

ALTERNATIVE MATERIALS AND CONFIGURATIONS FOR PRESTRESSED-PRECAST CONCRETE PILE SPLICE CONNECTION

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1. Introduction and Background

Establishing bridge foundation when there is a top layer of weak soils normally requires application of deep foundations such as pile foundation. One of the options among various types of piles and installation methods is driving prestressed-precast concrete piles (PPCP) (Figure 1). Since it employs pile segments prefabricated in precast plants and delivered to the site for installation, it follows the principals of Accelerated Bridge Construction. Comparing to other types of piles, this option is in many cases more cost and time effective. Accordingly, PPCP generally reduces the construction time in line with the benefits promised by ABC methods. However traditional PPCPs which use conventional passive and none passive carbon steel reinforcements are prone to corrosion especially when they are in a marine environment. In such environments, accumulating salts in piles which are caused by alternating the level of water and water splash accelerate corrosion. Corrosion causes the piles to fail prematurely and incur costs. According to the Cost of Corrosion (Lampo et al., 1997), in highway bridges the dollar impact of corrosion on concrete and steel bridges is substantial and the indirect costs including the user and maintenance increase the overall costs tenfold. Accordingly, attempts have been made to increase corrosion resistance of PPCPs. Using Carbon Fiber Reinforced Polymers (CFRP) and High Strength Stainless Steel (HSSS) for strands and other types of reinforcements has shown a great improvement in corrosion resistance.



Figure 1: Prestressed-Precast Concrete Piles

(<https://dlsprestressed.com/services/driven-concrete-piles/>)

For various reasons, it becomes necessary or is desirable to splice PPCPs. The merits of casting shorter pile segments and splicing them on-site are: 1- easy handling, transporting, and driving,

2- possible reduction in concrete cracking during handling, transportation, and driving, 3- suitability of pile extension in unforeseen situations and soil conditions where longer piles become necessary, 4- reduction in transportation cost, 5- ability to be store in the precast yard and construction site (Venuti, 1980). It should be stated that these advantages can only be achieved if the use of splice is economical, can develop the structural capacity of pile section and the connection can be made quickly without the need for special skilled labors. With this in mind, splicing of pile segments has to be performed at the site to achieve longer lengths using various types of joints. There are various means of establishing bearing-type splices. Splicing with the use of corrosion-resistant material is the focus of this project. State Departments of Transportation including FDOT have Specifications and Standard Drawings showing details and designs for pile splices including those using corrosion-resistant materials.

Nevertheless, because of lack of understanding of the structural behavior and sometime complexity and cost associated with splicing, especially for the case of corrosion-resistant materials, their use has been very limited. On the other hand, much has been done in relation with ABC connections and details for bridge sub- and super-structure joints and connections, and a variety of new and effective joints have been developed and are in use. The aim of the proposed study is to build upon the experiences gathered in general for ABC connections and develop an effective yet simple splice connection for prestressed-precast concrete piles to provide the necessary pile lengths for reaching the required resistance and at the same time to promote corrosion resistance.

2. Objectives and Research Approach

The objective of this project is to explore alternative pile splice connection configurations and materials, and to investigate the feasibility of these connections in comparison with the existing epoxy dowel splice for prestressed-precast concrete piles. The project begins with reviewing literature on types of driven piles, existing pile splice configurations and materials, as well as available ABC connections implemented for bridge sub- and superstructures. This will be followed by exploring alternative connection configurations and alternative materials. The performance of the promising designs will be compared to the existing designs using analytical modeling. Among other materials, a non-proprietary Ultra-High-Performance Concrete (UHPC) mix currently under investigation by ABC-UTC will be considered in detailing of the splice connection zone as well as its use as filler/bonding material for dowels. Additionally, the use of mechanical connection types utilizing corrosion resistant materials will be explored to address the time constraint associated with pile driving operation. The project will culminate in development of the most promising alternative splice connection details and materials for prestressed-precast concrete piles. This research project focuses on the use of analytical modeling and computational means for investigation on the structural behavior, and comparison between performances of existing details for pile splices and newly developed designs using alternative configuration and material. This will include finite element modeling of pile segments and splices, as well as section analysis using available analysis tools. Future activities will include performing experimental verification of the newly developed details.

3. Description of Research Project Tasks

The following is a description of tasks carried out to date.

Task 1 - Literature Review

3.1. Types of Driven Piles

Driven piles are divided into piles made of wood, steel, concrete, and various types of composite materials. These types of pile are reviewed briefly here, however, this study focuses on prestressed precast concrete piles to be discussed in more details.

3.1.1. Wooden Piles

Wooden piles have a long-rooted history. There are some reasons for using them. The ease and the speed of installation, being an eco-friendly or "green" construction, and being cost-effective are among the reasons that make wooden piles popular (Figure 2). However, wooden piles, especially in coastal areas, are prone to damage caused by marine borer activity. Therefore, fabricating more durable piles is needed in the marine environment and when piles are in the water, especially in the splash zone (Figure 3) (Iskander, 2003).



Figure 2: Wooden piles

<https://www.pinerivergroup.com/blog/wood-pilings>



Figure 3: Tunneling in a timber pile caused by Teredo and Bankia (M. Iskander, 2003)

3.1.2. Steel Piles

The use of steel piles has been limited due to the susceptibility to corrosion (Figure 4). Whenever employing a load-bearing steel pile foundation has been considered for a structure, the probability and the amount of corrosion have always caused concerns (OHSAKI, 1982). The rate of corrosion of steel piles immersed in fresh water is estimated to be 0.03 mm per year which increases to four times in the splash zone (Fleming et al., 2008). Localized corrosion of steel sheet piling has been investigated by E. Melchers et al. (2014) (Figure 5). In their research, samples of two types of sheet piling were exposed to natural seawater for 1, 2 and 3 years. The samples demonstrated localized corrosion in the central zone and close the flange-web junction. The corrosion in steel piles can affect the load-bearing capacity of piles dramatically. Therefore, there is a need for alternative materials for pile fabrication that are resistant to corrosion.



Figure 4: Corrosion in steel pile

<https://www.ducorr.com/ducorr-blog/2018/3/20/conventional-steel-corrosion-and-durability-design>

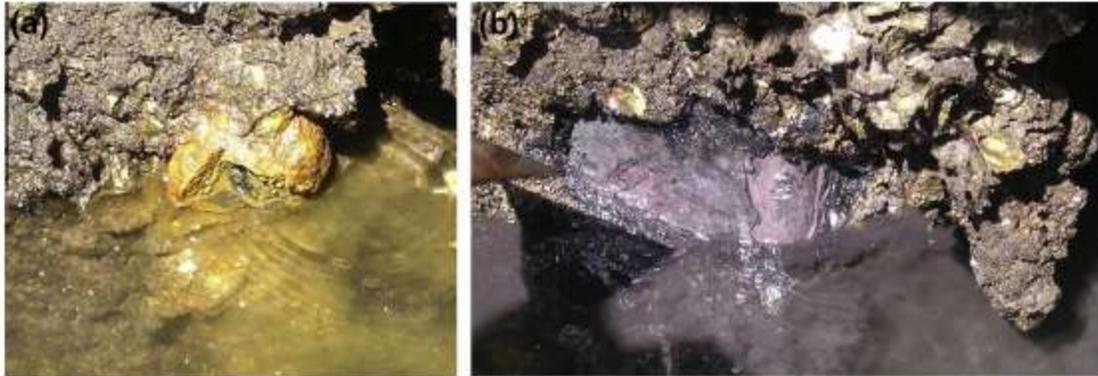


Figure 5: Local corrosion of sheet piling (Melchers et al., 2014)

3.1.3. Composite Piles

Composite materials, due to their resistance to electrochemical corrosion and versatility of fabrication, provide alternative to customary material. The price for the composite is however high. Fiber Reinforced Plastic (FRP) composites are used in some cases in hybrid construction with concrete where the concrete provides the role of bulk mass, and the FRP has a role of load carrying partner and protector of the concrete from the exterior environment. This combination provides for a cost effective use of composites. Concrete-filled FRP tubes as a hybrid system, can be used for pile fabrication (Shahawy, 2003). They have been used in many marine environments (Figure 6).



Figure 6: FRP tubes for composite piles

[\(https://www.harbortech.us/products/composite-pilings/\)](https://www.harbortech.us/products/composite-pilings/)

The first recycled plastic pile was driven at the port of Los Angeles (Horeczko, 1995). It was a steel core composite pile. This experience showed that due to thermal stresses, the steel core composite piles experience core delamination. Therefore, producers presented a type of composite piles that included fiberglass and HDPE combined with fiberglass reinforcement and stabilizers. In 1998, Iskandar and Hassan reviewed the types of composite piles and compared them in term of material properties, durability, drivability, and the interaction between soil and piles. They found that piling materials made of FRP or fiberglass offer performance advantages for employing in harsh and marine environments. The advantages of using them are durability

and environmental benefit. However, disadvantages include high cost, less drivability and high compressibility (Iskander & Hassan, 1998).

3.1.4. Prestressed precast concrete piles

One of the options for establishing pile foundation is the use of prestressed-precast concrete piles (PPCP) (Figure 7). This option provides in many cases an economic alternative to other pile foundation types and accelerates the construction process, especially in marine environments. In PPCPs, prestressed strands provide the pile with the required tensile strength during the driving process. The strands, provide the extra strength to resist the moment bending which will be caused during lifting, transporting, and the bending moment as a result of lateral loads. PPCPs have been made in different shapes with different types of materials for strands.



Figure 7: Prestressed-Precast Concrete Piles in marine environment

3.1.4.1. Prestressed Precast Concrete Piles Using Conventional Prestressed Strand

Prestressed concrete piles can be reinforced with prestressing strands including threaded rebars (e.g., Dywidag rods), prestressing wire or seven-wire strands (Figure 8), and with other reinforcing bars and welded wire mesh. The most commonly used prestressing reinforcement is seven-wire strands. Two types of seven-wire strands have been used: 1- stress-relieved 2- low-relaxation. The difference in the behavior of these two types of strands is shown (Figure 9). In conventional PPCPs, the low relaxation seven-wire strands with the various nominal diameters including the common 0.5 and 0.6 inches have been used. However, traditional prestressed piles that use carbon steel strands and bars are prone to corrosion, especially when they are in marine environments. In such environments, alternating water levels and water splash promote deposit and migration of chlorides into the pile and provides a condition for accelerating the corrosion. Among other states departments of transportation, the Florida Department of Transportation (FDOT) has also implemented programs for the utilization of alternative prestressing strand materials that are corrosion resistant. The use of Carbon Fiber Reinforced Polymers (CRFP) and High Strength Stainless Steel (HSSS) for strands, longitudinal and transverse reinforcement in

the precast concrete piles have shown great improvements to resistance against corrosion (Belarbi et al., 2017; Mullins et al., 2014; Rambo-Roddenberry et al., 2016).

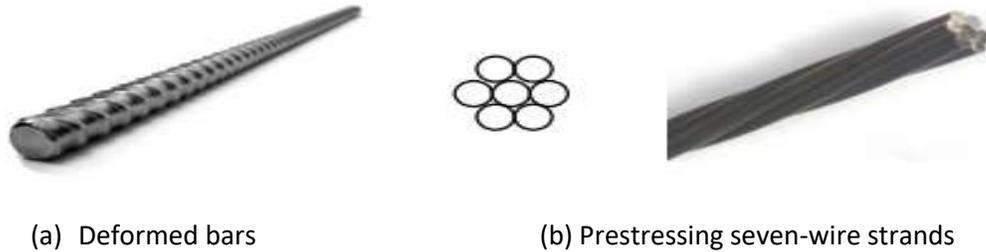


Figure 8: Type of reinforcement for prestressing

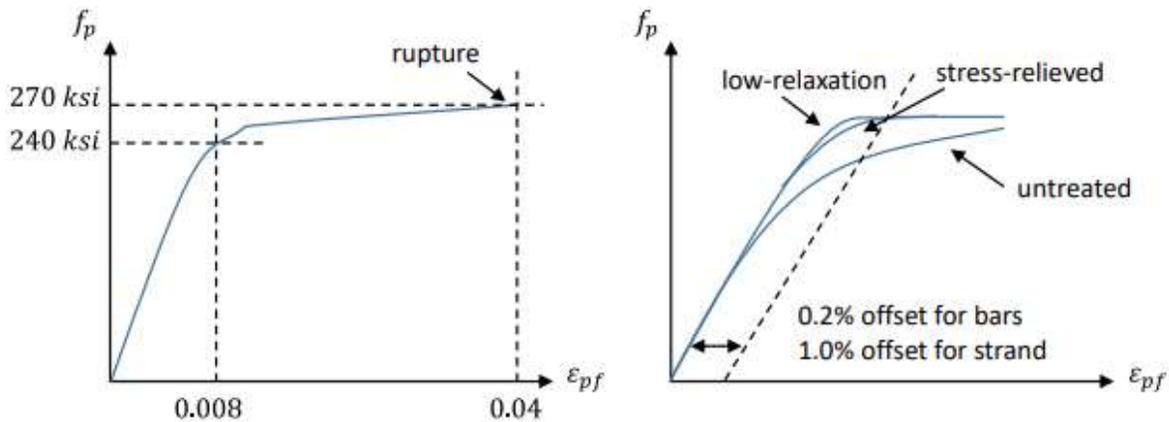


Figure 9: Difference in the behavior of the low-relaxation and stress relieved strands

3.1.4.2. *Prestressed Precast Concrete Piles Using Alternative Strand Materials*

There have been several investigations on the application and performance of PPCP using alternative prestressing strand material. CFRP and its variant Carbon Fiber Composite Cable (CFCC) is one of the materials that has shown great promise for replacing the normal prestressing strands. ACI-440-04 covers an extensive review of the background, material properties and design recommendation for the use of these materials and other FRPs. CFCC has shown high bond strength to concrete (about twice of that of steel), has light weight and high tensile strength, its relaxation is less than steel, and can be coiled in its twisted wire form. However, CFCC is more expensive than steel, has low impact resistance, and it is brittle in failure not as ductile as its steel counterpart (Rambo-Roddenberry et al., 2016). Grace (2007) used CFRP for post-tensioning tendons and reinforcing bars for the first time in the Bridge Street Bridge in Southfield, MI. His study monitored the performance for long period of time and demonstrated its suitability for use in prestressing/post-tensioning applications. Roddenberry et

al. (2014, 2016) tested PPCP using CFCC of various lengths to investigate the flexural strength, transfer length, development length, and drivability (Figure 10). They concluded that transfer and development length for CFCC is noticeably shorter than that of steel, and flexural strength higher than anticipated. Pile driving and installation were without any major damage to the pile despite the hard condition and high stress level. Some challenges in production were noted and modifications recommended including use of wood versus steel cap, care in installation and handling, lower stress rate, avoiding the use of regular vibrator, and strong quality control (QC).



Figure 10: Flexural testing of PPCP with CFCC (Roddenberry et al., 2014)

PPCP using HSSS strands and spirals have also been studied as another alternative to carbon steel strand piles. Mullins et al. (2014) tested three types of stainless steel material that are available in strand form and compared their corrosion resistance and structural performance to conventional carbon steel prestressing strand. They showed that the use of HSSS strands had no adverse effect on transfer length, while it improves the corrosion resistance significantly (Figure 11). Paul et al. (2015) demonstrated through testing that transfer and development length for HSSS-2205 prestressing strands are considerably smaller than that predicted by AASHTO LRFD, the flexural and shear strengths of piles using SS were greater than predicted by both ACI-318 and AASHTO LRFD, and the stress loss was smaller than that predicted by AASHTO LRFD refined method. These properties were not affected after installation and extraction.



Figure 11: PPCP with Stainless Steel Strand and Spiral (Mullins et al., 2014)

Prestressed Precast Concrete Piles (PPCP) often require splicing for one or more of the following reasons such as (i) limits on length for shipping and transportation, (ii) limited pile-driving headroom that will force planned splicing, (iii) and when the required capacity is not achieved with the piles existing lengths resulting in unforeseen splicing, and others (Figure 12). The focus of this report is on the types of splices for precast prestressed concrete piles which can provide the piles with corrosion resistant materials and accommodates a time effective method.

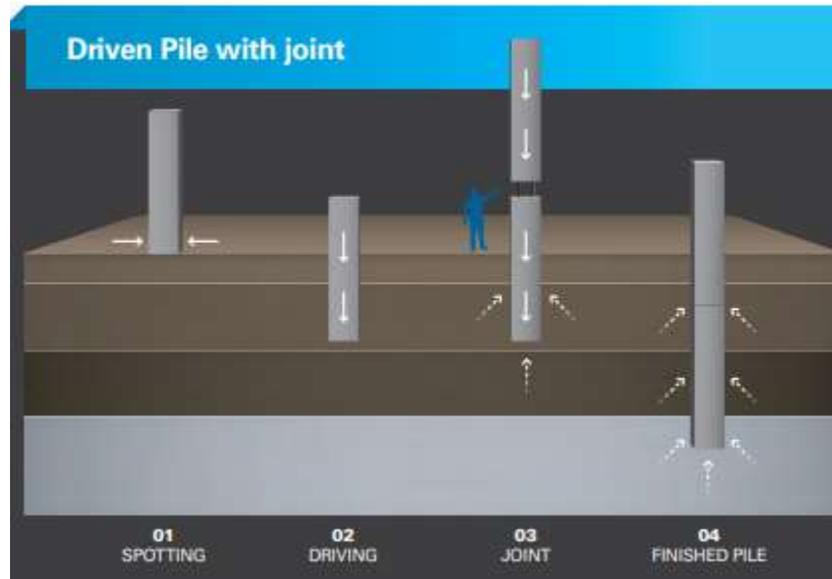


Figure 12: Driven pile with joint/splice

3.2. Pile Splices

3.2.1. Existing Splice Systems for Driven Piles

There are various means for establishing bearing-type splices including wedge, pinned, welded end plates, post-tensioned, sleeve, connecting ring, mechanical and finally dowel splices as illustrated in Figure 13.

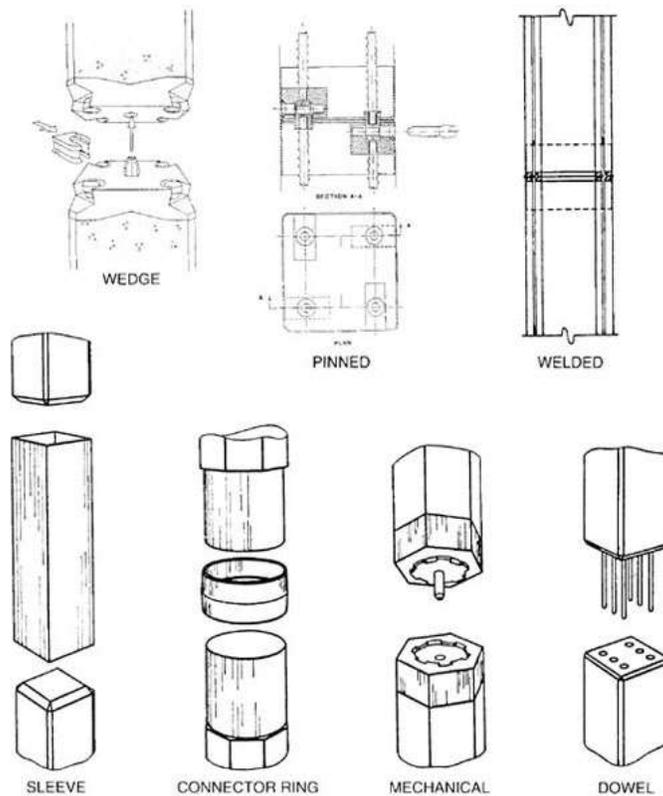


Figure 13: Various types of existing pile splicing (Pile Buck Magazine, <http://www.pilebuck.com/education/pile-points/concrete-pile-splices/> 1/7)

Gerwick (1968) reviewed the formation, utilization, and installation of the PPCPs, and discussed their failure and damages. In his work, epoxy dowel splices were mentioned as the most desired type in providing resistance for piles in flexural design. He also mentioned that mechanical splices are the most economical type of pile splices. In 1970, Liu presented a report which helped designers with splices. Driving and no driving conditions, the required concrete strength for piles, driving stress, head and tip design practice, and the requirements for an ideal splice were discussed. A combination of sleeve and wedge for establishing pile splices were discussed by Alley (1970). This splice was used in Seattle, WA, for splicing octagonal piles. The splice includes outer and inner steel sleeves which were connected to four steel wedges welded to form the piles. In 1971, a chapter in a textbook by Gerwick (1971) discussed typical detail of prestressing pile splices used in the U.S, Japan, Sweden, and Norway. In 1974, a comprehensive research was carried out on 20 types of splices by Bruce and Hebert (1974a). Details of various splices and their strengths were presented in this study. Also, the performance of each splice in tension, compression, and flexural was discussed. The results of this investigation is summarized in Table 1 (Bruce Jr & Hebert, 1974a).

Table 1: Type of splices (Bruce Jr & Hebert, 1974a)

Type of Splices for Piles					
Type	Splice type	Does this detail require preplanning?	Time needed (minutes)	Labor skill (procedure)	Country of Origin
Mechanical	Marier Splice	yes	minimal-30	average	Canada
Mechanical	Herkules Splice	yes	minimal-20	simple	Sweden
Mechanical	ABB Splice	yes	minimal-20	simple	Sweden, western Europe
Welded	NCS Splice	yes	high-60	average	Japan, Pacific, Northwest
Welded	Tokyu Splice	yes	high-60	average	Japan(Tokyo)
Welded	Raymond Cylinder	yes	high-90	average	USA
Welded	Bolognesi-Moretto Splice	yes	minimal-50	average	Argentina
Bolted	Japanese Bolted Splice	yes	minimal-30	average	Japan
Connecting Ring	Brunspile Connector Ring	yes	minimal-20	simple	USA
Sleeve	Anderson Splice	no	minimal-20	simple	USA
Welded Sleeve	Fuentes Splice	yes	minimal-30	average	USA(Puerto Rico)
Sleeve	Hamilton Form Company Splice	no	high-90	simple	USA
Dowel	Cement-Dowel Splice	yes	average-45	simple	USA
Post Tensioned	Macalloy Splice	yes	high-120	average	Great Britain.
Combination	Mouton Splice	yes	minimal-20	simple	USA
Combination (Sleeve and Wedge)	Raymond Wedge Splice	yes	minimal-40	simple	USA
Connecting Ring	Pile Coupler Splice	yes	minimal-20	simple	USA
Mechanical	Nilsson Splice	yes	minimal-20	average	Sweden
Wedge	Wennstrom Splice	yes	minimal-20	simple	Sweden
Mechanical	Pogonowski Splice	yes	minimal-20	average	USA

In Table 1, types of splice, the required time for installation, the skill of labor which needed during construction, and the country of origin are shown. This table also specifies whether preplanning is required to establish each type of splices. The installation time, as it is on any ABC method, is of extreme importance. By reducing the construction time, the impact of splicing on the overall bridge construction time will be reduced and the bridge usage by the public is greatly improved, especially when the replacement of an existing bridge is involved. In addition to requiring minimal time to establish the splice, the splice should be strong enough to resist all load effects including tension, compression, shear, and flexural. In Table 2, the performance of these splices has been summarized (Bruce Jr & Hebert, 1974a).

Table 2: Performance of the splices in compression, tension, and flexure in comparison with un-spliced pile (Bruce Jr & Hebert, 1974a)

Type of Splices for Piles					
Type	Splice Type	Splice Performance in Compression	Splice Performance in Tension	Splice Performance in Flexure	Patent
Mechanical	Marier Splice	100 percent of pile strength	100 percent of pile strength	100 percent of pile strength	yes
Mechanical	Herkules Splice	100 percent of pile strength	100 percent of pile strength	100 percent of pile strength	yes
Mechanical	ABB Splice	100 percent of pile strength	100 percent of pile strength	100 percent of pile strength	yes
Welded	NCS Splice	100 percent of pile strength	100 percent of pile strength	100 percent of pile strength	yes
Welded	Tokyu Splice	100 percent of pile strength	100 percent of pile strength	100 percent of pile strength	yes
Welded	Raymond Cylinder	100 percent of pile strength	100 percent of pile strength	100 percent of pile strength	yes
Welded	Bolognesi-Moretto Splice	100 percent of pile strength	50 percent of pile strength	100 percent of pile strength	yes
Bolted	Japanese Bolted Splice	100 percent of pile strength	90 percent of pile strength	90 percent of pile strength	yes
Connecting Ring	Brunspile Connector Ring	100 percent of pile strength	20 percent of pile strength	50 percent of pile strength	yes
Sleeve	Anderson Splice	100 percent of pile strength	no strength	100 percent of pile strength	no
Welded Sleeve	Fuentes Splice	100 percent of pile strength	100 percent of pile strength	100 percent of pile strength	yes
Sleeve	Hamilton Form Company Splice	100 percent of pile strength	75 percent of pile strength	100 percent of pile strength	no
Dowel	Cement-Dowel Splice	100 percent of pile strength	40 percent of pile strength	65 percent of pile strength	no
Post Tensioned	Macalloy Splice	100 percent of pile strength	100 percent of pile strength	100 percent of pile strength	yes
Combination	Mouton Splice	100 percent of pile strength	40 percent of pile strength	100 percent of pile strength	yes
Combination(sleeve and Wedge)	Raymond Wedge Splice	100 percent of pile strength	100 percent of pile strength	100 percent of pile strength	yes
Connecting Ring	Pile Coupler Splice	100 percent of pile strength	100 percent of pile strength	100 percent of pile strength	yes
Mechanical	Nilsson Splice	100 percent of pile strength	100 percent of pile strength	100 percent of pile strength	yes
Wedge	Wennstrom Splice	100 percent of pile strength	100 percent of pile strength	100 percent of pile strength	yes
Mechanical	Pogonowski Splice	100 percent of pile strength	100 percent of pile strength	100 percent of pile strength	yes

As it was shown, splice types Bolognesi-Moretto, Japanese Bolted, Brunspile Connector Ring, Anderson, Hamilton Form Company, Cement-Dowel, and Mouton Splice are weak in tension. Also, Japanese Bolted, Brunspile Connector Ring, and Cement-Dowel Splice could not pass the flexural design requirement. In the following sections, various types of splices and their advantages/disadvantages are discussed.

3.2.1.1. *Wedge Splices*

This type of splice which is also called mechanical wedges is used mainly for square piling but it is also used for octagonal, round, and hollow cross sections. In Scandinavia and Western Europe, it is used for precast reinforced concrete piles. Also, Venuti (1980) in his research successfully employed this type of splice for precast prestressed concrete piles. Both the lower and upper part of pile to be spliced have to be the same shape (Figure 14). It is made of two plates, cone, and four internally threaded bolts. The piles internal reinforcing bars are threaded into the bolts (Figure 15). The procedure of wedge splice is simple. The alignment cone is placed into the center of the lower pile. The upper pile section then is placed on the lower part till the splice plates are in their correct position. After that, the wedges are driven into each of the four corners of the splice by using a sledgehammer. The wedge become locked in the splice. This detail applies directly to reinforce concrete piles. However, with some modification, i.e., pre-installation of auxiliary bars inside the pile, it can also apply to prestressed piles.

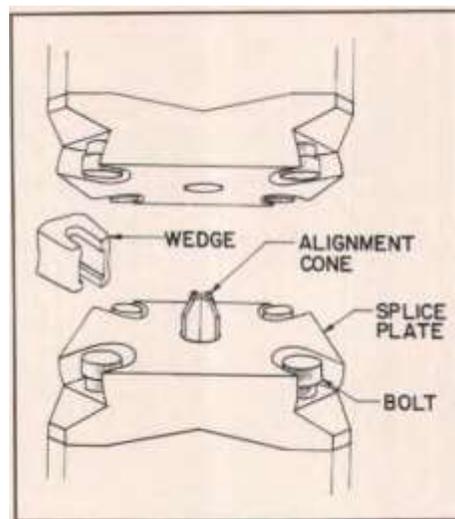


Figure 14: mechanical wedge splice (Venuti, 1980)

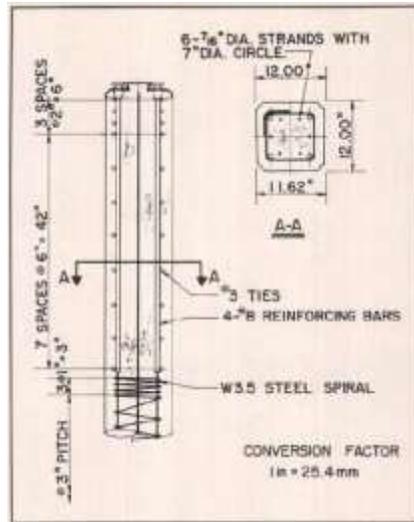


Figure15: mechanical wedge splice details (Venuti, 1980)

According to the investigation of Venuti (1980), this type of splice is designed to perform similar to un-spliced section in compression, tension, torsion, shear, and bending. After experimental testing on this type of splice, he concluded that wedge splice; 1- can develop the full capacity of the pile in tension, compression, and bending, 2- has the same strength for both the torsion and shear in all direction 3- requires minimum space for storage, 4- can be fabricated and handled simpler and faster since the splice parts are the same in each plie section, 5- can be installed easily and quickly and does not need skilled labor forces, 6- due to having zinc alloy alignment cone has a sacrificial role and improves corrosion resistant. The only disadvantage of using this splice is the need for careful and quality fabrication at a prestressing plant.

3.2.1.2. Welded Splices

One of the problems with using welded splices is its corrosion potential, especially in corrosive soils and marine environment. Also, the lack of certified field labor and concerns with the quality of field welds have limited the use of welding systems (Michael P Culmo, 2009). Figure 16 shows welding of pile segments in welded splice (Li et al, 2014). Nippon Concrete Systems (NCS) type welded splice is a very common type of welded splice in the State of Washington. Tokyo splice can be used in prestressed concrete cylindrical piles. Also, temperature due to welding does not seem to affect concrete and the strength will not be reduced. Raymond splice can also be used in cylindrical piles. However, its use is limited due to longer time for installation. The last type of welded splice is Bolognesi-Moretto which is not common because the use of dowel in the plate causes warping (Bruce Jr & Hebert, 1974a).

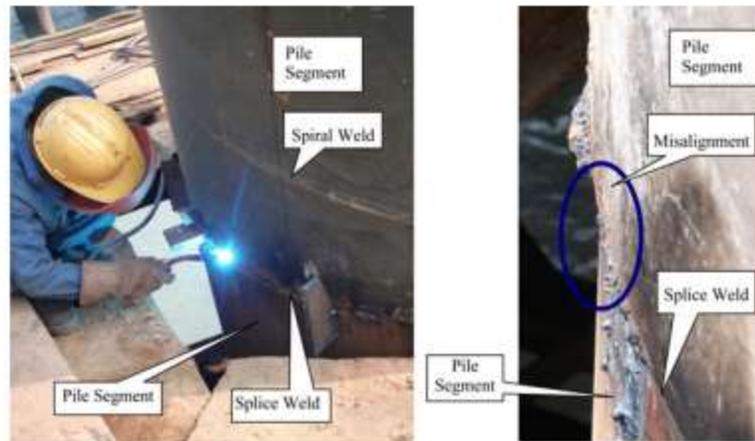


Figure 16: welded splice (Li et al., 2014)

3.2.1.3. Dowel Splices

The most common type of pile spliced used in the state of Florida is dowel splices. In this type of splice, holes are cast or field drilled into the top of the pile segment driven into the ground. Rebar dowels which are protruding of the end of the top pile segment are placed into the holes of the bottom pile and filler/bonding material is used to fill the spaces around the dowels in the holes and to bond them to the lower segment (Figures 17,18)(Wu, 2016). Dowel rebars can be made of conventional carbon steel or Stainless Steel (SS), Carbon Fiber Reinforced Polymer (CFRP) or Glass Fiber Reinforced Polymer (GFRP). Different types of resin and cement can be used as filler and bonding agent to connect the piles section. The setting time and the amount of strength that can be resisted by the filler and bonding materials should be considered in choosing (Bruce Jr & Hebert, 1974b; Canner, 2005). Installation of this type of splice causes the construction delay since it requires the top section of pile to be held till the filler or bonding materials cure. Epoxy is the most common type of bonding material that is used for PPCP splices. There have been efforts to decrease the curing time of epoxy (Navaratnarajah, 1981). Also, it is realized that some filler and bonding materials that are effective require more setting time. One of these materials which is under investigation by the FIU and UF researchers on ABC-UTC projects is non-proprietary UHPC. The bond strength of bars (No. 8 and No. 11) embedded with UHPC is 8 times of the bond strength between bars and conventional concrete (Tazarv & Saiidi, 2017). It is also realized that time to set and time to achieve desirable strength may be a challenge for the use of UHPC.

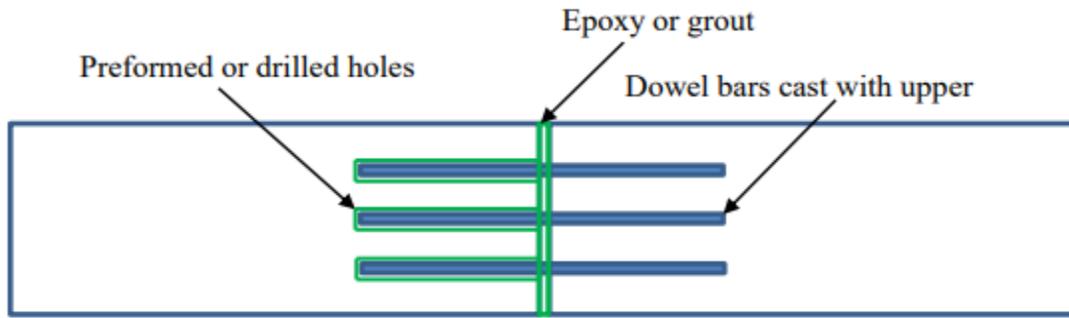


Figure 17: Dowel splice (Wu, 2016)



A: Step 1: Inserting dowel rebars B: step 2: Filler or bonding material C: Step 3: Final installation

Figure 18: Dowel splice process at Econfina River Bridge in Taylor County, Florida

3.2.1.4. Sleeve Splice

In this method, between two segments of voided piles, a steel tube is inserted (Cook & McVay, 2003). The steel tube is grouted to the pile for bond and transferring the load (Figure 19). Also, for improving the bond between the steel tube and the pile segments, spiral bars are welded to the steel tube. The required time for establishing the sleeve splice depends on the time needed for grout to reach the desired strength. The grout should reach the required strength before driving, otherwise, driving will fail (Wu, 2016).

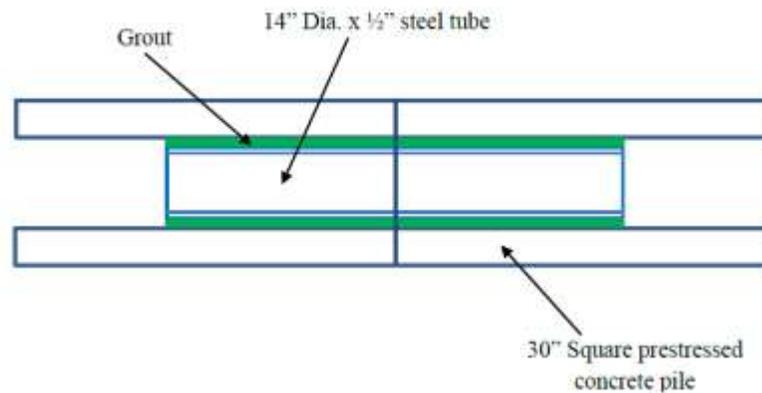


Figure 19: Sleeve splice (Wu, 2016)

3.2.1.5. Mechanical Splices

Mechanical splice has been considered as the most economical type of splices. It needs minimal installation time, can provide good flexural and tensile capacity (500-1000psi tensile) and can develop full bending capacity. In general, there are several types of mechanical splices that can be used. One type of mechanical splice, often with octagonal PPCS, uses steel caps, one male and one female. At the end of the each pile matching holes or grooves are devised. The steel caps are mechanically connected with high strength steel pins inserted into the holes. (Figure 20) (Mullins & Sen, 2015).



Figure 20: Mechanical splice (Mullins & Sen, 2015)

In 1990, Gamble and Bruce investigated another type of splice called ABB splice. They experimentally investigated the behavior of ABB splice under different loading conditions and found that this splice which previously was used for shorter piles, can be used to extend piles to longer lengths. ABB splices are used often for square piles (Gamble & Bruce Jr, 1990) (Figure 21). In the late 1990s, GYA mechanical splice was developed (Figure 22) that is made of two steel caps, four grooved pins and four holes. This type of splice has performed well in load tests and is currently used in many projects (Korin, 2004).



Figure 21: ABB splice



Figure 22: GYA mechanical splice (Korin, 2004)

3.2.2. Other Pile Splices under Development

In 2019, FDOT initiated an investigating on the behavior and effectiveness of epoxy dowel splice, experimentally and analytically, for prestressed precast concrete piles using corrosion resistant material for dowels (SS, CFRP, and GFRP), and comparing their performance to conventional carbon steel dowel splices. This investigation is being performed by researchers at Florida International University (FIU). They are investigating the effectiveness of GFRP dowels to economically substitute other corrosion-resistant dowels (Mehrabi & Farhangdoust, 2019).

3.3. ABC Connections with Potential for Using in Piles

There have been a large amount of research in relation with joints and connections in Accelerated Bridge Construction (ABC), and many types of joints are implemented successfully and perform well. Some of these connections are used for connecting columns to pier caps, columns to footing, or column segments to each other. These concepts can be adopted or modified for pile splices. Table below summarizes some of the available concepts for connecting ABC columns.

Table 3 Different connections of cap beam and column (Mehrabi, A.B., and Torrealba, 2019)

Type	Connection method	Usage
Formed in cap beam	Grouted sleeve	-Connect precast cap beam to cast-in-place or precast concrete column
	Grouted pocket	-Connect precast cap beam and precast or cast-in-place concrete column -Connect precast cap beam and steel pile or column
Formed along the Columns	UHPC column segment	-Connect precast cap beam and precast concrete column
	Grouted sleeve	-Connect precast cap beam and precast concrete column
	Mechanical couplers	-Connect precast column to cap beam
Other types	Welding	-Connect precast cap beam and steel pile or column
Cap beam segments	Closure pour	-Connect precast cap beam segments
	Mechanical couplers	-Connect precast cap beam segments to create moment connection

Following describes some of ABC connections with more relevance to pile splices. Figure 23 shows an example of grouted sleeve connection for column to cap formed inside the cap (left) and a grouted sleeve connection for column to footing connection (right). The concept of mechanical couplers perhaps is closer to the application to pile splices. Figure 24 shows connection of column to footing using mechanical coupler and a series of commercially available couplers. This type of coupler has been used also for connecting column segments and therefore, conceptually applicable to pile splices. One challenge in adopting these concepts would be their corrosion resistance that is a major issue for pile performance especially in the marine environment. Hence, emphasis should be on the use of alternative material to establish such connections. Use of corrosion resistant materials such as stainless steel (SS) and fiber reinforced plastics (FRP) has been investigated broadly and showed promising to be included in precast elements that are exposed to harsh and corrosive environment. Accordingly, these materials will

be considered in this study for reinforcement as well as for establishing mechanical connections. SS material has been incorporated in almost all types of reinforcing and prestressing elements and therefore can establish forms, mechanisms and systems equivalent to conventional carbon steel. It has also been attempted widely to create shapes and mechanisms for FRP material so that they can be used as replacement to carbon steel. To this end, bars, strands and various profiles have been introduced. FRP threaded rods and fasteners are also becoming more available. Figure 25 shows some of these products that are available in the market. Production of FRP elements are quite versatile and can be adjusted to the project details if needed. These elements can be configured to accommodate connections similar to grouted sleeve and other mechanical connections for pile splice. This way, both strength and durability can be provided for piles and pile splices in corrosive environment. In the following mechanical couplers and grouted post-tensioning connections are discussed further.

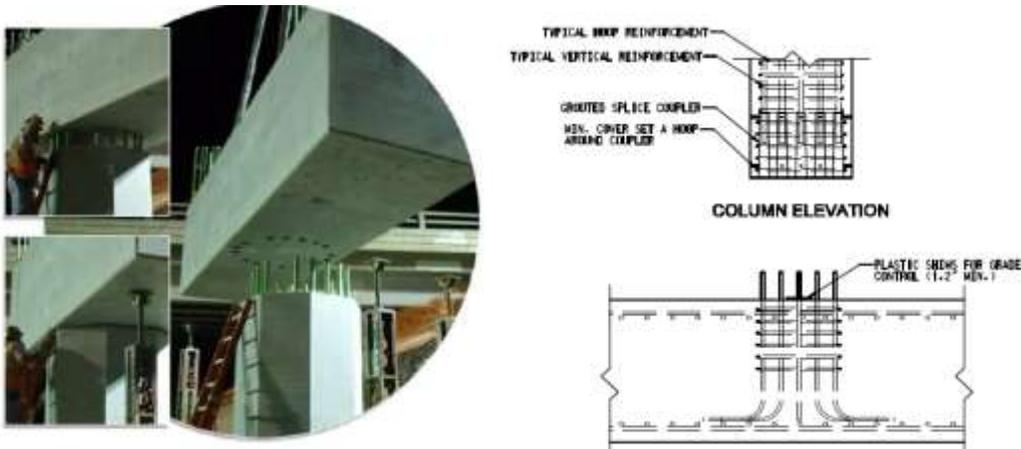


Figure 23: Grouted sleeve connection for column to cap (left- (Roddenberry & Servos, 2012)) and column to footing (right-(M P Culmo, 2009))

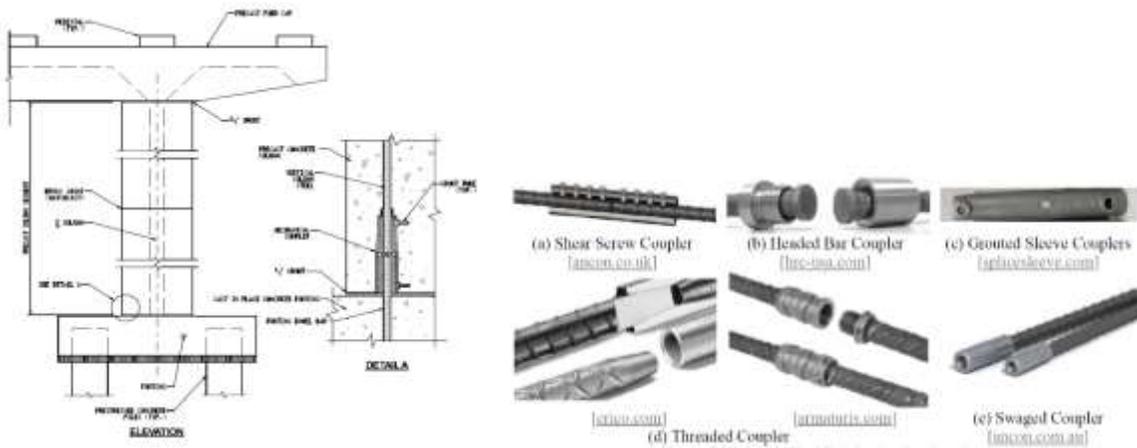


Figure 24: Mechanical coupler connection for column to footing (M P Culmo, 2009; Michael P Culmo et al., 2017)



Figure 25: FRP bars, bolts and fasteners

3.3.1. Mechanical Couplers

Prefabricated elements are often joined by splicing steel reinforcement. Joining prefabricated elements can therefore be performed using mechanical splicer. According to the AASHTO LRFD Bridge Design Specifications, mechanical bar splices, also called couplers should provide 125% of the specified yield strength of the bars which are connected to (Michael P Culmo et al., 2017). Several types of couplers are in the market (Figure 26). In general, they are divided into five categories (Figure 27). These are: (a) shear screw couplers, (b) headed bar couplers, (c) grouted sleeve couplers, (d) threaded couplers, and (e) swaged couplers. Shear screw splice is made of lock shear screw, shear rails, and coupling sleeve. Equal length of bars is placed into the sleeve, then the screws are tightened till the heads of screw shear off. In headed bar couplers, the plated end of bars are encased in sleeves that are threaded into each other. In grouted sleeve, two bars are connected to each other by placing them into a steel sleeve. Then the sleeve is filled with grout. In one version of grouted sleeve splice, the length required for coupler is reduced by threads inside the sleeve. In threaded couplers, the threaded bars are installed in a coupler with matching internal threads. Both straight and tapered threads can be used for the bar. In swaged coupler, straight bars are connected to pressed steel sleeve (Tazarv & Saiidi, 2016). The most common type of mechanical couplers are grouted splice couplers. They transfer loads between bars based on the grout filled device. The load is transferred between the bars by the coupler. They have been used to connect prefabricated elements. One prefabricated element has the role of host. There are holes at the face of the host element to receive the protruding bars from the element to be connected. The connection between the host and the joining element is established when the bars are inserted into the sleeves and filled with the grout (Figure 28). Pouring the grout in the sleeve can be performed before the positioning of the bars, referred to pre-grout, or it can be done after placing the bars in the sleeve by use of grout pump (Michael P Culmo et al., 2017).

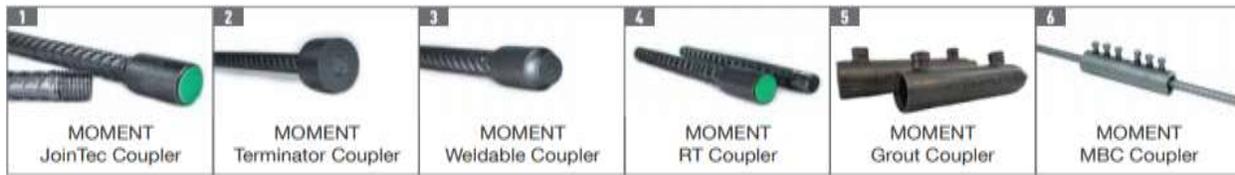


Figure 26: Mechanical couplers in market (Nvent)

(<https://www.nvent.com/us/en/products/concrete-reinforcing-steel-connections.html>)

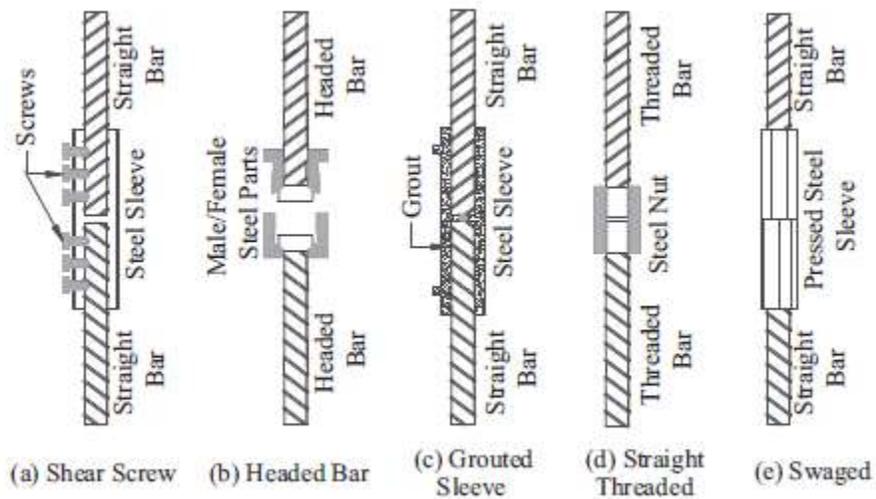


Figure 27: Types of mechanical couplers (Tazarv & Saiidi, 2016)

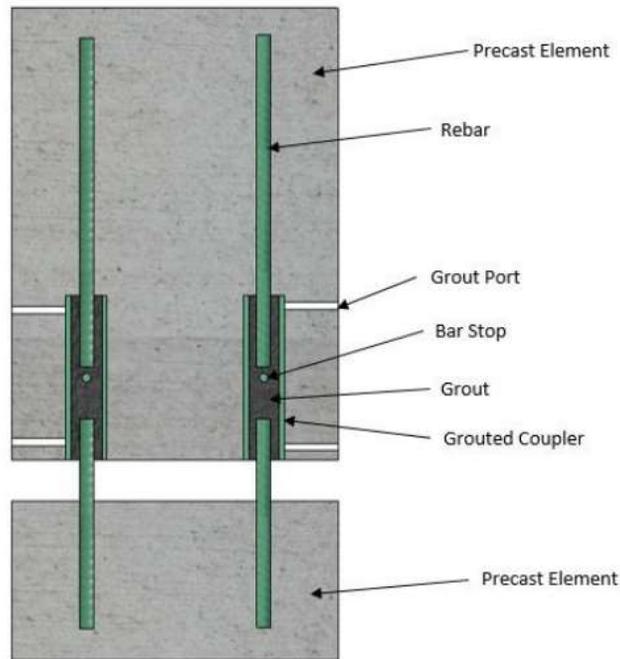


Figure 28: Grouted coupler in precast element (Redd, 2016)

3.3.2. Grouted Post-Tensioning Duct Connections

In grouted post-tensioning duct connections, protruding reinforcements from one prefabricated element are embedded into the post-tensioning ducts cast at the end of the receiving prefabricated element. The duct is then filled with grout. The main difference between this splice with grouted coupler is that the reinforcing steel is not spliced but bonded to concrete. The mechanical coupler is a structural member. The role of grout is to transfer the force from the bar to the coupler. However, the grouted duct is a non-structural member that transfers the force from the reinforcement to the surrounding concrete. There have been much research that investigated the grouted post-tensioning duct connection. The research has shown that using duct reduces the development length of bars in mass concrete. Also, it decreases the probability of cracking in the element at the ultimate load (Michael P Culmo et al., 2017).

Task 2 –Development of New Splice Details and Configurations

The results of literature review will be analyzed to identify candidate concepts regarding details and configurations that would be applicable to pile splices. Modifications will be applied to better fit the details to the purpose of pile splicing, or new configuration will be explored to accommodate the splice requirements.

No work was performed for this task.

Task 3 – Modeling and Analysis

The candidate details and configurations identified in the previous task will be analyzed using FE modeling and section analysis, and their structural performances will be compared to that of the existing splice details. This should result in selection of few configurations as most promising splice connections.

No work was performed for this task.

Task 4 – Constructability Analysis

The most promising configurations will be scrutinized for their constructability according to ease of implementation, time to use, and cost.

No work was performed for this task.

Task 5 – Design Considerations

Means and methods for designing the selected splice connections will be investigated. The results will be organized in the form of a design procedure.

No work was performed for this task.

Task 6 – Draft and Final Report

A comprehensive draft final report including the activities performed in the previous tasks will be prepared and submitted first for review by the research advisory panel (RAP). The report will identify the alternative splice connection(s) for prestressed-precast concrete piles, and will attempt to provide an analysis and design procedure. After incorporating the comments received from RAP, the final report will be submitted to BAC-UTC for publication on the website.

No work was performed for this task.

4. Schedule

Progress of tasks in this project is shown in the table below.

Item	% Completed
Percentage of Completion of this project to Date	15%

Duration of this project is 18 months. Scope and timeline for various tasks are shown below.

PHASE	RESEARCH TASK	2020										2021					
		A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	
I	Task 1- Literature review	■	■	■	■												
	Task 2- Development of New Splice Details and Configurations		■	■	■	■	■	■	■	■							
	Task 3- Modeling and Analysis			■	■	■	■	■	■	■	■	■					
	Task 4- Constructability Analysis									■	■	■	■				
II	Task 5- Design Considerations									■	■	■	■				
	Task 6- Draft and Final Report													■	■	■	

■ Work Performed
 ■ Work to be Performed

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