Use of UHPC Jackets in Coastal Bridge Piles

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Abstract:

Concrete deteriorates for a variety of reasons, but corrosion of steel reinforcement has been one of the most prevalent mechanisms of deterioration since concrete structures were introduced in the early 1900s. It affects many types of concrete elements, especially the substructures of coastal bridges. Steel reinforcement used in coastal bridge piles has exhibited corrosion damage within twenty years of construction. Therefore, it degrades the durability and reduces the service life of the bridges severely. As a result, it costs billions of dollars in rehabilitating or repairing the deficient components. The recent development of UHPC can mitigate these deficiencies because of its exceptional properties. However, the cost of UHPC is significantly higher than that of the conventional concrete. Therefore, it appears to be attractive to use UHPC jackets in coastal bridge piles, which allows to taking advantage of the superior properties of UHPC without using excessive amount of UHPC in the full section. This paper presents a study of the structural design of piles using UHPC jackets, including the working stress design and strength design. A numerical example of a square pile using a UHPC jacket is included to show how the flexural strength design can be handled.

Keywords:

Ultra-high performance concrete jackets, coastal bridge piles, interaction diagram, corrosion

1. Introduction

The Federal Highway Administration estimates that there are over 36,000 bridges within 15 miles of coastal waters in the United States [FHWA, 2013]. Precast prestressed concrete piles are being used increasingly in these bridges. However, recent studies have found that the piles of many coastal bridges are deteriorating because the concrete is subjected to sulfate and biological attack and the prestressed and non-prestressed reinforcement exhibits corrosion damage as early as 20 years after construction [Moser et al., 2011, Griggs, 1987, Hamilton, 2007, and Thaesler et al. 2005]. Figure 1 shows the deterioration typical of precast prestressed concrete piles. A study of Georgia Department of Transportation bridge inspection records showed that approximately 30%, or 85 of 290, coastal bridges had pile substructure ratings of 6 or lower, indicating that the piles exhibited visible damage [Schuetz, 2013]. Similar problems have been discovered in several other states, including Florida. Flexural tests of the Bryant Patton Bridge piles in in Florida indicated that some piles were able to carry only 31% of the calculated capacity because of corrosion damage [Hamilton, 2007].

Figure 1. Deterioration typical of precast prestressed concrete piles [Moser et al., 2011, and Griggs, 1987]

Ingress of chloride ions from seawater is the primary cause of concrete piles' corrosion. When these ions reach a sufficient concentration at the steel reinforcement, it causes localized breakdown of the protective passive film and initiates corrosion. As a result, the steel reinforcement's corrosion degrades the structures' durability and shortens their service life significantly. Numerous corrosion-initiated failures have occurred in precast prestressed concrete piles that cause costly repair and replacement of the whole bridge or some structural members. Consequently, concrete piles' deterioration has increased bridge maintenance costs tremendously to achieve the design life of 75 or 100 years. Therefore, it is necessary to develop a feasible solution to mitigate the pile deterioration.

2. Background

Advances in concrete materials technology have led to the development of a new generation of cementitious materials referred to as ultra-high performance concrete (UHPC). UHPC is a composite material composed of an optimized gradation of granular constituents, a water-to-cementitious materials ratio less than 0.25, and a high percentage of discontinuous internal fiber reinforcement [Fehling et al., 2014]. UHPC's mechanical properties include compressive strength greater than 21.7 ksi and pre- and post-cracking tensile strength greater than 0.72 ksi [Russell and Graybeal, 2013]. UHPC formulations often consist of a combination of portland cement, fine sand, silica fume, high-range water-reducing admixture, fibers (usually steel), and water [Graybeal, 2007, and Ahlborn et al., 2008]. Commercial UHPC's cost is significantly higher than that of conventional concrete. However, several researchers have developed nonproprietary UHPC recently using local materials, which can reduce its cost by up to 70 percent [Giesler et al., 2016, El-Tawil et al., 2016]. A literature review showed that UHPC jackets had been used particularly in seismic retrofit or repair of bridge or building members. For example, UHPC can be used in critical regions, such as potential plastic hinges, to improve earthquake-resistant columns' strength and deformability characteristics [Ichikawa et al., 2016].

UHPC's dense microstructure decreases its porosity and consequently, its permeability. Chloride penetration tests on UHPC specimens indicated that corrosion of discontinuous steel fibers in the concrete mix occurred typically on and very close to the surface, and did not progress into the specimens' interior [Graybeal, 2006]. Thomas et al. tested three series of UHPC mixtures in a marine exposure site at Treat Island, Maine (2012). The exposure conditions included 20-ft tides and more than 100 freeze-thaw cycles per year. After 5 to 15 years of exposure and more than 1,500 cycles of freezing and thawing in some cases, there was no evidence that the UHPC's mechanical properties deteriorated or degraded. The depth of chloride penetration for UHPC was approximately one third that of typical high-performance concrete after 12 years of exposure to the same environment.

Therefore, use of UHPC jackets in precast prestressed concrete piles is a potential solution to steel reinforcement corrosion, and also is cost-effective because UHPC is used at the most critical portion of the pile section. Figure 2(a) shows the cross section of a conventional precast prestressed concrete pile. Possible uses of jackets are illustrated in Figures 2(b) to 2(d): a relatively thick UHPC jacket accommodating the strands and tie reinforcement, a thin UHPC jacket within the concrete cover, and a thin UHPC jacket using a reduced concrete cover, respectively. The same concept is applicable to other pile section types. This paper focuses on the use of thick jackets as illustrated in Figures 2(b).

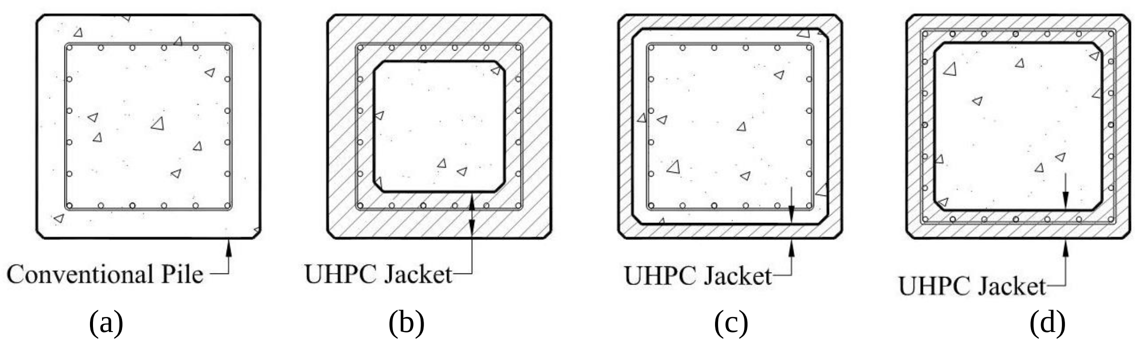


Figure 2. Pile sections. (a) Conventional pile. (b) Pile with a thick jacket. (c) Pile with a thin jacket using the same concrete cover as conventional pile. (d) Pile with a thin jacket using a reduced cover.

This paper presents the use of jackets from the view of producing new piles by assuming that the layout of the strands in conventional piles remains the same when UHPC jackets are included. It is meant to minimize the extent of changes to the existing structural details so that the use of jackets can be more receptive to precast producers. In terms of fabrication sequences for the pile with a thick jacket in Figure 2(b), it is expected to involve the following steps: 1) fabricate the core section using conventional concrete; 2) install the pretensioning strands and stirrups and tension the strands; 3) pour the UHPC jacket; and 4) release the strands once the UHPC reaches the required strength. These sequences will be revised for the piles using a thin jacket in Figure 2(c): the jacket is produced first and works as a form for the core concrete. After the strands are tensioned, the core concrete can be poured. Afterwards, release the strands when the core concrete achieves the specified strength. In both cases of thick and thin jackets, the intent of the proposed sequences is to apply prestressing forces to the full section including both conventional concrete and UHPC.

3. Structural Design

This paper discusses the working stress design and flexural strength design of the piles using UHPC jackets. The discussions focus on the resistance (or strength) of the piles with or without UHPC jackets and no external loads are accounted for. It addresses the structural design of a solid square pile using pretensioning strands. Slenderness effect is excluded in this study. A fully composite action is assumed to be achieved between the UHPC jacket and the conventional concrete at the ultimate strength limit. Formliners or other positive connections between the UHPC and conventional concrete may be required, if deemed necessary from the analysis. The thickness of UHPC jackets is assumed to satisfy the driving requirements. The confinement effect due to the UHPC jacket on the conventional concrete, if any, is ignored in this study. A numerical study is performed to determine the flexural strength of piles with UHPC jacket accounting for various variables including the jacket thickness and strength of the conventional concrete, etc.

3.1. Working Stress Design

When prestressed strands are released, the full pile section is subject to the prestressing effect. When working stress design is performed, a transformed section can be accounted for. Figure 3 illustrates both gross and transformed sections. Prestressing strands are not shown for clarity. The effective width of the transformed section can be determined by dividing the ratio of moduli of elasticity between UHPC and conventional concrete.

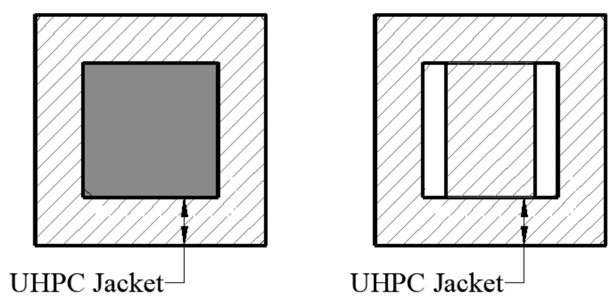


Figure 3. Pile sections. (a) Gross section. (b) Transformed section.

3.2. P-M Interaction Diagram

A number of assumptions are necessary to develop the P-M interaction diagram, including mechanical properties of the materials. Apparently, the UHPC properties vary among different suppliers. For discussion purpose, the stress-strain relationship of a commercial UHPC product is shown in Figure 4, which was proposed by Graybeal (2008). This particular concrete has a compressive strength of 24 ksi and a tensile strength of 1.5 ksi. The modulus of elasticity of UHPC is calculated by the following equation:

$$E_C = 1460\sqrt{f_c'} \quad (f'_c \text{ in ksi})$$

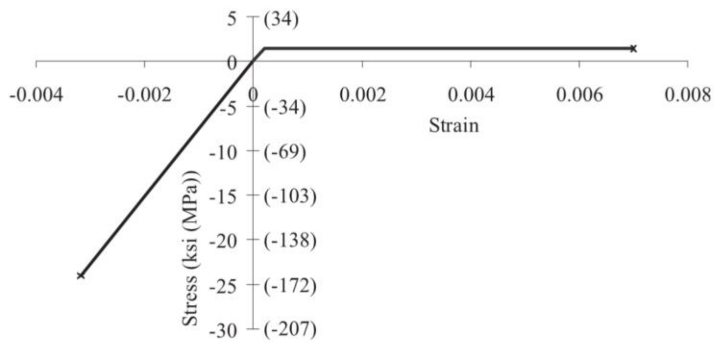


Figure 4. Simplified uniaxial stress-strain diagram [Graybeal, 2008]

The stress-strain relationship of the conventional concrete is assumed to be linear up to 85 percent of the specified compressive strength and remain constant up to the ultimate strain of 0.003. The stress-strain relationship of prestressing strands is given by the power formula in the PCI Bridge Design Manual as follows:

$$f_s = \varepsilon_s E_s \left[Q + \frac{1-Q}{\left[1 + \left(\frac{\varepsilon_s E_s}{k f_y} \right)^R \right]^{1/R}} \right]$$

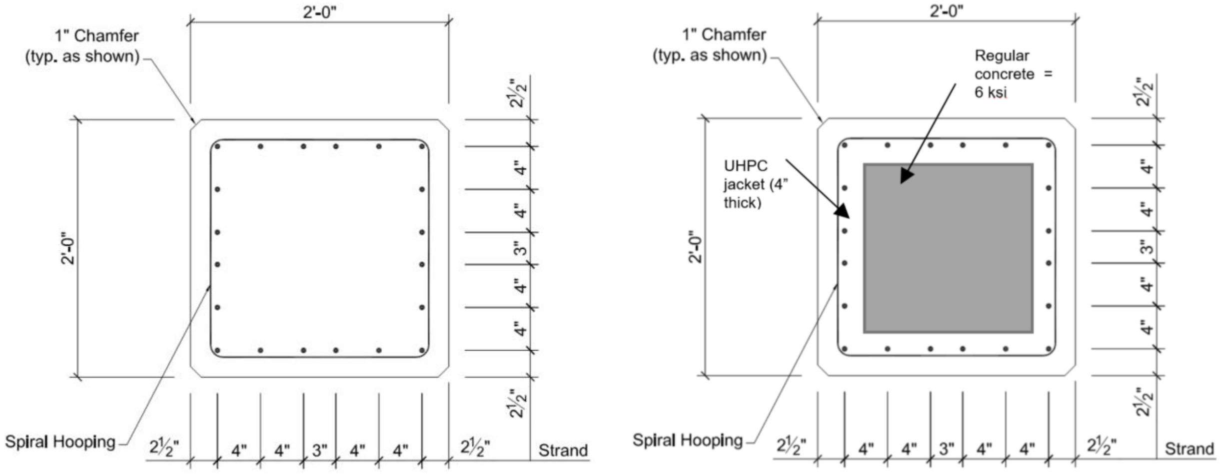
Where: f_s = steel stress, and ε_s = steel strain; The constants E_{si}, Q, f_{yi}, k, and R for Grade 270 prestressing strands are 28,500 ksi (197 GPa), 0.031, 243 ksi (1,680 MPa), 1.04, and 7.36, respectively [Devalapura and Tadros, 1992].

When the P-M interaction diagram is developed, strain compatibility and force equilibrium are satisfied. The strain compatibility approach is based on the three well-accepted fundamental assumptions:

1) plain section remains plain after bending,
2) compatibility of strains, i.e., full bond between steel and concrete, and
3) equilibrium of forces within a section.

4. Results

To illustrate the strength design of the pile using a UHPC jacket, a numerical example is presented for a 24 in. (610 mm) square pile. The pile sections are shown in Figure 5, which consists of a conventional pile and a pile using a UHPC jacket. The precast prestressed concrete pile includes 20-0.5 in. (12.7 mm) diameter, Grade 270 ksi (1,862 MPa) low-relaxation strands. 10% prestress loss is simply assumed. The conventional concrete has a compressive strength of 6 ksi (41.4 MPa) at 28 days. The UHPC jacket is 4 in. (102 mm) thick.



(a) (b)

Figure 5. Pile sections. (a) Conventional pile. (b) Pile with a UHPC jacket.

Figure 6 illustrates the nominal P-M interaction diagrams of both conventional pile and the pile using a UHPC jacket. It can be found that the nominal strength of a pile with a UHPC jacket significantly exceeds that of the conventional pile. Because of relatively large thickness of the jacket, the interaction diagram accounting for the jacket only approaches that of the full pile section, especially at the tension-controlled region.

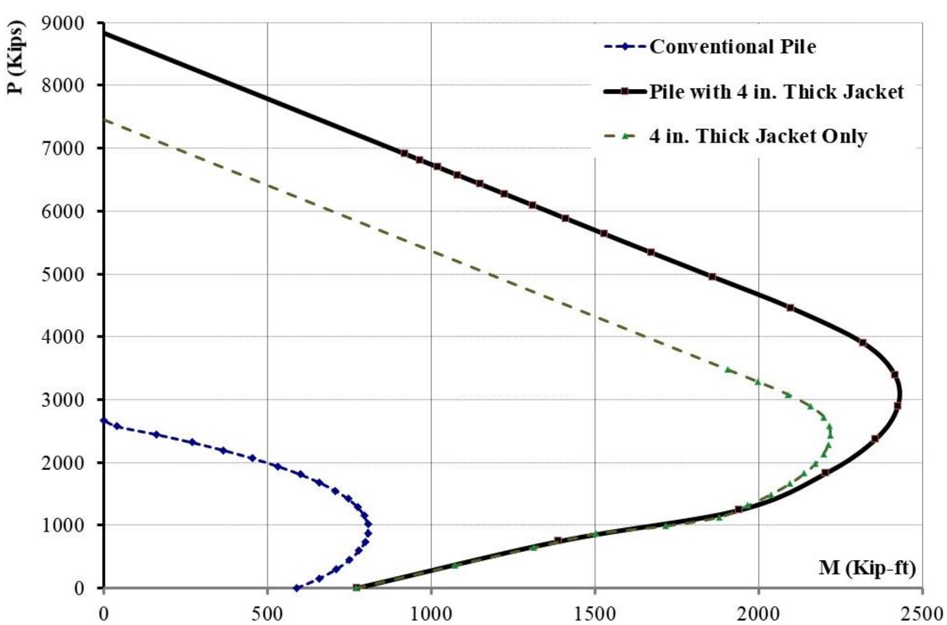


Figure 6. Nominal P-M interaction diagrams of a 24 in. square pile with 4 in.-thick jacket

Similarly to Figure 6, Figure 7 shows nominal interaction diagrams of piles using various jacket thickness, 4 in., 4.5 in., and 5 in. Because of the slight increase in jacket thickness, the increase in pile strength is insignificant.

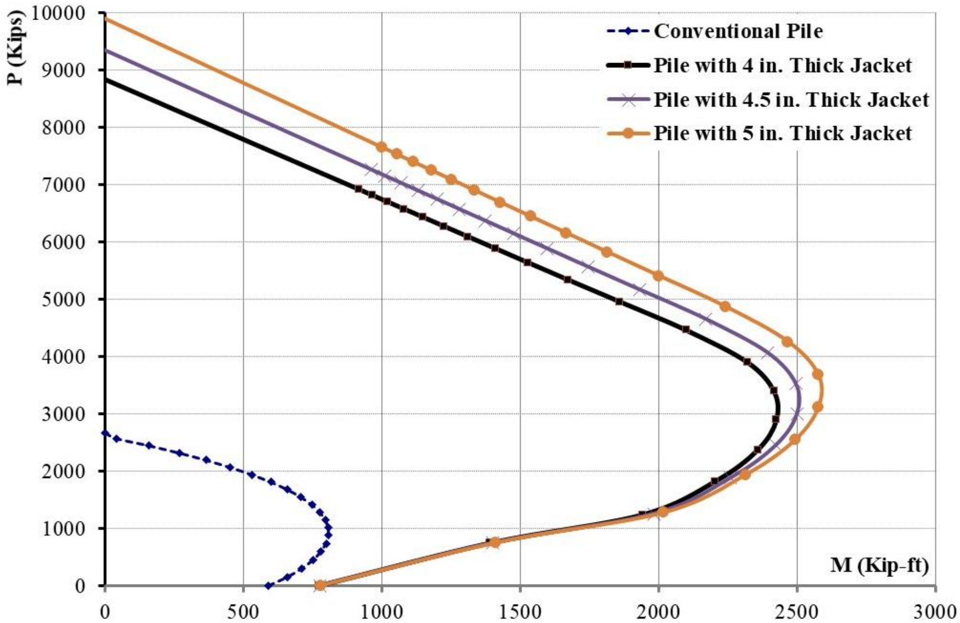


Figure 7. Nominal P-M interaction diagrams of a 24 in. square pile with various jacket thickness

An increase of the concrete strength in a conventional pile affects its strength significantly. Figure 8 plots the nominal interaction diagrams of a conventional 24 in. square pile using 6 ksi, 8 ksi, and 10 ksi, respectively. When a 4 in.-thick UHPC jacket is included, the strength of the core concrete slightly affects the pile strength. It can be found that the contribution of the UHPC jacket to the pile strength is more dominant than the core concrete.

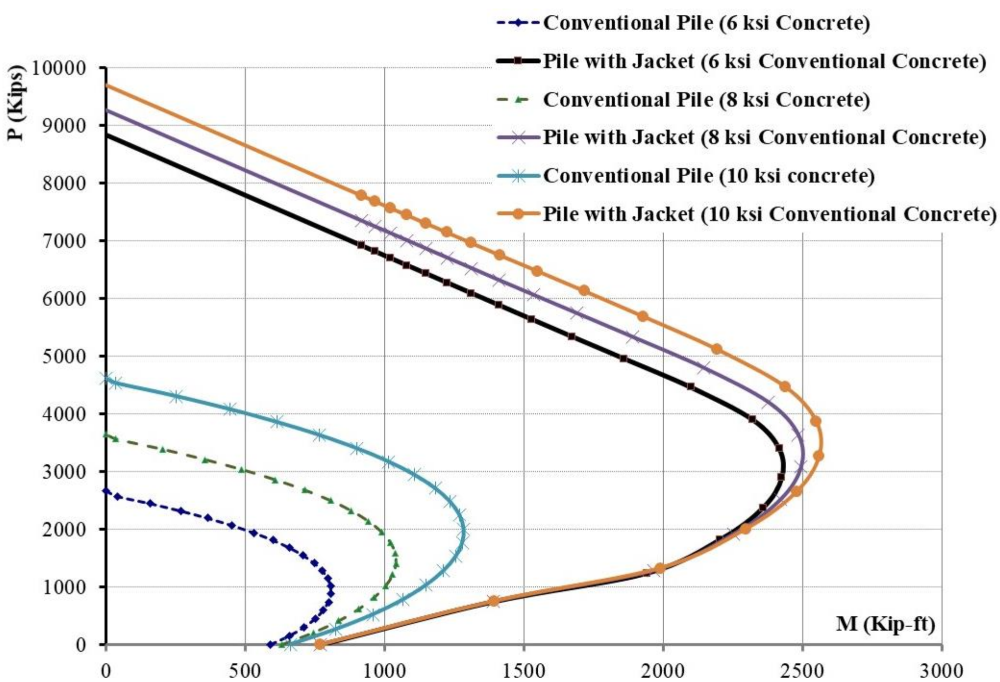


Figure 8. Nominal P-M interaction diagrams of a 24 in. square pile with various strengths of conventional concrete

Figure 9 plots the nominal interaction diagram of a conventional pile, 24 in. x 24 in., using 6 ksi concrete. Also plotted is the diagram for a pile section of 20 in. x 20 in. with a 4 in.-thick jacket. It can be found that a significantly higher strength can mostly be achieved even using a reduced pile size and reduced number of strands, when the UHPC jacket is included. According to the standard details by Heldenfels Enterprises, a 24 in. square pile uses a total of 20 strands, while a 20 in. square pile accounts for 16 strands (Figure 10). The reduced number of strands results in decreased flexural strength of the pile slightly, which is illustrated in the tension-controlled regions of the diagrams. A similar conclusion can be drawn for piles using 10 ksi conventional concrete with and without the UHPC jacket.

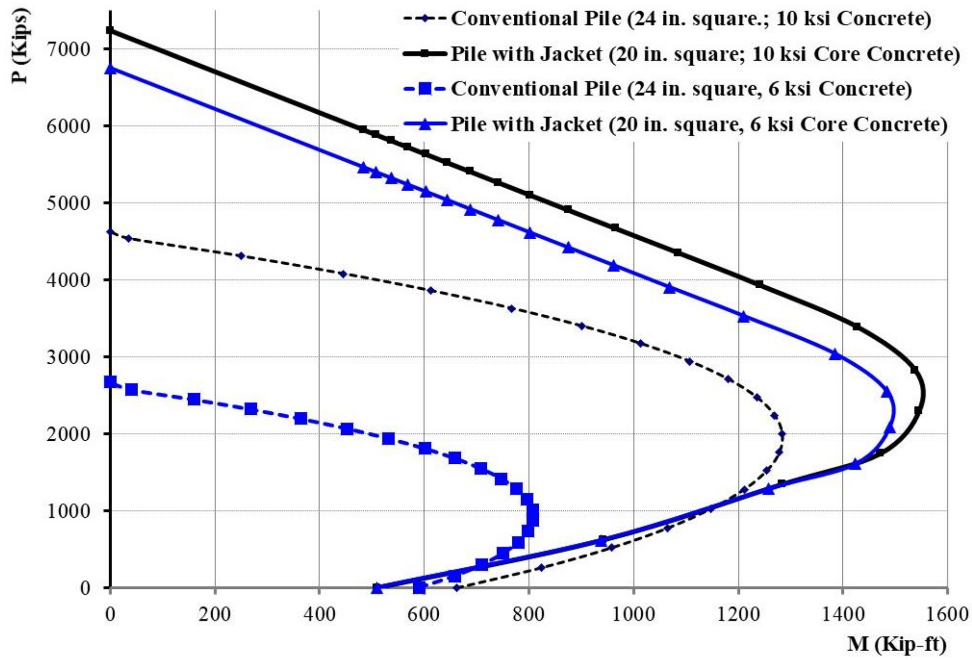


Figure 9. Nominal interaction diagrams of 24 in. conventional pile and 20 in. piles with jacket

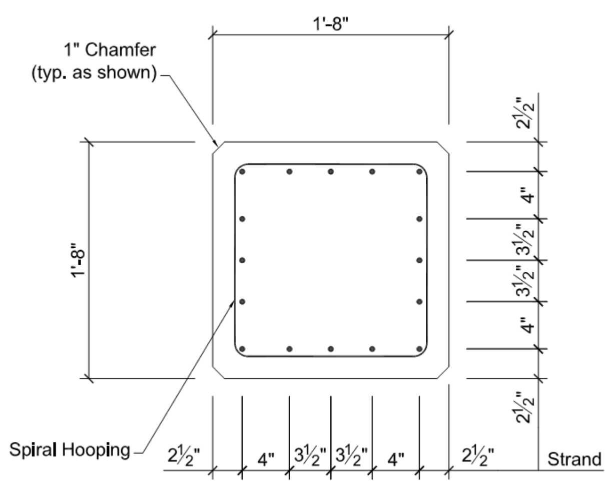


Figure 10. Strand layout of a 20 in. square pile

5. Discussion

The P-M interaction diagrams of the piles show that the UHPC jacket can increase the structural capacity tremendously. This indicates that a smaller pile section may be sufficient to satisfy the structural design requirements, if a UHPC jacket is included. If the number of strands is designed properly without following the existing strand layout in standard details, the pile section may be further optimized when a UHPC jacket is added. Alternatively, piles can use thick UHPC jackets only without conventional concrete by doing the following: 1) include stay-in-place (SIP) forms such as expanded polystyrene along the full length of the piles except the pile ends; and 2) provide solid UHPC blocks at the ends of the piles. The justification of eliminating the conventional concrete is that its contribution to the pile strength is insignificant and the use of SIP forms may simplify the pile production.

6. Conclusions

This paper presents the use of UHPC jackets in precast prestressed concrete piles. It addresses the structural design of the piles with UHPC jackets, including the working stress design and the flexural strength design. It shows how to handle a composite pile section incorporating both UHPC and conventional concrete. The superior properties of UHPC allow to enhancing the strength of the piles significantly. More important, the extremely low permeability of UHPC can mitigate the corrosion of the reinforcement and therefore enhance the structural durability of the piles. This concept of including UHPC jackets in piles is particularly applicable to marine bridges that are subject to severe environments.

7. References

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