Post-tensioned splice system for precast, prestressed concrete piles: Part 1, conceptual design

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P recast, prestressed piles are commonly used in foundations of structures, such as bridges or tall buildings, and must resist large loads. In applications where the required pile length exceeds 120 ft (37 m), installation can sometimes be simplified by using shorter spliced piles instead of a single longer pile. Shorter piles weigh less, are easier to transport, and are less prone to cracking during handling and placement.

The majority of pile splicing systems are proprietary with mechanical steel-type connections. Since Bruce and Herbert's 1974 state-of-the-art review,[1] there have been limited new developments. These have largely been confined to a few new patent filings and occasional research findings.[2–4]

Although most engineers avoid pile designs that require splicing, the need does exist. The three most commonly used splicing systems for piles in the United States are a mechanical system, a welded-end-plate system, and an epoxied-dowel method.[5] The mechanical splicing system is perhaps the most commonly used mechanical splice for piles in the United States. Because the mechanical components are cast into the piles in the prestressing bed, this system can only be used for preplanned splices. The connection detail incorporates reinforcing bars that must extend into the pile segments sufficiently to develop strength using reinforced concrete principles. The two pile segments are connected in the field by aligning the mechanical couplers and inserting interlocking bars or cables through the openings in the male and female plates to form a shear key.

- ■ When a pile must be driven after splicing, the splice connection is prone to tensile failures due to its inability to transfer driving stresses through the connection and into the other pile segment.

- ■ A post-tensioned splice was developed that eliminates the tensile-stress limitations during driving.

- ■ This is the first of three papers that details the development of this alternative approach, including the conceptual basis for the design and its implementation into a prototype system.

A precast concrete pile welded-end-plate system developed in Malaysia is another innovative pile design that uses prestressing bars—instead of strands—that extend through the steel end plates secured by deformed *button* ends. The bars are stressed simultaneously via the end plates, which become part of the finished pile. This results in concrete precompression that extends along the full length of the concrete pile, while the steel end plates provide a weldable interface for splicing.[6] Because all precast concrete piles are cast with steel end plates, splicing is always anticipated, thereby negating concerns over unplanned splices. The welding and splicing process rivals mechanical splice efficiency.

The epoxied-dowel splice is far less effective than the other two options, but given its simplicity, it is widely used and accepted. This method is often used when splicing conditions arise unexpectedly. The lower precast concrete pile is prepared simply by drilling holes into it in a prescribed pattern. The upper pile typically is cast with reinforcing bars embedded in the bottom end (with the same pattern as the holes in the lower pile) with sufficient length to bond in the lower pile. The design of the epoxied-dowel splice must provide sufficient reinforcement, thereby incorporating reinforcement development length concepts and the epoxy strength properties.

Need for a new splicing system

Each of the methods discussed previously has limitations related to pile splice efficacy or applicability. While some states allow the mechanical-pile-splice tensile stresses during driving to approach one-piece pile limits, more prudent specifications restrict tension stresses by about half. Most mechanical splice systems used in the United States are foreign made and can be restricted from use due to the statutory Buy American Act.[7]

Like the mechanical splicing system, the Malaysian system is vulnerable to corrosion attack at the splice interface and is subject to fatigue considerations at the welded interface. The prestressing bars are not domestically produced, which raises the same Buy American Act concern, and the welded cage detail introduces additional fatigue concerns.[6]

Although the epoxied-dowel method has the advantage of handling unforeseen splice scenarios in virtually all concrete pile types, it severely limits the tensile and bending capacities of the piles. Tensile stresses during driving are often limited to one fifth of that allowed in a one-piece prestressed pile.[8] The upper pile segment must be aligned and held in place continuously while the epoxy cures, which can occupy equipment and cause construction delays.

The main weakness in mechanical or epoxied-doweled splices is their low tensile strength. In these regions, the splice strength is comparable to that of a reinforced concrete section. Because piles can encounter large tensile stresses when driven, the poor tensile strength of these splices affects construction efficiency. In one-piece piles, tensile stresses are readily resisted by the precompression from prestressing. A spliced pile is driven more slowly using lower fuel settings or thicker, energy-reducing pile cushions to ensure that there is no failure at the weakened splice interface (with no precompression). Given that millions of prestressed piles are driven in the United States, the aggregate effect of the longer time taken to drive spliced piles adversely affects construction time and costs.

Restoring precompression in spliced piles

A post-tensioning approach to splicing provides a means of restoring the tensile capacity lost near the ends of a prestressed pile at a splice. Attempts were previously made to develop a post-tensioned splice (discussed later), but an important weakness of these systems was that precompression stresses were introduced into the entire pile segment being post-tensioned, not just to the spliced region.

This paper presents findings from a two-and-a-half-year research project that developed a new post-tensioning splice system that limits the precompression splicing stresses to the spliced region.

Objectives and scope

The goal of the proposed research was to develop an alternative post-tensioning concept that meets the requirements of an ideal splice for bending, shear, and tensile strength and is amenable to field practices.

The initial scope of the project was to demonstrate proof of concept through laboratory and full-scale testing. The success of this phase of the study led to additional support for its field implementation through a full-sized demonstration project. Although the core post-tensioning concept remained unchanged, details were continually refined and simplified to facilitate the fabrication of full-sized specimens at commercial prestressing facilities. Because fabrication of the pile segments and their subsequent assembly were critically important, the findings of the research project are presented in three different parts as follows:

- Part 1 covers the conceptual design and development of the splicing system.

- Part 2 includes capacity verification through laboratory and full-scale testing.

- Part 3 discusses field implementation and driving instrumented spliced pile.

This paper covers the conceptual design. It outlines the core elements of the new system and describes how the prototype components were developed. This constitutes the basis for the subsequent papers that will address capacity verification and driving a full-sized spliced pile.

Pile specifications for driving stresses

Florida Department of Transportation (FDOT) specifications[9] section 5.11.2 limits the stresses developed in prestressed concrete piles during driving based on the wave equation.[10] Equations (1) through (4) are used to determine the maximum allowed pile stresses measured during driving.

Allowable compressive stress:

$$s_{apc} = 0.7 f_c' - 0.75 f_{pe} \qquad (1)$$

Allowable tensile stress for piles less than 50 ft (15 m) long:

$$s_{apt} = 6.5 \sqrt{f_c'} + 1.05 f_{pe} \qquad (2)$$

Allowable tensile stress for piles 50 ft long and greater:

$$s_{apt} = 3.25 \sqrt{f_c'} + 1.05 f_{pe} \qquad (3)$$

Allowable tensile stress within 20 ft (6 m) of a mechanical splice:

$$s_{apt} = 500 \text{ psi} \qquad (4)$$

where

s_{apc} = maximum allowed pile compressive stress, psi

s_{apt} = maximum allowed pile tensile stress, psi

f_c' = specified concrete compressive strength, psi

f_{pe} = effective prestress (after all losses) at the time of driving = 0.8 times the initial prestress force (0 for dowel spliced piles), psi

For Grade 270 (1860 MPa) steel, the initial prestress is 189 ksi (0.7 × 270) (1300 MPa) and the effective prestress f_{pe} is taken as 151.2 ksi (0.8 × 189) (1042 MPa). Piles without splices are permitted to develop between 1300 and 1700 psi (9.0 and 12 MPa) of tensile stresses during driving (with f_c' equal to 6000 psi [41 MPa]), depending on the pile size (**Table 1**).

Once a splice is made, the maximum allowable tensile stresses are significantly reduced to either 250 psi (1.7 MPa) (Eq. [3]) or 500 psi (3.4 kPa) for dowel or mechanical splices, respectively. This causes a 58% to 83% reduction in the allowable tensile stresses during driving depending on which initial level is assumed (1200 or 1500 psi [(8.3 or 10 MPa]).

As a result, the contractor must reduce the driving energy, which increases the time required to install the piles. The 500 psi limit applies to the only FDOT specifications-approved mechanical splice. As more mechanical splice options become available, this may warrant a manufacturer-specified rating.

If a spliced pile can maintain full prestress through the spliced region, the driving efficiency will not be impaired and associated delays can be avoided. This was a primary goal of this study.

Splice specifications

Pile splices are categorized into three types by FDOT specifications section 455-7.7[11] and standard index 20601[12] as unforeseen nondrivable, unforeseen drivable, and preplanned drivable.

The unforeseen nondrivable splice is used after capacity has been satisfied during driving but the top of the pile elevation is too low to meet the cutoff elevation. The upper portion of this splice is a cast-in-place concrete buildup and is not intended for driving.

Table 1. Allowable driving stresses (f_c' = 6000 psi)

Pile size, in.	f_{pe}, psi	Allowable compressive stress, psi	Allowable tensile stress, psi		
			<50 ft	≥50 ft	Within 20 ft of mechanical splice
14	1012	3441	1566	1314	
18	1027	3430	1582	1330	
24	1033	3425	1588	1336	500
30	1127	3355	1687	1435	

Note: f_c' = specified concrete compressive strength; f_{pe} = effective prestress after losses. 1 in. = 25.4 mm; 1 ft = 0.305 m; 1 psi = 6.895 kPa.

The unforeseen drivable splice applies when capacity has unexpectedly not been met and it may or may not be known how much farther it will need to be driven, or when a buildup (case 1) exceeds the maximum permissible length of 21 ft (6.4 m).[10] Epoxied-dowel splices are essentially the only option available for conventional prestressed piles.

The preplanned drivable splice, in which splices are planned in advance and necessary provisions are met, is perhaps the most desirable of the three. This type can use either an ep-oxied-dowel splice with preformed holes in the lower segment or the only approved mechanical splice system. For this study, the last type (planned splices) had the greatest potential for immediate improvement, but considerations for unplanned splices were reviewed.

Although driving stresses are limited to 250 or 500 psi (1.7 or 3.4 MPa) in tension, the FDOT specifications require the strength of a pile splice to meet the following criteria for compression, tension, or bending once in place:

- compressive strength = (pile cross-sectional area) × (28-day concrete strength)

- tensile strength = (pile cross-sectional area) × 900 psi (6.2 MPa)

- bending strength

    — = 245 kip-ft (332 kN-m) for the 18 in. (460 mm) pile size

    — = 325 kip-ft (441 kN-m) for the 20 in. (510 mm) pile size

    — = 600 kip-ft (810 kN-m) for the 24 in. (610 mm) pile size

    — = 950 kip-ft (1300 kN-m) for the 30 in. (760 mm) pile size

Previously developed post-tensioned splices

Two post-tensioned splice systems have been developed that use either high-strength strands or threaded bars.

Spun-cast, post-tensioned concrete cylinder piles

Spun-cast cylinder piles are concrete pipe piles cast as rela-tively short reinforced concrete pile segments (for example, 16 ft [4.9 m]) that are spliced together using full-length post-tensioning strands to achieve the required length. This type of splicing, however, is a required step in making the piles the desired length and not technically the focus of this paper. These piles have been shown to be highly durable in marine environments and are driven as one-piece piles.[5,13] If the final pile length is too long to be lifted or driven in one piece, then the resulting splice is subject to the same limitation as other spliced piles because post-tensioning cannot be performed again.

Threaded bar post-tensioned splice stressed full length

Although this splice has been used in the United Kingdom, there are no published case studies of its use in the United States. In this system, prestressing bars were placed inside ducts of both pile segments and connected at the splice using couplers. Because these couplers were located at the splice, a special driving helmet was required to protect them during driving.

After the bottom section was driven, a jointing compound was applied to the splice interface and the upper pile segment was placed into position. Threaded bars (one of the first post-tensioning systems) were then screwed into the mechanical coupler. Post-tensioning was applied using hydraulic jacks and the bars anchored from the top. This implies that if the system were used for today's prestressed piles, the region of the pile immediately adjacent to the interface would be brought to a usable level of precom-pression while subjecting the rest of the upper pile segment to additional stress or doubling the precompression in the upper segment.

Development of a new post-tensioned splice

Post-tensioning principles are well known and discussed in texts and manuals.[14,15] For this application, these established principles had to be incorporated to introduce precompression only within the transfer-length region at the splicing ends of each precast concrete pile segment. This new system also had to meet FDOT performance requirements for driving, ultimate strength, corrosion, and constructibility. Because different pile sizes and prestress-ing configurations are permitted, the system had to be versatile so that it could be adapted for every case.

Performance requirements

The highest stresses experienced in the life span of a pile are those imposed during driving (tension and compres-sion). For a splice, the tensile strength has traditionally been the most difficult to restore where ideally it should match that of a one-piece continuous pile. While existing splices have limited tension capacity during driving, the new system was intended to remove this limitation by restoring full prestress through the splice. In so doing, several obstacles had to be overcome.

Splicing forces restricted to transfer-length region To avoid overstressing portions of the pile that were already prestressed, a post-tensioning configuration was necessary that would gradually add splicing and post-tensioning forces such that all splicing strands would exist at the splice interface (full post-tensioning force). In theory, post-tensioning stresses would be highest where prestressing stresses were smallest and vice versa.

Figures 1 and **2** show the conceptual superposition of prestressing and post-tensioning stresses for two scenarios. In the first scenario, intermediate anchorages are placed at the same location (at the back of the transfer-length zone) at each end of the two piles being spliced (Fig. 1). This results in full precompression at the splice interface, increasing to twice the target prestress level at the anchor locations.

The second scenario mitigates overstressing by staggering the location of the intermediate post-tensioning anchorages (Fig. 2). This allows a stepwise gradual increase in precompression over the splicing zone. The number of stress steps can be as many as half the number of strands used. Strands on opposite sides of the centroid of the pile cross section can be paired at the same elevation so as not to put the pile in a state of permanent eccentric loading (up to 12 steps for a 24-strand pile).

Short post-tensioning strands with large losses If the strands used to splice the pile only impose stresses over the short transfer length region (60 × strand diameter = 30 in. [760 mm] for ½ in. [13 mm] strands), anchor set losses would be unreasonably high. The prestressing chucks therefore need to be redesigned or modified to keep these losses manageable, or some form of wedge seating

control would be necessary (for example, power wedge-setting jacks).

Locally high stresses behind the anchorages The concentrated post-tensioning force introduces large localized stresses in the concrete at the anchorages. The magnitude of these stresses depends on the applied force and the size of the bearing plate. **Figure 3** shows the stress distributions obtained from numerical modeling for two trial plate sizes, $1.8 \times 1.8 \times 0.5$ in. ($46 \times 46 \times 13$ mm) and $2.5 \times 3.0 \times 0.5$ in. ($64 \times 76 \times 13$ mm). The center hole shows where the post-tensioning duct would enter the anchorage. The results showed that a ½ in. thick plate with a bearing area of approximately 7 in.² (4500 mm²) would produce an average stress of 3 ksi (21 MPa) over the already existing level of precompression. The effect of this additional stress could be mitigated using additional confinement steel around the post-tensioning ducts.

Number of splicing strands and positioning To provide the same effective prestress and ultimate strength as an unspliced pile, the number of post-tensioning strands and their location in the cross section should be identical if the same-sized strands are used. Alternatively, if the post-tensioning strands are larger, then fewer strands could conceivably be used. However, one of the project design constraints was to use conventional pile configurations (for example, in terms of number, size, and position of strands) so that the new splice could be readily adapted to existing prestressing beds. This meant that the splicing strands could not occupy the same location as the existing prestressing strands but would need to occupy only those regions between strands or within the core of the pile. If strands were concentrated within the core, the requirements
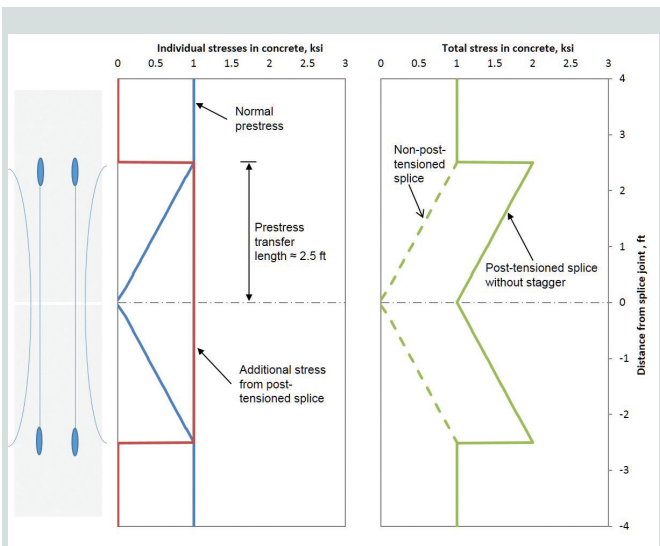
Figure 1. Superposition of initial prestressing and stresses from a post-tensioned splice. Note: 1 ft = 0.305 m; 1 ksi = 6.895 MPa.
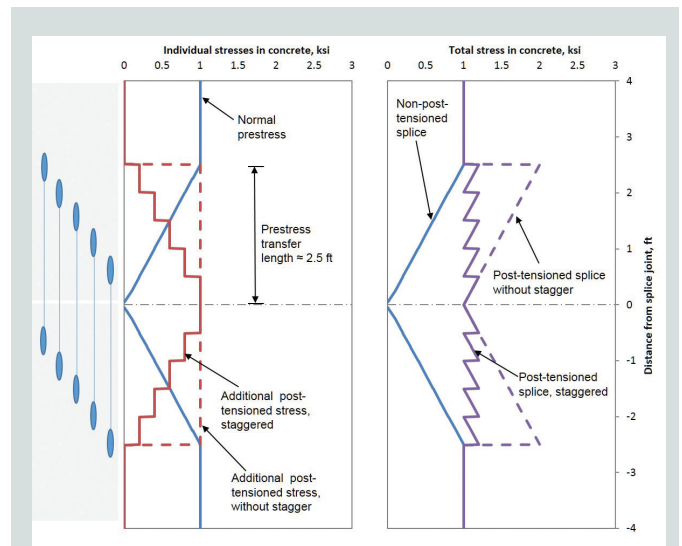
Figure 2. Superposition of initial prestressing and a post-tensioned splice with staggered anchorages (five stagger positions). Note: 1 ft = 0.305 m; 1 ksi = 6.895 MPa.
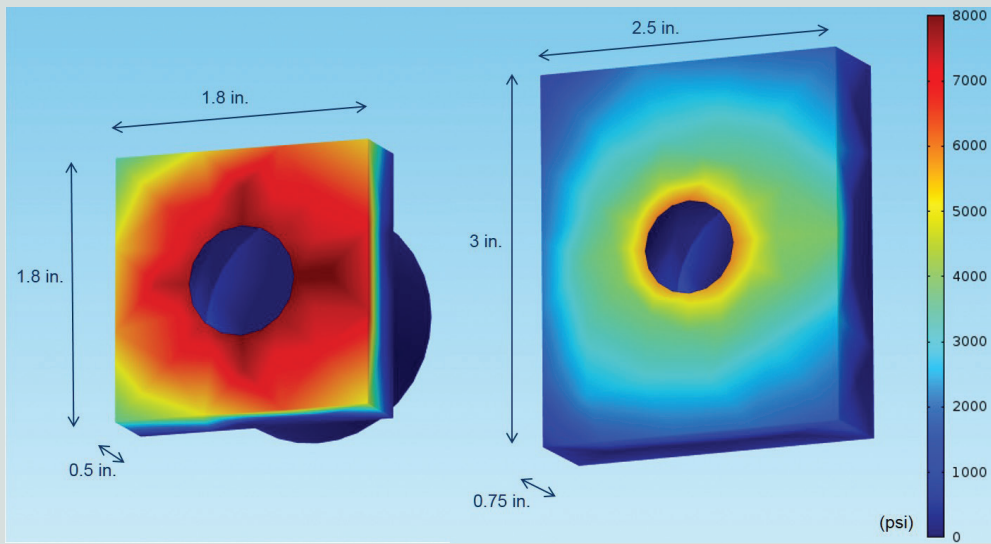
Figure 3. Contact pressure on anchor plates in pounds per square inch (psi) for two different anchor plate dimensions. Note: 1 in. = 25.4 m; 1 psi = 6.895 kPa.
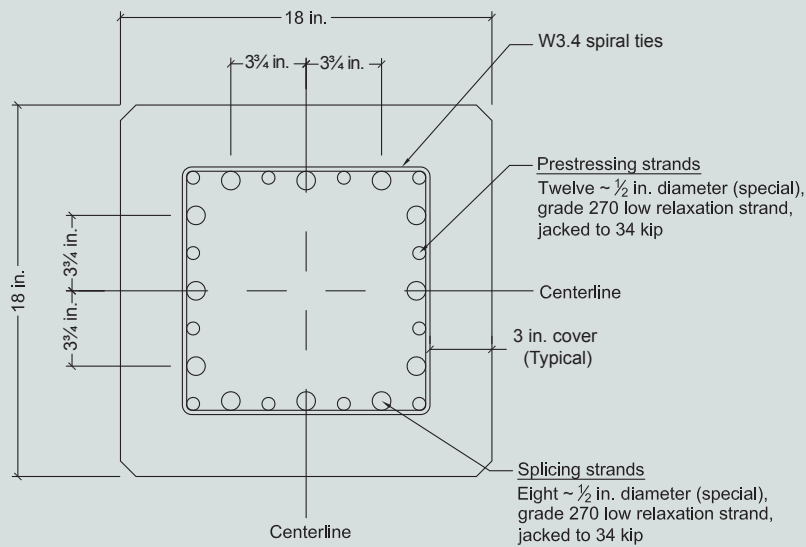
Figure 4. Example splicing strand layout for common 18 in. pile. Note: Grade 270 = 1860 MPa; 1 in. = 25.4 mm.

for ultimate moment could not be met, though the splice would have adequate tensile strength.

Conveniently, the available space between the strands dictated the layout of the post-tensioning strands. In the simplest configuration, one splicing strand was used for every prestressing strand, resulting in a splice strand occupying every space between the pile strands (**Fig. 4**). For larger piles, fewer larger diameter splicing strands could eliminate some congestion.

A more practical limitation restricts the splicing strand selection to diameters that can be easily stressed with

conventional equipment (that is, 0.5 in. [13 mm], 0.5 in. special, or 0.6 in. [15 mm]). Larger 0.7 in. (18 mm) diameter strands require larger stressing jacks that are not as commonly available.
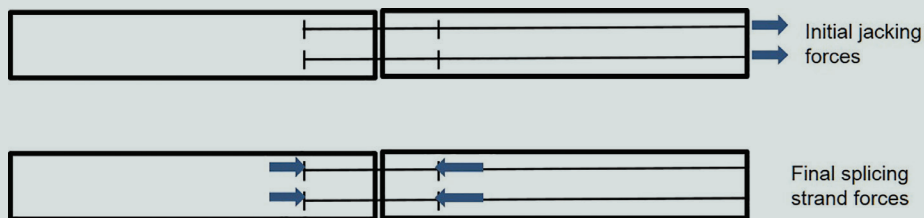
Implementation of post-tensioning principles

Initially, four different layout concepts were envisioned for positioning the post-tensioning anchorages (**Fig. 5**):

1. intermediate post-tensioning anchorages (along the pile sides) on both the upper and lower pile segment
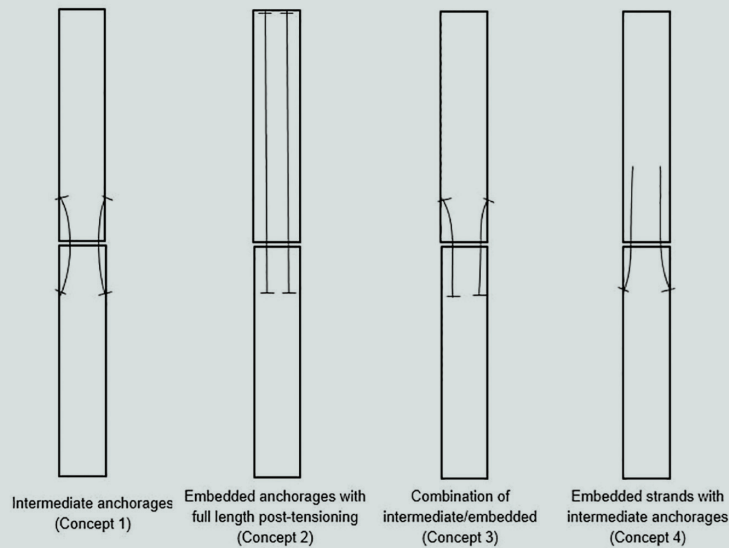
Figure 5. Basic concepts for post-tensioned pile splices.

Figure 6. Dually embedded anchorage concept (upper segment right).

2. embedded anchorages cast into the lower pile with full-length post-tensioning of the upper segment

3. a combination of the first two concepts, where embedded anchorages are used on the lower pile and intermediate anchorages are used on the upper pile (or vice versa)

4. unstressed strands embedded in a standard pile section (upper) with extensions that could be threaded into a lower pile with intermediate side-of-pile anchorages

Concepts 1, 3, and 4 were ruled out due to corrosion considerations and because of the inherent complexity of providing inclined openings for external anchorages in a regular prestressing bed used for precasting pile specimens. Concept 2, a variant of the threaded bar splice, was the only one deemed viable from a corrosion and durability standpoint. However, modifications were necessary: this concept left the entire top pile

(outside the transfer length and spliced zone) in a state of superimposed prestress and post-tensioning stress (doubled precompression).

Dual embedded anchorage concept

To eliminate overstress and limit the splicing precompression to the spliced zone, a dually embedded anchorage concept was devised (**Fig. 6**). Anchorages in the bottom pile would be cast in with individual ducts to the splice interface. In the upper pile segment, similarly positioned duct and anchor assemblies would be cast in, but with ducts that exit the back of the anchor and extend to the top of the pile.

As each anchorage was envisioned to be fabricated from off-the-shelf prestressing chucks, strands could be inserted but not removed. Therefore, and in preparation for splicing, the concept procedure would require all splicing strands to be inserted in the upper pile segment ducts feeding from the splice face until the strand was exposed at
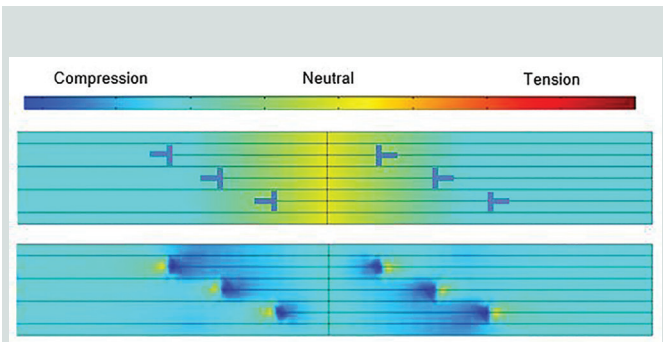
Figure 7. Stress distribution before (top) and after (bottom) splicing.

the top and bottom. During splicing, the upper pile with a sufficient length of strand hanging from the bottom would then be lowered onto the lower pile, and the splice strands would be inserted into the lower pile ducts until they were fully embedded in the lower pile anchorages. Some form of a clamp would be needed to keep the strands from moving upward into the upper pile instead of downward into the lower pile anchor wedges. The strands would then be stressed from the top to achieve the same prestress as the original pile, but only over the splicing region between the embedded anchors.

Using the concepts discussed and shown in Fig. 2, 3, 4, and 6 (staggered anchors, bearing plate, strand layout, and dually embedded anchorages), numerical models were run to show the splice region of a prestressed pile both before and after splicing (**Fig. 7**). The locations of three staggered anchorages are shown on one side. This layout is similar to the standard 18 in. (460 mm) pile strand layout (Fig. 4).

Figure 7 shows normal precompression from prestressing before splicing transitioning to no compression at the interface. After splicing, the interface showed the same level of precompression as the rest of the pile, as well as zones of higher compression stress behind the anchorages. A secondary benefit of the concept splice is that the upper segment includes twice as much steel (half stressed and half unstressed), which provides additional moment capacity beneath a pile cap, where there is often the highest demand.

Prototyping

Transforming the dually embedded anchorage concept into a prototype required component fabrication and testing and consideration of the following aspects:

• strand layout for a spliced system

• design of embedded anchorages

• positioning of anchorages

• required strand length in the bottom segment beyond the anchor

• detailing

• anchor set loss

The final design was developed using a combination of physical and numerical modeling as well as component testing. A relatively small but full-scale 14 in. (360 mm) square pile size was adopted for the first trial assemblies.

Strand layout

The strand layout and the number of strands used in the splicing system are dictated by the performance requirement for strength and by the spacing of the strands in the original pile. For the trial splice prototype, the 14 in. (360 mm) pile used eight ½ in. (13 mm) prestressing strands (three on a side, where the corner strands are shared by two sides). Given so few strands, there would have been no advantage to using fewer larger diameter post-tensioning strands. Therefore, the same number of splice strands was selected for the splice with two splice strands per side between the three prestressed strands (Fig. 4).

The header was milled flat on all faces and fastened to spacer rods of the same length. This allowed the two pile faces to mate without stress concentrations and the spliced pile to be perfectly straight.

Design of embedded anchorages

Because large concentrated forces are introduced at the anchorage, attention was paid to ensure that there was no localized failure in the concrete. Finite element analysis (Fig. 3) showed that a ½ in. (13 mm) plate of at least 7 in.[2] (4500 mm[2]) was needed. However, the shape of the plate had to fit between the strands without encroaching into the cover concrete. The ducts of neighboring splice strands in the corner are also conflicted. The final shape maintained the centroid of the plate at the center of the strand location. Given that the anchorages were staggered, only two bearing plates exist on any given cross section for the 14 in. (360 mm) pile prototype (on opposite sides).

Although the shape of the bearing plate was important, the primary anchor component was a spring-loaded three-wedge off-the-shelf prestressing chuck that was welded to the bearing plate. The welded assembly was then counter-bored in both the back cap and bearing plate locations to permit concentric connections to the individual strand ducts (**Fig. 8**).
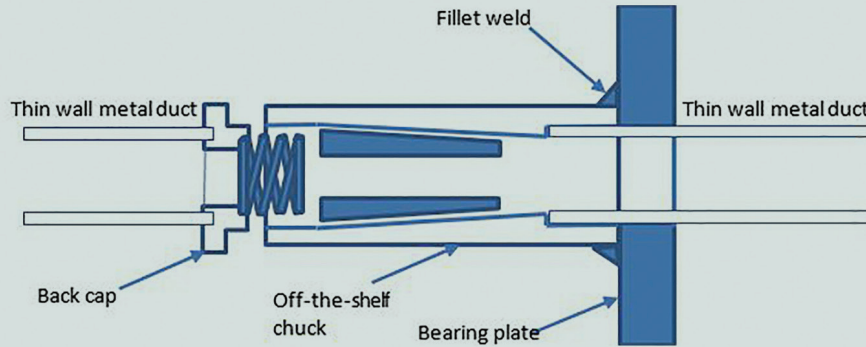
Figure 8. Anchorage assembly.

Positioning of staggered anchorages

The forces in prestressing strands are transferred to the concrete over its transfer length. Tests indicate that this length can vary from about 50 to 160 times the diameter of the tendon tested.[14] In design, the force is assumed to increase linearly. If the post-tensioning force was applied over the entire transfer length, the superimposed concrete would appear as illustrated in Fig. 2 when the anchorages are staggered.

More practical aspects dictate that the strands be paired or grouped in even numbers so that post-tensioning forces stay balanced about the centroid of the pile. For the 14 in. (360 mm) prototype, the largest possible number of staggered anchor positions would be four. Recall that the more stagger points (load steps) there are, the smoother the transition back to full precompression at the splice interface will be. The strands should also all have the same length so that the wedge seating losses are the same for all strand pairs. This means that if one end of a splicing strand terminates closest to the splice interface (for example, in the bottom pile segment), its counterpart in the other pile segment is farthest from the splice interface. The distance between anchors for each strand was constant (Fig. 7).

A large possible variation exists in the possible transfer length ($50d_b$ to $160d_b$, where d_b is the diameter of the prestressing strand), and there is some leeway in the selection of the most appropriate strand length between anchorages. The ideal splice zone can extend $50d_b$ to $160d_b$ in both directions from the splice interface (that is, 50 to 160 in. [1270 to 4060 mm] total length for ½ in. [13 mm] strands). However, the actual stressed strand length can only be slightly more than half of this splice zone length. For example, if the transfer length is assumed to be $75d_b$, then the deepest anchor into the pile would be 37.5 in. (953 mm) (for ½ in. strand) on one side of the splice and its counterpart would be the shallowest anchor into the other pile. Numerical

modeling showed that the shallowest anchor could be as little as 10 in. (250 mm) from the interface, but more practically a value of one pile diameter was chosen for general designs. The first prototype used 10 in. as the shallowest anchor position and 40 in. (1020 mm) as the deepest. This resulted in a 50 in. stressed strand length anchor to anchor. With only four stagger steps in an eight-strand pile, this resulted in the first trial piles having anchor depths of 10, 20, 30, and 40 in. (250, 510, 760, and 1020 mm), with two strands on opposite sides of the centroid terminating at each depth. **Figure 9** shows the splice header plate with all post-tensioning ducts installed in their respective staggered positions.

Strand length in bottom segment

The post-tensioned splice concept revolves around providing full precompression at the splice interface. Therefore, the cracking moment for the splice zone is the same as for a one-piece pile. However, after cracking, the ultimate moment capacity requires the splice strands to reach their ultimate capacity. There was some concern that the strands must extend beyond the anchorage by a suitable length to fully develop the strand. This length is approximately 57 in. (1450 mm) for a low-relaxation Grade 270 (1860 MPa) strand.[3] Because the strands in the top segment

Figure 9. Splice header with staggered ducts and embedded chuck assemblies. All post-tensioning ducts are the same length.

extend to the pile top, this consideration is more important for the bottom segment where it needs to be extended beyond the bottom segment anchorages. As a result, all strands should be inserted into the lower pile segment with the same minimum distance (for example, 60 in. [1520 mm]), which means that shallower anchors have longer extension ducts (that is, 50 in. [1270 mm] beyond the 10 in. [250 mm] anchor position) than the deeper anchors.

Detailing

Further design considerations addressed the details associated with locally high compression stresses on the bearing plate and the performance of the bonded strands within the ducts.

Confinement coils Finite element analysis results showed that high stresses develop in the concrete at the face of the post-tensioning anchorages. To ensure that the locally higher stresses did not affect overall pile capacity, confinement coils were designed to bolster the local concrete strength and offset this effect.[16] The diameter of the coil was matched to fit the bearing plate dimensions, and the pitch of the coils was set to permit adequate concrete flow (**Fig. 10**).

Strand ducts To fully develop the splice strands after cracking, the strands need to be bonded, even if not during driving. Therefore, two provisions were addressed: grouting the ducts and duct deformations. Grouting was accommodated by plumbing the ducts together in the bottom pile segment at the point where each duct terminated (all at the same position, as noted previously). This enabled grouting to be performed either after splicing or after driving when the top of the upper pile segment was nearer the ground.

To better ensure bond between the grouted strand and the surrounding concrete, the ducts were deformed (**Fig. 11**) such that the strand could still be easily pushed through without catching the deformations. The effectiveness of these deformations was demonstrated via pull-out tests on strands grouted into embedded ducts that were either deformed or smooth. Deformed ducts were crimped at spacing intervals of 1 or 2 in. (25 or 50 mm), and the strands were embedded to two different depths (30 or 40 in. [760 or 1020 mm]). Figure 11 shows the results of these tests.

All three of the strand specimens in the deformed ducts broke in the jack chuck wedges, while the specimen in the smooth duct pulled out at a much lower load, encapsulated in grout, and with no visible distress (Fig. 11). Interestingly, the specimen embedded 30 in. (760 mm) with the 2 in. (50 mm) deformations performed just as stiffly as the 40 in. (1020 mm) specimen with the 1 in. (25 mm) deformation spacing. The tests concluded that any of the duct deformation patterns would suffice and that the strand would not develop capacity without deformations.

Anchor wedge set losses

The post-tensioned region was relatively short, and therefore wedge set losses were expected to be large. Losses in short post-tensioning strands, such as those used in slabs, are often remedied using hydraulically actuated wedge-setting systems (power wedge setters). For a power wedge-setting system to be effective, it must be able to push directly on the wedges; for the concept in Fig. 6, this distance can be long (for example, 50 to 100 ft [15.2 to 30.5 m]). As a result, power wedge setting was not used and a series of chuck improvement experiments were conducted. These experiments were used to determine the magnitude of loss associated with normal spring-loaded

Figure 10. Strand pull-out tests on strands grouted in various duct configurations.
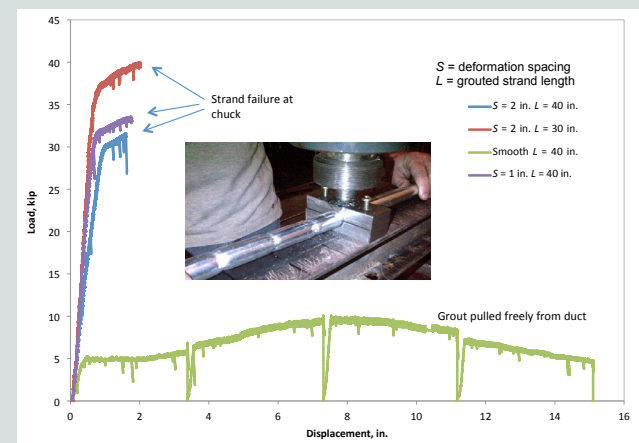
Figure 11. Strands in deformed ducts developed full capacity; strands in the smooth duct (right) did not. Note: 1 in. = 25.4 mm; 1 kip = 4.448 kN.
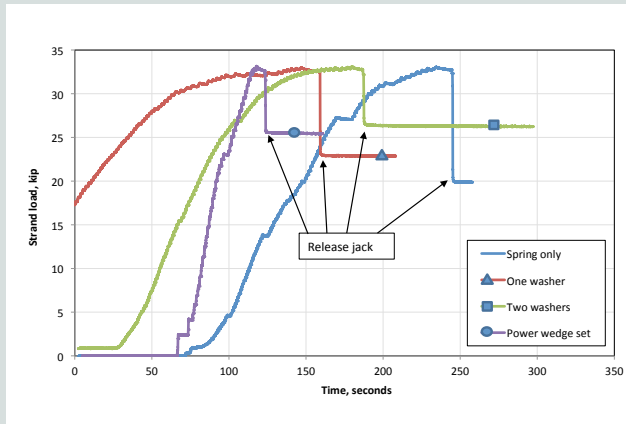
Figure 12. Effect of varied wedge-setting techniques on final post-tensioning force. Note: 1 kip = 4.448 kN.

Figure 13. Spliced pile halves after removal from casting bed.

wedges and whether these losses could be reduced. As discussed, the strand length selected for splicing was 50 in. (2540 mm), based on the estimated transfer length. Using the 50 in. spacing between anchorages, a series of wedge-setting tests was conducted that measured the losses from varying wedge-setting methodologies. This included normal chucks with spring-loaded back caps, a power wedge-setting jack (for reference), and two variations of shim thicknesses placed between the springs and wedges in standard spring-loaded back caps.

When jacking the 50 in. (1270 mm) long ½ in. (13 mm) diameter strands (270 ksi [1860 MPa]) to 80% of ultimate (33 kip [150 kN]) and releasing where only the spring-loaded caps pushed the wedges into the locked position, the load fell to 20 kip (90 kN). This corresponded to 0.146 in. (3.71 mm) of wedge travel δ before seating calculated from $\Delta P = \delta AE/L$, where ΔP is the change in force, A is the strand area, E is the modulus of elasticity of the strand, and L is the strand length. For a 14 in. (360 mm) square pile with eight strands, this equates to 816 psi (5.63 MPa) concrete prestress (the target design level is 1000 psi [7 MPa] minimum). Using a power wedge-setting jack, the final load after release was 25.5 kip [113 kN] (or 1041 psi [7.178 MPa] concrete prestress). Although this level of prestress is reasonable, it is not a practical solution for embedded intermediate anchorages with the wedges so far from the jacking surface. Therefore, washer-shaped shims were inserted between the spring and wedges to reduce the 0.15 in. (3.8 mm) of wedge travel to a more acceptable level of movement and loss. **Figure 12** shows the effect of one and two shim washers relative to the other two methods. The net result from using two 0.060 in. (1.5 mm) shim washers was a final load after release of 26.5 kip (118 kN) (1080 ksi [7450 MPa]). This corresponds to a 0.073 in. (1.9 mm) wedge set movement. The two 0.060 in. shims (0.120 in. [3.0 mm]) reduced wedge movement and losses by half.

Trial assembly and casting

The first steps in testing the concept splice components, physical layout, and tolerances were performed in a fully instrumented self-stressing casting bed designed specifically for short piles and fabricated in an outdoor research facility. The bed was designed to cast two 20 ft (6 m) long specimens simultaneously (that is, one splice specimen and one unspliced control specimen). The internal instrumentation in the bed allowed the strand tension forces to be monitored and to verify that both the splice and control specimens were identically prestressed. The bed was constructed from three commercially produced 14 in. (360 mm) piles with the upper casting face turned down so that the natural bed taper would be reproduced on the test piles.

After verifying that the components fit correctly, spirals were placed in the beds and strands were threaded through both beds. The beds were stressed, the spirals were spaced per FDOT specifications, and the concrete was placed. **Figure 13** shows the splice region after removal from the bed.

Discussion

The most successful and robust splices for standard prestressed concrete piles have been mechanical splices that cast into the ends of the piles some form of steel connection detail where a key, bolts, or pins fasten the two segments together in a fashion more aligned with structural steel connections. These connections, while effective, must transfer tension stresses during driving from one pile segment to the next but via reinforced concrete concepts (that is, development length of large reinforcing bars cast into the ends of each pile segment). As a result, some state specifications restrict tension stresses to less than half that allowed in a one-piece unspliced prestressed pile. This study investigated the use of an alternative approach that

incorporates post-tensioning pile segments together to form a splice.

At the beginning of the study, preplanned splices, where both halves of a spliced pile could be cast with the necessary internal components, were targeted for consideration. Further development and study revealed that the concept splice is also applicable to unplanned splices. In such an event, the lower pile could be drilled with a relatively small-diameter hammer drill instead of larger-diameter coring.

Splicing strands extending from the bottom of an upper pile segment fabricated using the presented duct and anchor assemblies could then be grouted or epoxied into the lower pile and post-tensioned using the same procedures discussed herein. Depending on the curing time of the grout (or epoxy), some delay may be experienced, but the performance of the splice would be the same. This is an area for future development and testing.

Based on the success of the concept development, full-scale spliced piles were cast and tested for bending capacity and field drivability. Future work is planned to extend these efforts to on-site contractor splicing and production casting without the assistance of the development team.

Conclusion

The concepts and challenges of creating a post-tensioned splice for prestressed concrete piles are presented with specific attention given to direct applicability to commercial prestressing beds. To this end, practical considerations were dovetailed with theory in the design of the components and splicing procedures. The most important aspect of the proposed splice is the restoration of full tensile capacity, thereby removing all driving restrictions. However, additional advantages were identified, including an increase in bending resistance in the upper pile splice region that commonly requires the most capacity.

The findings of the study are presented in three parts. This paper provides a brief overview of the conceptual model adopted to comply with performance requirements for both strength and driving. The concept was fully developed through numerical modeling and laboratory testing, which culminated in full-scale strength testing and eventually pile driving, the subject of two forthcoming papers.

Throughout the process of development, strength testing (part 2), and the drivability demonstration (part 3), the bulk of the original concepts remained unchanged. However, refinements were made continuously, making the application more conducive to production casting conditions.

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Notation

A = strand area

d_b = diameter of the prestressing strand

E = modulus of elasticity of the strand

f_c' = specified concrete compressive strength

f_{pe} = effective prestress (after all losses) at the time of driving

L = strand length

s_{apc} = maximum allowable pile compressive stress

s_{apt} = maximum allowable pile tensile stress

δ = wedge travel before seating

ΔP = change in force

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Abstract

Splicing precast, prestressed concrete piles has historically been difficult because the attachment detail either requires preplanned considerations and cast-in connection details or requires on-site coring and doweling when unplanned pile extensions are needed. When the pile must be driven after splicing, the splice connection is prone to tensile failures due to the inability to transfer driving stresses through the connection and into the other pile segment.

Focusing on preplanned splices, the Florida Department of Transportation limits tension stresses during driving to 250 or 500 psi (1.7 or 3.4 MPa) for epoxied-dowel splices or mechanical splices, respectively. This can limit the ability to efficiently drive the pile, to the point where it might even be impossible.

In response to the need for a more robust splicing methodology, an alternative concept was sought; this alternative concept forms the basis of this study. To this end, a post-tensioned splice that eliminates the limitations on tension stresses during driving was developed. This is the first of three papers that detail the development of this alternative approach. It covers the conceptual basis for the design and its implementation into a prototype system. Two forthcoming papers will cover bending strength testing and field implementation/driving verification of the system.

Keywords

Driving stress, pile, pile driving, post-tensioned pile splice, prestressed concrete pile, pile transfer length.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

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