over both concrete and steel piles, even in the corrosive environments of bridge piers.

Keywords: UHPC, Pile, Durability, Section Design, Precast, Prestressed, Driveability

INTRODUCTION

Typical concrete and steel piles are subject to long-term deterioration, which often goes unnoticed unless it leads to failure of the structure supported by the piles. Spalling of concrete piles and corrosion of reinforcement or of steel piles can severely reduce their load-carrying capacity, so piles in corrosive environments are often overdesigned to attempt to account for losses in capacity over time. Noticeable corrosion can also occur in environments not necessarily considered severe.

Ultra High Performance Concrete (UHPC) has advantages over normal concrete in both strength and durability. Compressive strengths of up to 30 ksi (207 MPa) and capillary porosity as low as 1.5 percent make UHPC ideally suited even in harsh environments[1]. The relatively high cost of UHPC, however, emphasizes the need to use this material efficiently. This paper describes the development of a UHPC H-pile that is expected to be used in lieu of concrete or steel piles in bridge foundations, with eventual expansion of UHPC to other substructural elements.

BACKGROUND

LIMITATIONS OF CONCRETE AND STEEL PILES

Although concrete and steel piles are commonly used for the design of bridge foundations, both pile types can limit the lifespan of a bridge. Concrete piles are susceptible to cracking during driving as well as during service from large flexural stresses. The potential for cracking of concrete piles during driving can be minimized with large amounts of prestressing, but this increases the construction difficulties in the end regions of the piles and reduces the axial compression capacity of a pile, although the compression capacity is not typically an issue in current design practice. Cover on normal concrete piles can be critical in severe environments, as cracks and capillary pores allow corrosive compounds to penetrate concrete and corrode steel reinforcement. Eventual spalling and deterioration of concrete can significantly lower the capacity of a concrete pile to resist structural loads. The inability of concrete piles to sustain large lateral displacements expected due to thermal movements has also limited the use of concrete piles in integral bridges that have no expansion joints between the abutments and the superstructure.

Corrosive environments can also affect the performance of steel piles. Gaps under structures formed by settling or laterally moving soil may be filled alternately with air and water, leading to significant corrosion near the location of the maximum moment in the steel piles, as noted in some Iowa bridges[2]. Furthermore, steel piles are more expensive and require several months of lead-time for delivery due to an increased foreign demand for steel.

MATERIAL PROPERTIES

The most striking aspects of UHPC are its excellent material properties, especially the compressive strength. Material properties for a UHPC mix that has been used for research at Iowa State University (ISU) are shown in Table 1[3,4].

Table 1 Key material properties of UHPC[3,4]

Property	Typical Value
Compressive Strength	26.0 ksi (179 MPa)
Elastic Tensile Strength	1.3 ksi (9.0 MPa)
Ultimate Tensile Strength	1.7 ksi (11 MPa)
Elastic Modulus	8000 ksi (55.2 GPa)
Shrinkage	450×10^{-6} *

*Assumed from results reported by Lafarge[5], Cheyrezy et al.[6], and AFGC[7]

Most of the 450×10^{-6} shrinkage strain reported in Table 1 occurs during thermal curing of the UHPC members. After curing, the UHPC members are expected to undergo almost no further shrinkage. For more information on the casting and curing process of UHPC, see the Federal Highway Administration (FHWA) report by Graybeal[8]. Because prestressing is applied prior to curing, prestress losses associated with shrinkage must be accounted for in design of pretensioned members. Though the tensile strength of UHPC is only a fraction of the compression strength, large amounts of prestressing can be used in UHPC members to significantly enhance their resistance to tensile stresses.

A tri-linear compression stress-strain diagram suggested by VSL Proprietary Limited was followed for the design of the UHPC pile section[9]. The Association Française de Génie Civil (AFGC) uses a very similar diagram for UHPC in compression[7]. The tension stress-strain diagram used for the analysis is based on the work of Bristow and Sritharan[3]. Fig. 1 shows the monotonic stress-strain curve of UHPC as used in the current study.

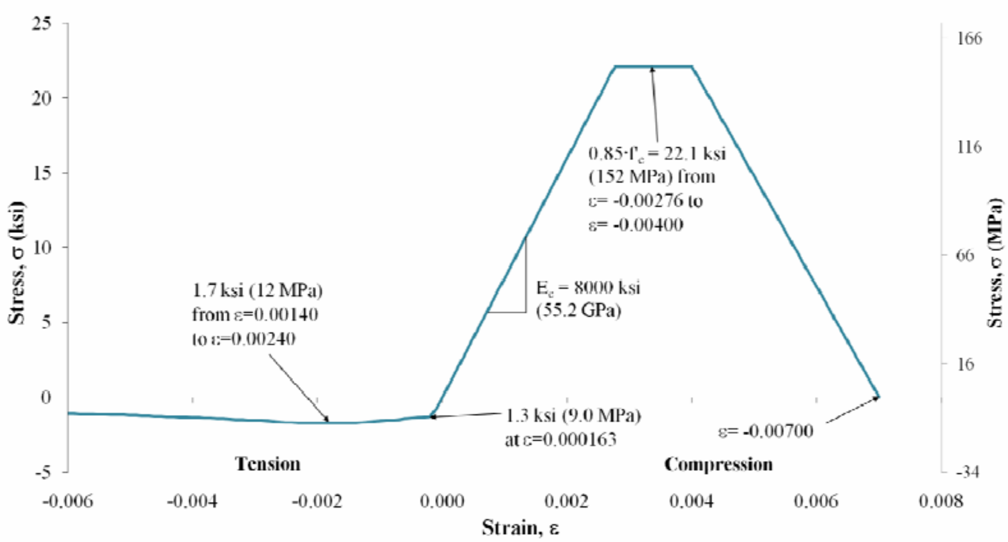

Fig. 1 Stress-strain behavior for UHPC

DURABILITY

The durability of UHPC, listed in Table 2, is as notable as the material properties. The greatly improved durability characteristics of UHPC, particularly its low capillary porosity and associated resistance to chloride ion penetration, make it extremely resistant to corrosion, even with the inclusion of a large proportion of steel fibers in the UHPC mix.

Table 2 Typical durability properties of UHPC

Property	**UHPC**	**HPC**	**NC**
Capillary Porosity[1]	1.5 %	5.2 %	8.3 %
Water Absorption Coefficient[1]	0.002 lb/(ft^2·h^{½}) (0.01 kg/(m^2·h^{½}))	0.025 lb/(ft^2·h^{½}) (0.12 kg/(m^2·h^{½}))	0.12 lb/(ft^2·h^{½}) (0.60 kg/(m^2·h^{½}))
Chloride Ion Penetration Depth[1]	0.04 in. (0.1 cm)	0.3 in. (0.7 cm)	0.91 in. (2.3 cm)
Carbonation Depth[10]	0.1 – 0.2 in. (0.3 – 0.5 cm)	NA	1.1 in. (2.7 cm)

APPLICATIONS

UHPC has begun to see implementation in many types of structural applications, but some of its most promising uses are in bridges. To date, pedestrian bridges have been constructed in Canada, Japan, South Korea, New Zealand[5], and Germany[11]. Vehicular bridges have been constructed in the United States, France, Australia[12], the Netherlands, and Germany[11]. All of these bridge projects have used UHPC only in the superstructure. Substructure for bridges or buildings is an application with great potential for UHPC, especially with the aforementioned limitations of concrete and steel piles.

DESIGN OF A PILE SECTION

SECTION SHAPE

Initially, prestressed concrete pile sections similar to those used by the precast industry were examined for UHPC piles. Solid square, octagonal, and circular shapes were considered, but UHPC piles do not require the large cross-sectional area of such shapes to provide high structural capacity in axial compression. With a reduced area, a reduced amount of prestressing is needed to make the pile section effective to resist tensile stresses resulting from driving forces and flexural actions. Reducing the cross-sectional area of the pile also reduces the material costs. Hollow sections, shown in Fig. 2, were studied to reduce cross-sectional area but maintain a large perimeter for skin friction. All shapes shown in this figure are more efficient in resisting flexure since area is concentrated where stresses are expected to be greater. Hollow sections must use a collapsible center form, however, creating challenges with the forming and casting of the pile. The reduction in material costs could be largely offset by labor and production costs associated with these hollow sections. Alternatively, procedures exist for producing spun-cast hollow circular concrete piles[13]. The presence of steel fibers in UHPC adds to the complexity of this process, however. Also, since a goal of this project is to develop a pile design that may be easily used in local precasting plants with appropriate certification for UHPC, a spun-cast pile was not further considered.

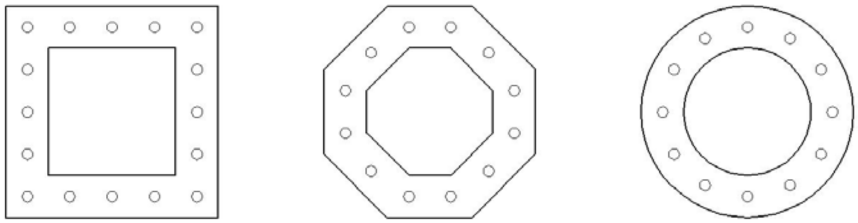

Fig. 2 Hollow prestressed UHPC sections initially considered in the study

An alternative section that is both structurally efficient and fairly easy to construct is an H-shaped section. First, a simple H-shaped pile with a small cross-sectional area and 13 prestressing strands was developed, and the interior corners were chamfered to prevent stress concentrations and the potential cracking at the corners. After discussion with a representative from Iowa Prestressed Concrete (IPC), further modifications to the UHPC section were necessary to avoid the possibility of air pockets forming on the top surface of the lower flanges during casting. Therefore, an H-shape section with a circular arc between the flanges, referred to as an X-shape, was developed. The curved surfaces help air escape as UHPC flows into the forms during casting, although the X-shape is more difficult to form and requires more concrete. With the possibility of accommodating up to 15 prestressing strands, the X-shaped section was considered less susceptible to stress concentrations or local buckling.

Finally, an H-shaped section with a tapered flange thickness was designed to create a section with minimal concrete area and simple forming, like the one envisioned for a simple H-shaped section, but with a shape that eliminated the formation of air pockets during casting. The resulting section, referred to as the tapered H-shaped section, contains only 10 prestressing strands, and is shown in Fig. 3, together with a simple H-shaped and an X-shaped section.

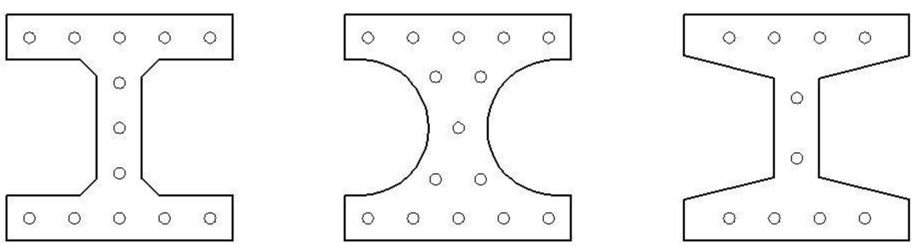

Fig. 3 Different H-shaped sections investigated for UHPC piles

SECTION DETAILS

Depth

Pile depths (or diameters) ranging from 4-in. (100-mm) deep micropiles to 14-in. (360-mm) deep foundation piles were examined, but a 10 by 10-in. (250 by 250-mm) UHPC pile section was chosen for further study, since this section matched the outer dimensions of the HP 10 x 57 pile commonly used in the state of Iowa[14]. In the 10-in. deep section, up to 13 prestressing strands can be used, but a design using only 10 strands was chosen. Furthermore, since the section is comparable in both outer dimensions and in weight to an HP 10 x 57, the UHPC piles may be driven using the same equipment, including the same capacity crane and same size driving helmet (anvil), that are used for driving steel piles.

Concrete Cover and Spacing between Strands

The required cover for UHPC piles is critical to the selection of the details of the 10-in. (250-mm) deep H-shaped sections. In addition, the required spacing is critical to the number and size of prestressing strands used in the final UHPC section.

The American Concrete Institute (ACI) in ACI 318-05, Section 7.7.3, specifies a minimum required cover of 1¼ in. (31.8 mm) for prestressing strands up to ⅝-in. (15.9-mm) diameter[15]— a requirement also referred to by the Precast/Prestressed Concrete Institute (PCI) *PCI Design Handbook*[16]. ACI notes that the required cover is for protection against weather and other effects and may need to be increased to develop the stress in the strand. The durability properties of UHPC suggest this required cover for weather protection could be reduced.

Furthermore, research conducted by others suggests that the cover required for developing the prestressing strands in UHPC may be reduced from values used for typical concrete piles. Tuchlinski et al. tested the transfer length and required cover and spacing of ½-in. (13-mm) diameter prestressing strands in UHPC beams. These researchers have recommended a center-to-center spacing of three times the strand diameter and a cover of 1.5 times the strand diameter[17]. In a study involving testing of full-scale UHPC bridge girders at ISU, a clear cover as small as 0.83 in. (21 mm) was successfully used on ½-in. (13-mm) strands that were placed near the top surface of the bottom flange of the girder. No failures due to insufficient cover or spacing occurred when the girder was tested to flexural and shear failure[4].

Following the recommendations of Tuchlinski et al., a minimum clear cover of ¾ in. (19 mm) was selected for the UHPC pile section. The precaster confirmed that the selected clear cover was sufficient for casting purposes but suggested avoiding any further reduction in cover.

ACI 318-05, Section 7.6.7.1, gives the minimum center-to-center spacing of prestressing strands as four bar diameters. A spacing reduction to 1¾ in. (44.5 mm) spacing for ½-in. (13-mm) nominal diameter strands is allowed for concrete with a compressive strength of 4000 psi (28 MPa) or greater at the time of prestress transfer[15]. The *PCI Design Handbook* states that 2-in. (51-mm) spacing is typically used for all strands up to 0.6-in. (15-mm) diameter[16]. The precaster also recommended 2-in. (51-mm) center-to-center spacing on ½-in. (13-mm) prestressing strands to ensure concrete is free to flow through the section during casting. Therefore a strand spacing of 2 in. (51-mm) was established for the UHPC section for prestressing strands with a diameter of ½-in. (13-mm) or smaller. Since ½-in. (13-mm) diameter prestressing strands are commonly used in prestressing applications throughout the United States, they were chosen for the UHPC pile section.

Final Section Dimensions and Strand Details

The final dimensions of the tapered H-shaped UHPC pile section are shown in Fig. 4 next to an HP 10 x 57 steel pile. The total area of prestressing in the UHPC pile is 1.53 in.^{2} (987 mm^2), equivalent to 2.7 % of the total area of the section. A total of 10 of the ½-in. (13-mm) diameter 270 ksi (1860 MPa) low relaxation prestressing strands are used, and the minimum cover and center-to-center spacing on the strands are 0.75 in. (19 mm) and 2.0 in. (51 mm), respectively. An initial prestress of 75 percent of the ultimate strength of the strands, or 202.5 ksi (1396 MPa) was used in design, and the elastic modulus of UHPC at transfer was taken as 5000 ksi (34.5 GPa)[3]. The assumed shrinkage strain of 450x10^{-6} in UHPC resulted in a prestress loss of 38.7 ksi (267 MPa) or 19 percent. As shown subsequently, the resulting prestress is sufficient to avoid tensile cracking during driving of the pile.

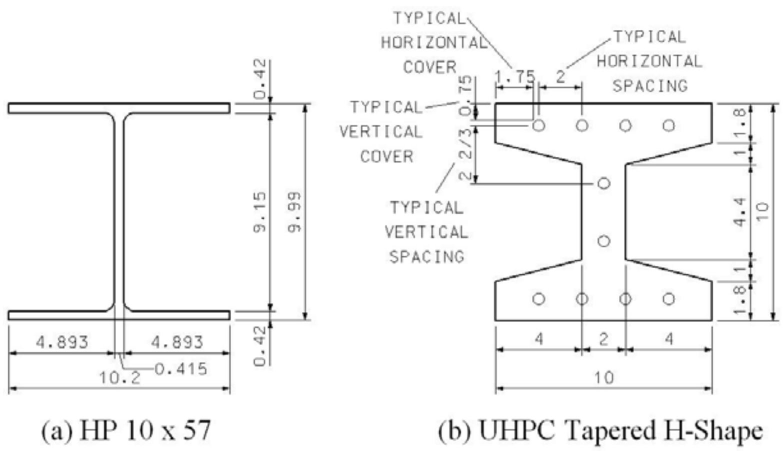

Fig. 4 Dimensions of comparable steel and UHPC pile sections

Table 3 compares the section properties of the UHPC pile with a comparable HP 10 x 57 steel pile. The UHPC pile weighs only slightly more than the HP 10 x 57, although it has a much larger cross-sectional area. The modulus of UHPC is only 29 percent of that of steel. Because the UHPC pile has a much higher moment of inertia, however, the stiffness term, EI, of the UHPC pile section is 75 percent of that of the steel pile. Further details on the section design and analysis will be available in the final report of the project[18]. Note the UHPC pile does not require ties or other shear reinforcement. Transverse reinforcement was also successfully eliminated in the UHPC girders used in a bridge in Wapello County, Iowa[4].

Table 3 Properties of steel and UHPC pile sections

Property	**HP 10 x 57 Steel Pile**	**UHPC Pile**
Total Area in.^{2} (mm^2)	16.8 (10,800)	56.8 (36,600)
Weight lb/ft (kg/m)	57.2 (85.1)	61.1 (90.9)
Moment of Inertia in^4 (mm^4)	294 (1.22 x 10^8)	795 (3.31 x 10^8)
Stiffness* kip·in^2 (N·mm^2)	8.53 x 10^6 (2.25 x 10^{13})	6.36 x 10^6 (1.83 x 10^{13})

*Stiffness represents the elastic modulus multiplied by moment of inertia, EI

SECTION BEHAVIOR

MOMENT-CURVATURE ANALYSIS

Moment-curvature analyses were performed on the section using axial loads ranging from 0 kips (0 kN) to 1064.9 kip (4736.7 kN), which is the failure load of the section under uni-axial compression. A spreadsheet was developed to facilitate the computations, which required finding the location of the neutral axis iteratively for a given combination of curvature and axial load. Then the moment corresponding to the specified curvature was calculated.

The moment-curvature analysis results can be used to establish an idealized response, which, in turn, can assist in defining the curvature ductility capacity of the UHPC section for a given axial load. Fig. 5 shows a moment-curvature diagram of the 10-in deep tapered UHPC pile section with 200 kip (890 kN) axial load. As identified in this figure, the first yield condition for the UHPC pile was defined as reaching the proportional limit in either tensile or compressive stress. Therefore, the first yield moment and curvature of the section at a particular axial load as well as the maximum moment resistance of the pile section can be readily established from the moment-curvature analysis results. The ultimate limit state was defined as the point which corresponded to UHPC or prestressing strands reaching their strain capacities or experiencing a drop in moment resistance of 20 percent below the maximum moment resistance, whichever occurred first.

DUCTILITY

The ability of the UHPC tapered H-shaped pile to undergo large curvature after reaching its maximum moment without failing or dramatically decreasing its moment resistance is a beneficial quality, which is not typical of normal concrete without including a significant amount of confinement reinforcement. Curvature ductility was calculated for the UHPC pile section using an idealized bilinear moment-curvature response for each axial load. An idealized response that accurately captured the behavior over the wide range of axial loads analyzed was formed first by extending the initial elastic portion of the moment-curvature response through the first yield point to the moment corresponding with a maximum compression strain of 0.0032 in./in. (mm/mm). The inelastic segment of the idealized response was established by connecting the yield point with a point defined by the ultimate curvature and the maximum moment resistance. Fig. 5 includes the moment-curvature idealization for the tapered H shaped UHPC pile with an axial load of 200 kips (890 kN). For all cases, the curvature ductility was defined by Equation 1.

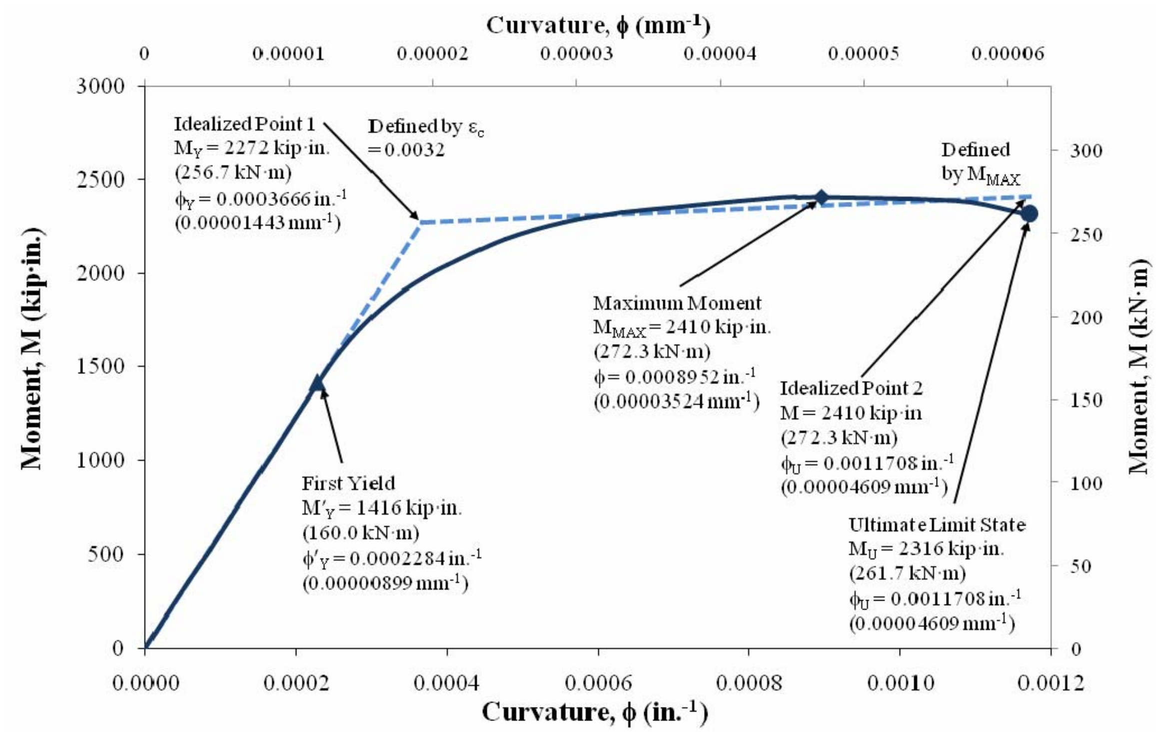

Fig. 5 Moment-curvature idealization for UHPC pile with 200 kip (890 kN) axial load (if you can, label the actual response and idealized response in the figure)

$$\mu_\phi = \frac{\phi_U}{\phi_Y} \tag{1}$$

Where:

μ_ϕ = curvature ductility

ϕ_Y, ϕ_U = Curvature at idealized points 1 and 2, respectively

The curvature ductility for the UHPC pile section ranges from approximately 1.8 to 10.4, depending on the axial load. The curvature ductility for the 200 kip axial load case shown in Fig. 5 is 3.2. Analysis currently being performed by the authors uses the moment-curvature results to simulate the lateral displacement capacity of the UHPC pile in soil. The lateral displacement capacity of the UHPC pile will also be compared with the response of other types of piles under lateral load.

INTERACTION DIAGRAMS

The interaction diagram of maximum moment and axial load of the 10-in (250-mm) deep tapered H-shaped UHPC pile section is shown in Fig. 6. The figure shows the UHPC maximum moment increases with increasing axial load up to a value of approximately 300 kips (1330 kN), and thereafter decreases with increasing axial load. A comparison between the predicted interaction diagrams of the UHPC pile section and a Grade 50 (50 ksi (345 MPa) yield strength) steel HP 10 x 57 is shown by plotting the interaction diagram of maximum moment and axial load for the steel pile with the UHPC pile in Fig. 6. For the steel pile section, the interaction equation specified by the American Association of State Highway and Transportation Officials (AASHTO)[19] was used, assuming that the soil surrounding the pile would adequately brace the flanges of the pile against lateral-torsional buckling.

The interaction diagram shows that for axial loads near the typical design load for an HP 10 x 57 steel pile (based on 6.0 ksi (41 MPa) design axial stress used in the state of Iowa[14]), the steel pile has a higher moment capacity than the UHPC pile. Using the same design axial stress limit of 6.0 ksi (41 MPa), however, the UHPC pile can sustain over three times more axial load since the pile section area is larger. At this axial load level, the UHPC pile moment resistance is 79 percent of the HP 10 x 57 moment resistance at its design axial load. Typically, the pile design is controlled by axial loads and not moment. In fact, the state of Iowa uses no moment demand for the design of piles in bridge piers[14]. Therefore, some reduction in moment resistance should not be of concern, but the potential to increase the design axial load by over three times in UHPC pile is expected to allow a reduction in the number of piles in a substructure and cost savings in both material and labor. For applications, where high moment capacity is a major concern, the pile section could be redesigned to provide additional moment resistance at the desired axial load.

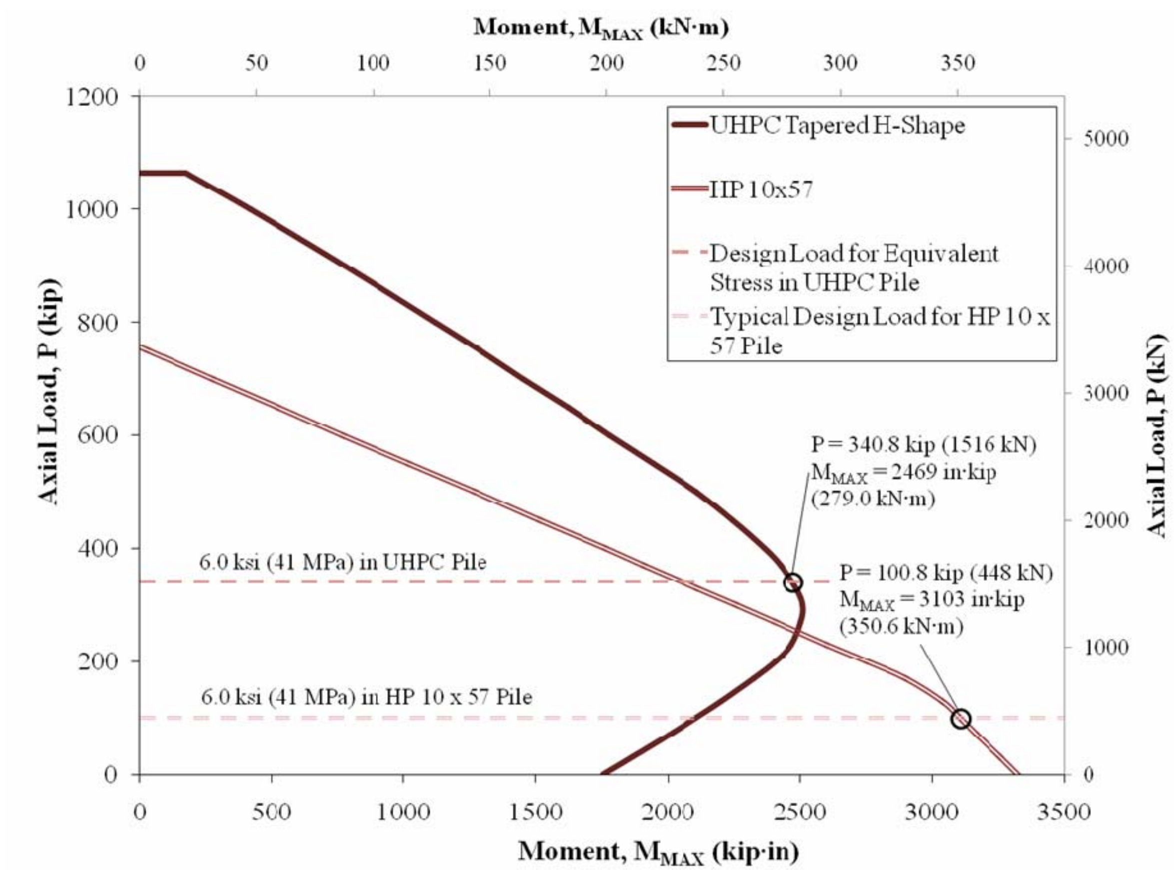

Fig. 6 Interaction diagram developed for the maximum moment resistance of a tapered H-shaped UHPC and a HP 10 x 57 steel section

STRESSES DURING DRIVING

Potential damage caused by driving stresses is a major concern with concrete piles. Large amounts of pile cushion are commonly used to ensure normal precast, prestressed concrete piles do not develop high tensile or compressive stresses during driving, which can crack or damage the pile. As shown in Table 4, potential damage to precast, prestressed concrete piles may be eliminated by limiting stresses to allowable values in AASHTO specifications[20]. The combination of higher level of prestressing and inherently high tensile strength of the UHPC pile, however, should alleviate the tensile cracking concern, allowing a much higher limit on tensile stresses that may be developed during driving.

Table 4 Maximum allowable stresses during driving of normal precast, prestressed concrete piles[19]

Allowable Stress	Psi	MPa
Tension	$f_{pe} + 3 \cdot \sqrt{f'_c}$	$f_{pe} + 0.25 \cdot \sqrt{f'_c}$
Compression	$0.85 \cdot f'_c - f_{pe}$	$0.85 \cdot f'_c - f_{pe}$

Where:

f_{pe} = effective prestress in concrete

f'_c = concrete compressive strength

In Table 5, the allowable driving stresses determined for a standard Iowa Department of Transportation 12-in. (300-mm) square concrete pile with 5.0 ksi (35 MPa) concrete and four ½-in. (13-mm) prestressing strands are compared to the possible stress limits of the UHPC pile. These stress limits were established using the equations in Table 4, but rather than the square root of f'_c term, a tensile strength of 1.0 ksi (6.9 MPa) was used for the UHPC pile, since this more accurately represents a conservative tensile capacity of UHPC. As seen in Table 5, the stress limits used in the state of Iowa for the 12-in. (300-mm) square normal concrete pile are 0.8 ksi (5.5 MPa) for tension and 3.5 ksi (24 MPa) for compression. However, stress limits of 5.5 ksi (38 MPa) for tension and 17.5 ksi (121 MPa) for compression could be specified for the UHPC pile, which is an increase of over four times the limits established for a normal prestressed concrete pile. Therefore, the thickness of the pile cushion needed for the UHPC piles would be small, and also the driving equipment now used for steel piles can be used to drive the UHPC piles.

Table 5 Calculated allowable driving stresses for normal concrete and UHPC piles

Allowable Stress	12-in. (300 mm) Square Normal Prestressed Concrete Pile	10-in. (250 mm) Tapered H-Shaped UHPC Pile
Tension	820 psi (5.7 MPa)	5740 psi (39.6 MPa)
Compression	3640 psi (25.1 MPa)	17660 psi (121.7 MPa)

MODIFICATIONS AT THE PILE TOP

Since the prestressing will not be fully effective over the prestress transfer length, tension at the top of the UHPC pile could still be a problem during driving. An 18 in. (460 mm) region near the pile head was therefore expanded to minimize tensile stresses. Recognizing the gradual increase in the effectiveness of the prestress, the tapered H-shaped section was flared out beginning 18 in. (460 mm) from the top of the pile, with a solid 10-in. (250-mm) square section for the top 9 in. (230 mm) of the pile, as shown in Fig. 7. Without effective prestress, the allowable tensile force that the pile can sustain without cracking at the end region is thus increased from 72 kips (320 kN) to 128 kips (569 kN) by expanding the section. Since the strand pattern is not changed in this region, the resulting modification required for the formwork at the pile head is not expected to be challenging.

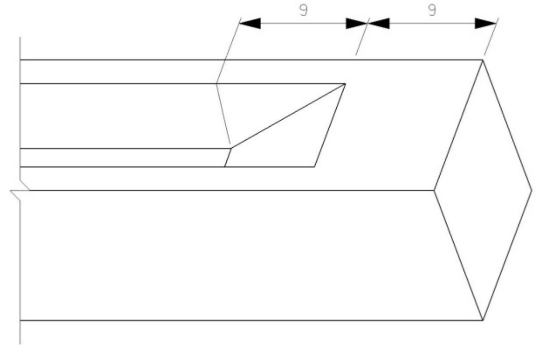

Fig. 7 Recommended expanded region at top of UHPC pile to minimize driving stresses

PRELIMINARY DRIVEABILITY ANALYSIS RESULTS

The wave equation analysis software GRLWEAP[21] has been used to analyze the behavior of UHPC and other piles during driving. More extensive analyses are currently in progress by the authors, but for the present time a simple example is included in this section to demonstrate the possible advantages of UHPC.

An HP 10 x 57 steel pile, the 12-in. (300-mm) square normal concrete pile discussed earlier, and the UHPC tapered H-shaped pile were analyzed using the same driving system in the same soil profile. The hammer used was a 4.0 kip (18 kN) single-acting diesel hammer with a rated energy of 48.7 ft·lb (66 kJ) and a 2.0 kip (8.9 kN) helmet. A 2-in. (50-mm) thick aluminum and conbest hammer cushion was used in all three cases. The normal concrete pile required a 4.0-in. (100-mm) thick pile cushion, so a 4.0-in. (100-mm) thick cushion was used on the UHPC pile as well for a direct comparison. The assumed soil profile was uniform sand with an SPT N-value of 20 to a depth of 59.5 ft, underlain by a thick claystone layer modeled with an undrained shear strength of 80 ksf (3.8 MPa). A total pile length of 60 ft (18 m) for each type of pile was driven into the soil. Table 6 compares the maximum tensile and compression stresses in each of the piles obtained from the driving analysis with the respective capacities.

Table 6 Maximum driving stresses and the corresponding capacities for piles driven into a uniform soil profile

Pile Type	Actual Tension Stress, ksi (MPa)	Tension Capacity, ksi (MPa)	Actual Stress/ Capacity	Actual Comp. Stress, ksi (MPa)	Comp. Capacity, ksi (MPa)	Actual Stress/ Capacity
12” Concrete*	0.45 (3.1)	0.82 (5.7)	54.9 %	2.4 (17)	3.6 (25)	66.8 %
10” UHPC*	0.49 (3.4)	5.54 (38.2)	8.9 %	5.0 (34)	17.6 (121)	28.3 %
HP 10 x 57	2.53 (17.4)	45.0 (310)	5.6 %	19.7 (136)	45.0 (310)	43.8 %

*Both using 4.0-in (100-mm) thick pile cushion

The percentages of driving stresses with respect to available capacities reported in Table 6 are significantly lower for the UHPC pile than the normal prestressed concrete pile. The percent of tensile capacity experienced by UHPC during driving is closer to that of the steel pile than the concrete pile. The significantly lower stresses developed in UHPC piles may enable them to be driven with a smaller or no pile cushion, similar to driving steel piles, in which current practice is to use no pile cushion. Using the same driving system and soil profile, the impact of driving the UHPC pile with the cushion thicknesses of 4.0 in. (100 mm) and 2.0 in. (50 mm) and 0 in. (0 mm) was investigated. The results are shown in Table 7. The maximum stresses do not drastically increase with the reduction in the cushion thickness. The actual stresses corresponding to the case of no cushion do not even exceed 14 percent of capacity in tension or 33 percent of capacity in compression, indicating the viability of driving the UHPC pile without a pile cushion.

Table 7 Maximum driving stresses for UHPC pile with varying cushion thickness

Cushion Thickness in. (mm)	Actual Tens. Stress ksi (MPa)	Tensile Capacity ksi (MPa)	% Tensile Capacity	Actual Comp. Stress ksi (MPa)	Comp. Capacity ksi (MPa)	% Comp. Capacity
4.0 (100)	0.49 (3.4)	5.54 (38.2)	8.9 %	5.0 (34)	17.6 (121)	28.3 %
2.0 (50)	0.71 (4.9)	5.54 (38.2)	12.9 %	5.2 (36)	17.6 (121)	29.5 %
None	0.78 (5.3)	5.54 (38.2)	14.0 %	5.8 (40)	17.6 (121)	32.8 %

UPCOMING LABORATORY AND FIELD TESTS

In order to confirm the results from section and driveability analyses, laboratory and field tests will be performed on the UHPC tapered H-shaped piles. Combined axial load and bending moment will be applied to a ¾ scale section to verify the moment-curvature behavior of the piles. Then, test piles will be driven at a bridge site in Iowa to allow direct comparison of the driveability with steel piles used in the bridge foundations on the site, followed by a load test to verify the resistance of the pile in the field.

CONCLUSIONS

A 10-in. deep UHPC pile with a tapered H-shaped cross-section has been designed as a constructible and efficient alternative to both normal prestressed concrete and steel piles. The cover and spacing requirements have been modified to reflect both the superior strength and excellent durability of UHPC. The axial capacity of the UHPC pile exceeds that of a steel HP 10 x 57. The curvature ductility capacity of this pile section was found to range from 1.8 to 10.7. Depending on the axial load, the flexural capacity of the UHPC pile may be greater or lower than that of a comparable steel pile. Since the design of piles in bridge pier foundations is not typically dictated by the moment demand, the moment resistance of the two piles is not usually an issue. Because of the larger cross-sectional area with the axial stress limit of 6.0 ksi (41 MPa) used in current steel pile design, the UHPC pile offers a larger axial load resistance than the steel pile, which will reduce the required number of piles and the construction cost of the foundations.

Driveability analysis indicates that driving stresses in the designed UHPC pile will be significantly below the capacities. The ratios between the driving tensile and compressive stresses and the respective capacities will be more comparable to those expected in steel piles than in normal prestressed concrete piles. Consequently, it was found that the UHPC piles may also be driven with a thin or no pile cushion without causing any damage to the pile. As long as the pile remains uncracked, the superior durability properties of UHPC could result in piles not susceptible to deterioration currently seen in both concrete and steel piles, ultimately helping increase the lifespan of bridges.

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