Technical Report Documentation Page

<table>
<tr><td>1. Report No.
FIU-EDPSE-01</td><td>2. Government Accession No.</td><td colspan="2">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
Epoxy Dowel Pile Splice Evaluation</td><td colspan="2">5. Report Date
July 2019</td></tr>
<tr><td colspan="2">6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author(s)
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<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
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Miami, FL 33174</td><td colspan="2">10. Work Unit No. (TRAIS)</td></tr>
<tr><td colspan="2">11. Contract or Grant No.
BDV29-977-52</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Organization Name and Address
FDOT Research Center
Phone: (850) 414-5260
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Tallahassee, Florida 32399-0450 Email:
research.center@dot.state.fl.us</td><td colspan="2">13. Type of Report and Period Covered
Interim Report- Task 1 Deliverable</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code</td></tr>
<tr><td colspan="4">15. Supplementary Notes</td></tr>
<tr><td colspan="4">16. Abstract
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<tr><td colspan="2">17. Key Words
Prestressed Precast Concrete Pile, Pile Splice, Epoxy Dowel Splice, CFRP, HSSS, SS, GFRP,</td><td colspan="2">18. Distribution Statement
No Restriction</td></tr>
<tr><td>19. Security Classification
Unclassified</td><td>20. Security Classification (of this page)
Unclassified</td><td>21. No. of Pages</td><td>22. Price</td></tr>
</table>

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Epoxy Dowel Pile Splice Evaluation

Project No. BDV29-977-52

Interim Report – Task 1 Deliverable

July 2019

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Florida Department of Transportation

A report from

FLORIDA INTERNATIONAL UNIVERSITY

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Abstract

The objective of this project is to investigate 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. The research project aims to verify the effectiveness of SS and CFRP dowels, and applicability of substitute GFRP dowels as a more economical alternative. It will develop design procedure and details for GFRP epoxy dowel splices, aims at recommending refinements to current designs, and develop design drawings for the recommended details. It will also develop an analytical framework that can be used for design of future variations of pile and splice systems. The primary focus will be on the flexural behavior of the pile splices. This report includes the literature review as Task 1 of the project.

1 INTRODUCTION

1.1 Problem Statement

Establishing bridge foundations where there is a top layer of weak soils normally requires application of deep foundations such as pile foundation. Driving prestressed-precast concrete piles (PPCP) is one of the options among various types of piles and installation methods. This option provides in many cases an economic and rapid alternative. However, traditional prestressed piles that use carbon steel strands and bars are prone to corrosion, especially when they are in a marine environment. In such environment, alternating water levels and water splash cause deposit and migration of salts into the pile that can accelerate corrosion. Florida Department of Transportation (FDOT) has recently implemented programs to use alternative prestressing strand material that are corrosion resistant. The use of Carbon Fiber Reinforced Polymers (CFRP) and High Strength Stainless Steel (HSSS) for strands and other reinforcement in concrete piles have shown great improvements in the resistance against corrosion.

For various reasons, it often happens that splicing of pile segments has to be performed at the site to achieve longer lengths. The shipping and transportation constraints may limit the length of precast prestressed pile segments that can be delivered to the bridge site. Also, when there is headroom limitation for pile driving, the length of pile segments may be smaller than the length required to establish adequate resistance. In such cases, splicing can be preplanned. Another reason that the pile segments would be less than the length required for resistance is the case of unpredictable soil resistance, which leads to unplanned splicing. Dowel-type splicing using epoxy grout is the focus of this project. In the dowel-type splice, holes are cast or drilled into the top of the lower pile to receive dowel rebars protruding out of the lower end of the upper pile. Dowel rebars can be made of carbon steel as in conventional splicing, or of Stainless Steel (SS), Carbon Fiber Reinforced Polymer (CFRP), or Glass Fiber Reinforced Polymer (GFRP) bars. FDOT has Standard Drawings showing CFRP and SS dowels, but does not cover a GFRP dowel application. Despite occasional use of alternate corrosion resistant dowel splicing, their true behavior is not fully understood yet. Analytical and experimental investigations for structural evaluation of these splices in comparison with splices using conventional bars are scarce.

1.2 Research Objectives

The objective of this project therefore is to investigate the behavior and effectiveness of the epoxy dowel splice 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. The project includes reviewing previous investigations on this subject and design of pile splices according to available codes

and analytical models. Pile segments will be fabricated at an approved precast plant, then moved to the FDOT Structures Laboratory, spliced and tested in bending. Using the test results, the project will aim to verify the effectiveness of SS and CFRP dowels, and applicability of GFRP dowels. Design procedure and details will be developed for GFRP epoxy dowel splices, and if applicable, refinements to the current designs for CFRP and SS dowels will be introduced, and design drawings for the recommended details will be developed. It will also develop an analytical framework that can be used in future for systems not covered in this project. The focus of this study will be on the flexural behavior of pile splices.
The objective includes quantifying the effectiveness of the current pile splice details and developing cost-effective versions for corrosion-resistant piles. The research intends to provide a better understanding of the performance and behavior of spliced bearing piles along with a refined design that will be incorporated within the FDOT Standard Plans (Index 455-series).

This report covers the literature review as Task 1 of the project.

2 LITERATURE REVIEW

In Florida, many bridge foundations are exposed to salt water and harsh marine environments which can cause expensive maintenance issues and shorten bridge life. Conventional piles mostly deteriorate prematurely in such corrosive environments. Corrosion in concrete piles also occurs in soils and groundwater where there are low pH levels, high level of chloride as well as sulfate. The consequence is a decrease in load-carrying capacities, and likely increase in settlement eventually resulting in the failure of superstructures (Han et al. 2003). Although deteriorated pile structures can be replaced or retrofitted, their maintenance will be costly and not reliable for their long-term serviceability (Roddenberry et al. 2016). It has been estimated that repair and replacement of the conventional pile systems cost the United States more than $1 billion annually (according to the estimate at the time of investigation) (Lampo, et al., 1997). Therefore, high durability, low maintenance, and high safety are always top priorities for any bridge owner. This report presents a comprehensive literature review on different types of precast piles and pile splices with an emphasize on epoxy dowel pile splices.

2.1 Driven Piles

Piles are divided into two main groups of driven and cast-in-place piles. Driven piles may be made of wood, steel, concrete, or various types of composite materials. All types of piles are reviewed briefly, but this study focuses on prestressed precast concrete piles.

2.1.1 Wooden Piles

Wooden piles in coastal waters are prone to damages caused by marine borer activity (Figure 1). Teredo, Bankia, and Limnoria have been recognized as the three most destructive borers who enter the wood as a larva or go through outside edges of the timber piles and follow the grain, tunneling deeper making the wood as holed as Swiss cheese (Figure 1). There are some solutions for preventing their attacks such as using creosote and arsenate for pressure treatment of wood, or the use of wood composites including timber piling encased in fiberglass, and extruded mixtures of wood cutting and polymers. However, these options do not stop borers from attacking the wood completely. Therefore, fabricating more reliable piles is needed, especially in the splash zone (Iskander 2002).

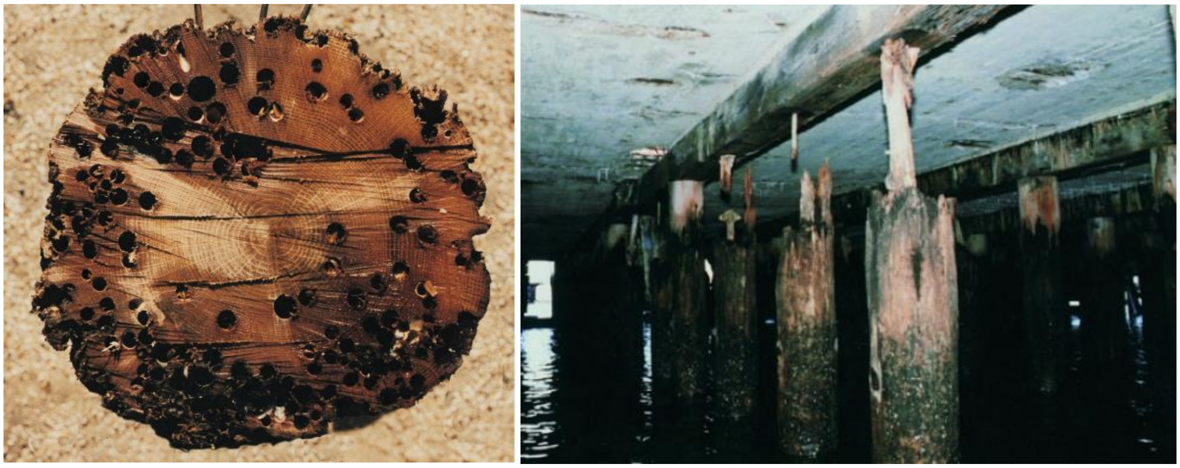

Figure 1: Tunneling in a timber pile caused by Teredo and Bankia (Left), untreated timber piles attacked by Limnoria (Right) (Iskander 2002)

2.1.2 Steel Piles

Steel piles are among cost-effective deep foundations. Their use has been limited due to their vulnerability to corrosion (Figure 2). Two main destructive salts are sodium and calcium chlorides causing corrosion of the steel piles, especially in industrial and marine environments (Iskander 2002). In regular soils, the rate of corrosion is around 0.03 mm per year which increases to 1.2 mm per year in the splash zone (Fleming et al. 2008). Coatings containing heavy metals can prolong the service life and enhance the lifecycle performance of the steel piles, but these treatments may be harmful to the environment. Therefore, there is a need for alternative materials for pile fabrication which are resistant to corrosion.

Figure 2: An example of corroded steel H pile supporting a harbor pier (Iskander 2002)

2.1.3 Composite Piles

Composite piles (plastic-and-steel type) were used for the first time as replacements for timber fender piles at the Port of Los Angeles in the United States in the late 1980s (Heinz 1993). In 1987, the use of the first composite pile prototype consisting of recycled plastic was reported (Horeczko 1995). Table 1, shows a list of some pile projects, their manufacturer and application in which composite piles have been utilized.

Table 1: Selective projects using composite piles (Pando et al. 2006)

Site	Year	Application	Pile Manufacturer	Pile Type	Source
Port of Los Angeles, CA	1987	Fender piles	Plastic Pilings, Inc.	Steel pipe with thick plastic shell	Heinz (1993), Hoy (1995)
	1991–5	Fender piles	Plastic Pilings, Inc.; Seaward International, Inc.; Hammer's Plastic Recycling	Plastic piling with steel core	
Port of NJ, Newark, NJ	1991	Fender piles	Plastic Pilings, Inc.	Steel pipe with thick plastic shell	Hoy (1995)
Naval Station Roosevelt Roads, Puerto Rico	1991	Trial fender piles	Plastic Pilings, Inc.	Steel pipe with thick plastic shell	Hoy (1995)
Port of Grays Harbor, Aberdeen, WA	1992–3	Fender piles	Plastic Pilings, Inc.	Steel pipe with thick plastic shell	Hoy (1995) www.plasticpilings.com
Port of Seattle, WA	1993	Fender piles	Plastic Pilings, Inc.	Steel pipe with thick plastic shell	Hoy (1995) www.plasticpilings.com
Port of Oakland, CA	1993	Fender piles	Plastic Pilings, Inc.	Steel pipe with thick plastic shell	Hoy (1995) www.plasticpilings.com
Pearl Harbor, HI	1994	Fender piles	Plastic Pilings, Inc.	Steel pipe with thick plastic shell	Hoy (1995) www.plasticpilings.com
Port of NY/NJ	1994	Fender piles	Seaward International, Inc. Creative Pultrusions, Inc.	Recycled plastic with fiberglass reinforcing Ultra high molecular weight polyethylene	Hoy (1995)
Pier Bravo, NAS North Island, San Diego, CA	1995	Fender piles	Plastic Pilings, Inc.	Recycled plastic reinforced with welded steel rebar cage	Tetra Tech EM, Inc. (1999)
Delaware Bay, DE	1996	Fender piles	Hardcore Composites	Fiberglass shell filled with concrete	Phair (1997) www.hardcorecomposite.com
Port of New Orleans, LA	1996	Fender piles	Seaward International, Inc.	Recycled plastic with fiberglass reinforcing	Eustis Engineering Co, Inc. (1996)
Pier 16—Naval Amphibious Base Coronado, San Diego, CA	1996	Fender piles	Plastic Pilings, Inc.	Recycled plastic reinforced with welded steel rebar cage	Tetra Tech EM, Inc. (1999)
US Navy EMR Facility Pier Ingleside, TX	1997	Pier piles	Lancaster Composites	FRP shell with concrete core	Stapleman (1997)
Pier 23, Norfolk, VA	1997	Fender piles	Lancaster Composites	FRP shell with concrete core	Lancaster (2000) www.lancastercomposite.com

Fiber reinforced plastic (FRP) is a thermally and electrically nonconductive, lightweight, and high corrosion-resistant material (Han et al. 2003). Hence, they can offer a superior alternative material to conventional materials (e.g., steel) for driven pile construction. FRP is an anisotropic material with an excellent strength parallel to the direction of the fibers. This property of the FRP has a considerable effect on shear strength, dowel action, and bond performance. Although the weight of FRP is almost one-quarter of steel, its tensile strength is almost three times greater than conventional steel materials (Hun et al. 2003). FRP is manufactured from two main parts of fibers and matrix resin. The former part provides strength and stiffness and can be made of Glass, Basalt, Carbon, or Aramid. The matrix of FRP protects and transfers stresses between fibers and can be made by Polyester, Epoxy, Vinyl Ester, and Urethane.

The most popular combinations of FRP are (Busel 2016):

- Glass/Vinylester (or epoxy)
- Glass/Polyurethane

- Basalt/Epoxy
- Carbon/Vinylester (or epoxy)

Some of the popular composite pile products available in the market today, include: steel pipe core piles, reinforced plastic matrix piles, concrete-filled FRP pipe piles, plastic lumber piles, and fiberglass pultruded piles (Pando et al. 2006, and Iskander 2002). Figure 3 shows the available commercialized types of composite piles.

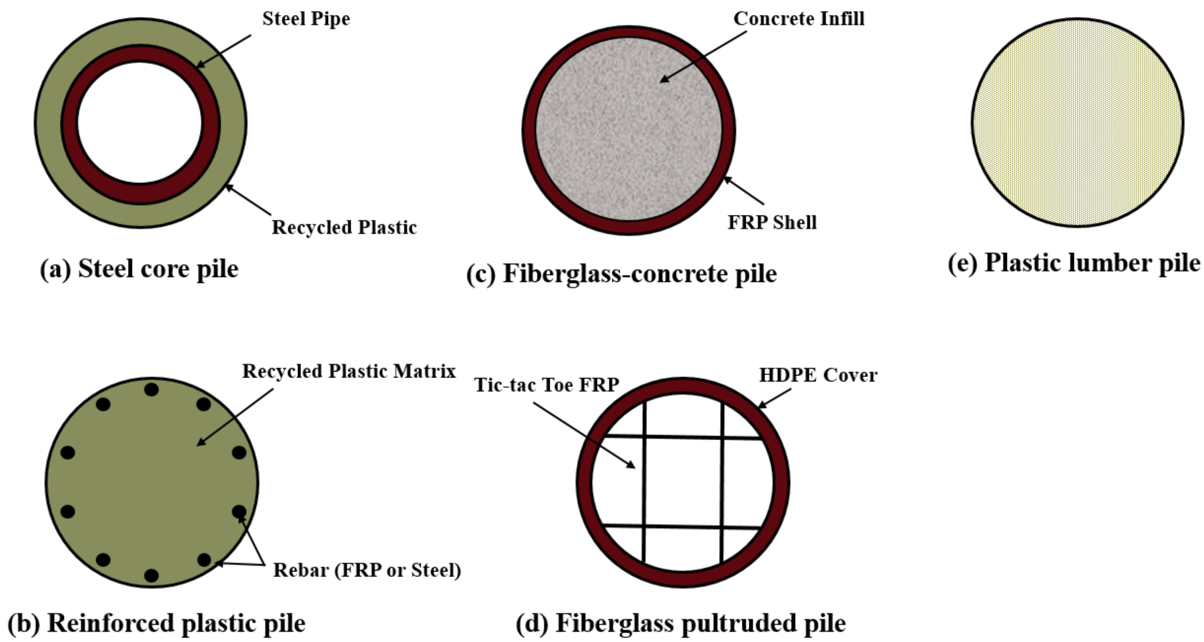

Figure 3: Available commercial composite piles

Steel pipe core piles, reinforced plastic matrix piles, concrete-filled FRP pipe piles have been recognized by Lampo et al. (1998) to be better suited for load-bearing applications among other types of piles. FRP composites have been used not only as internal reinforcements in concrete piles (Sen et al. 1991), but also as external reinforcement and protective sheathing. Three FRP-type of piles comprised of internal FRP-reinforced piles (concrete piles with FRP reinforcement), external FRP-enclosed piles (steel pipe piles enclosed by recycled plastic, concrete piles enclosed by FRP shell, and timber piles enclosed by FRP shell), and FRP structural piles (FRP pultruded shapes and fiberglass-reinforced recycled plastic piles) have been studied by Hun et al. 2003. The elastic modulus of FRP varies from about 20% to 80% of the modulus of mild steel and depends directly on the properties and the volume fraction of fibers and matrix (Han et al. 2003). New design methods for piles using FRP have been examined by Han et al. (2003) for vertical and lateral loads considering buckling and load-displacement responses. Low section stiffness and high ratios of linear elastic to shear modulus are some other important characteristics of FRP piles which cause more significant nonlinear load-deformation behavior than conventional piles under vertical and lateral loads (Han et al. 2003).

A test pile program was conducted by Pando et al. (2006) to evaluate the axial and lateral load behavior of the composite piles compared with that of prestressed concrete piles. Laboratory tests were performed on three different piles with a length of about 18 m (59.0 ft) (Figure 4):

- A conventional, 610-mm (23.8-inch) square, prestressed concrete pile,
- A 622-mm (24.3-inch) diameter composite pile made of an FRP shell filled with concrete reinforced with steel bars,
- A 592-mm (23.1-inch) diameter composite pile made of a polyethylene plastic matrix reinforced with steel bars.

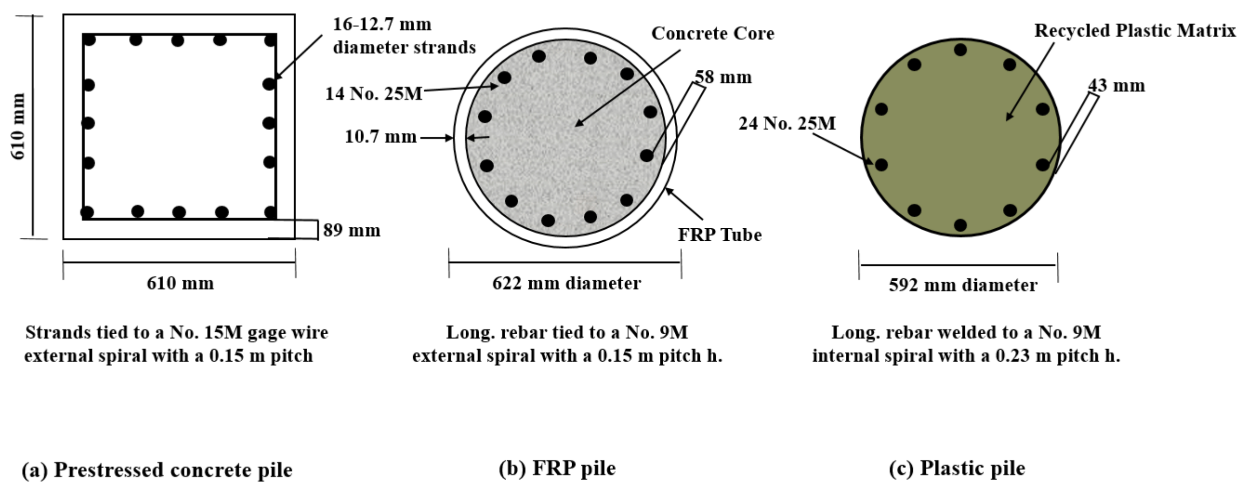

Figure 4: Cross section details of the three types of piles tested by Pando et al. (2006) (1 mm = 0.039 in, 1 m = 3.28 ft)

The following conclusions were made as a result of Pando's report:

- The prestressed concrete pile and the FRP pile have the same axial stiffness which was about 2.5 times more than the axial stiffness of the plastic pile.
- Over a working range of bending moments, the flexural stiffness increased in order from the plastic pile to the FRP pile to the prestressed concrete pile.

- The axial load capacities for the prestressed concrete pile, the FRP pile, and the plastic pile were found to be 3,090, 2,260, and 2,130 kN (695, 508, and 479 kip), respectively.
- The average unit shaft resistances for the prestressed concrete pile, the FRP pile, and the plastic pile were 61.8, 46.9, and 48.9 kPa (8.96, 6.80, and 7.09 psi), respectively.
- The corresponding unit toe resistances for the prestressed concrete pile, the FRP pile, and the plastic pile were 1,854, 2,564, and 2,339 kPa (268.8, 371.8, and 339.2 psi), respectively.
- From the static lateral load test results, they found that the prestressed concrete pile and the FRP pile have the same load-deflection response which was much smaller than the plastic pile at the same lateral loads.

2.1.4 Prestressed-Precast Concrete Piles

One of the options for establishing pile foundation is the use of prestressed-precast concrete piles (PPCP) (Figure 5). PPCP is a concrete prism element with prestressed strands providing initial compressive stress and transverse tie or spiral providing for confinement and shear resistance. Conventional PPCP uses concrete of various strengths and high-strength steel strands. It normally offers an adaptable, economical pile foundation with reasonable corrosion resistance provided by concrete cover that is less prone to cracking because of compressive stress introduced by prestressing. However, in marine environments, in time, corrosion damages the strands and reduces the load carrying capacity of the piles. Alternative corrosion resistant material can be used for strands and ties to address this shortcoming.

© https://www.gimrock.com/FoundationWork.html

Figure 5: Prestressed-Precast Concrete Piles in marine environment

2.1.4.1 *Conventional Presteressed Strand*

Conventional steel strands are normally made of seven wires (six wires spun around a king wire) of high-strength, low relaxation steel with various nominal diameters, most commonly 0.5 and 0.6 in. diameter. As an example, Figure 6 shows pile details which are commonly used by the Virginia Department of Transportation (VDOT) bridge projects (Pando et al. 2006). The prestressed concrete cross section is a 508-mm (20-inch) square pile with a length of about 13.1 m (43 ft). As shown in Figure 6, this prestressed pile contains a total of fourteen, 12.7-mm (0.5-inch) diameter, 7-wire strands of 1861 MPa (270 ksi) ultimate strength, pretensioned to produce a prestress level of 5.6 MPa (0.809 ksi) based on VDOT standards.

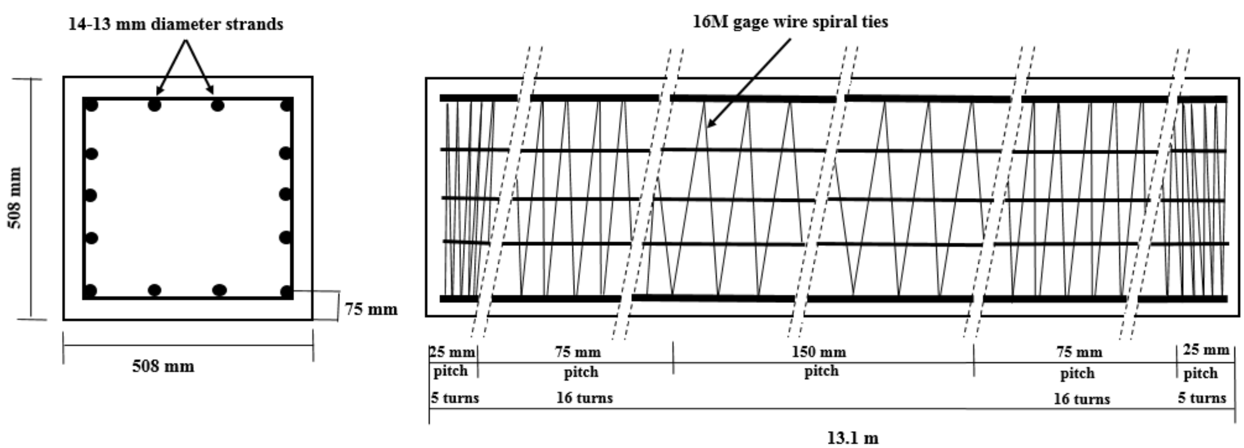

Figure 6: Details of prestressed concrete pile used in VDOT (Pando et al. 2006) (1 mm = 0.039 in, 1 m = 3.28 ft)

Florida Department of Transportation includes standard details for its precast prestressed square piles with conventional steel in FDOT Standard Drawings Index Series 455 (2018). Figure 7 shows these details for an 18x18 in square piles.

PPCP provides in many cases an economical alternative to other pile foundation types. However, traditional prestressed piles are susceptible to corrosion of the carbon-steel strands especially 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 corrosion. Florida Department of Transportation (FDOT) has implemented programs for utilization of alternative prestressing strand material that are corrosion resistant.

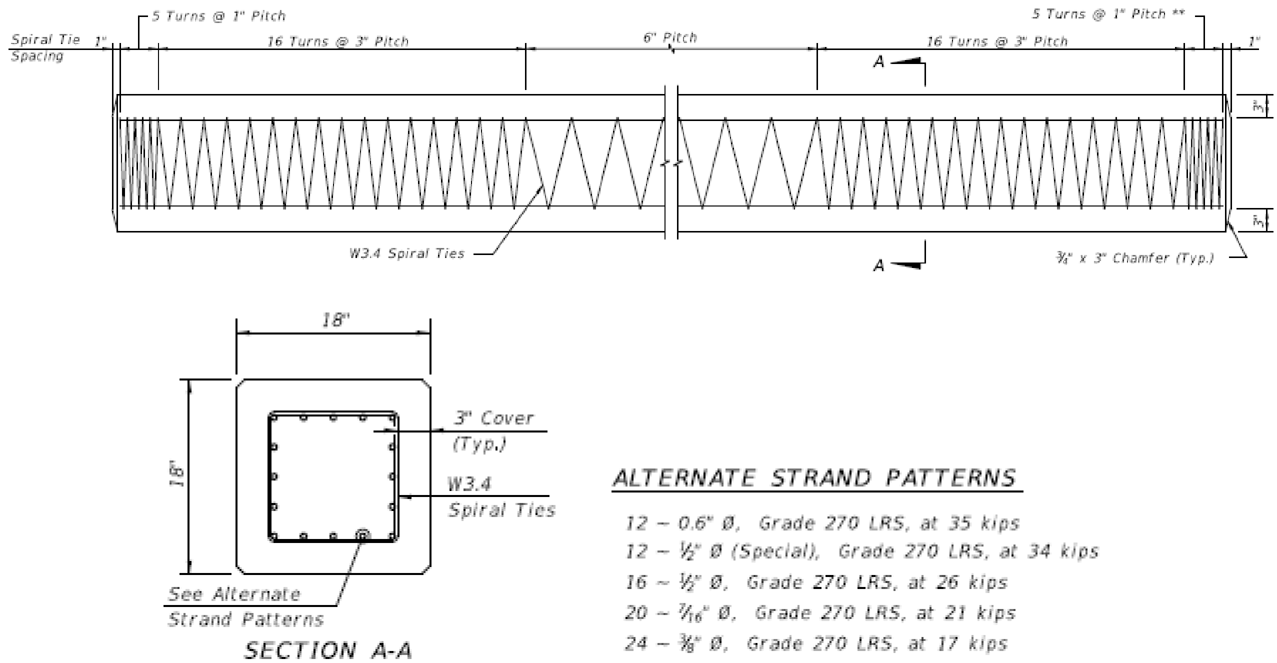

Figure 7: FDOT standard prestressed-precast concrete pile (FDOT Standard Drawings Index Series 455, 2018)

2.1.4.2 *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 normal prestressing strands. The use of Carbon Fiber Reinforced Polymers (CRFP) and High Strength Stainless Steel (HSSS) for strands, longitudinal (when needed) and transverse reinforcement in the precast concrete piles have shown great improvements in resistance against corrosion (Roddenberry et al. 2016, Mullins et al., 2014, Belarbi et al., 2017). ACI-440-04 covers an extensive review of the background, material properties and design recommendation for the use of these materials and other FRPs. Driving and installation of piles made with CFRP have been performed 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 QC. Grace (2007) used CFRP for post-tensioning tendons and reinforcing bars for the first time in the superstructure of the Bridge Street Bridge in Southfield, MI. Although this application was not for piles, the study monitored the performance for long periods of time and demonstrated in general suitability of CFRP for use as prestressing/post-tensioning applications.

PPCP using SS 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 SS strands had no adverse effect on transfer length, while it improves significantly the corrosion resistance (Figure 8).

Figure 8: PPCP with Stainless Steel Strand and Spiral (Mullins et al. 2014)

2.1.4.2.1 Carbon Fiber Composite Cable (CFCC)

As it was mentioned earlier, FRP can be manufactured using carbon (CFRP), glass (GFRP), or aramid (AFRP) fibers. Carbon fiber composite cables (CFCC) is a type of CFRP that has been used for prestressing and post-tensioning. In CFCC, wires containing carbon fibers of polyacrylonitrile and epoxy resin are twisted and wrapped with synthetic yarns to cover the fibers from ultraviolet radiation and mechanical abrasion (Roddenberry et al. 2016). CFCC has shown high bond strength to concrete (about twice of that of steel), 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 not as ductile as its steel counterpart (Roddenberry et al., 2016). According to the recorded data from pull-out tests, the bond strength of CFCC to concrete is 967 psi (6.67 MPa) which is more than twice that of steel.

CFCC has a longitudinal coefficient of expansion of 0.34 × 10-6/°F (0.62 × 10-6/°C) which is 1⁄20 of that for the steel. CFCC has a light weight with less relaxation of the strands compared to steel which makes it easy to handle. Roddenberry et al. (2014, 2016) tested PPCP using CFCC of various lengths to investigate the flexural strength, transfer length, development length, and drivability (Figure 9).

Figure 9: Flexural testing of PPCP with CFCC (Roddenberry et al. 2014)

They concluded that the development length of the tested CFCC strands is less than 72.0 in. and therefore less than the AASHTO LRFD specifications prediction of 123 in. (3120 mm) for steel strands (using CFCC's value for guaranteed ultimate tensile strength), and flexural strength higher than anticipated. Figure 10 shows the side view and cross-section of the 24 in. square piles and made by CFCC spiral transverse reinforcement.

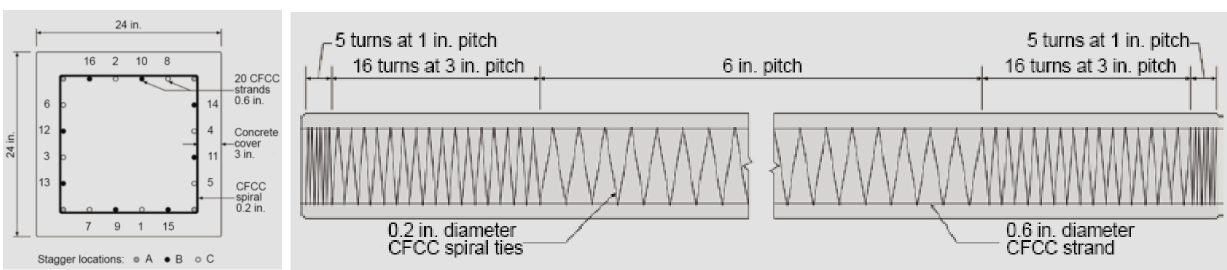

Figure 10: Cross-section (Top) and side view (Bottom) of the piles made by CFCC (Roddenberry et al. 2016)

Florida Department of Transportation includes standard details for its precast prestressed square piles using CFRP strands and ties in FDOT Standard Drawings Index Series 455 (2018). Figure 11 shows these details for an 18x18 in square piles.

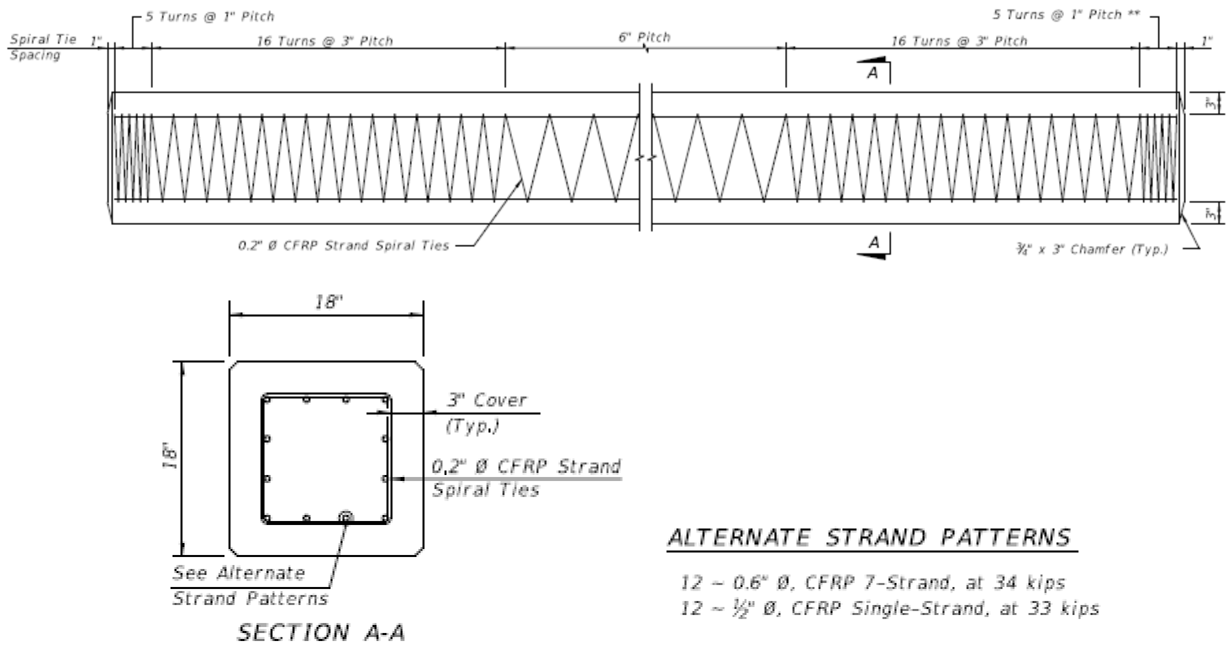

Figure 11: Details of prestressed concrete pile using CFRP strands and ties (FDOT Standard Drawings Index Series 455, 2018)

2.1.4.2.2 High Strength Stainless Steel (HSSS)

From metallurgy perspective, stainless steel material is recognized as an iron--carbon alloy with a minimum of 11.5 wt % chromium content (Wu and Nürnberger 2009). Stainless steel material is superior to conventional carbon steel due to their higher corrosion resistance property. Therefore, the stainless steel provides a better lifecycle performance for prestressed strands for piles as it relates to corrosion. To produce high strength stainless steel (HSSS), manufacturers use cold working or similar process to increase the strength of the stainless steel (Mullins 2014).

Florida Department of Transportation includes standard details for its precast prestressed square piles using HSSS strands and SS ties in FDOT Standard Drawings Index Series 455,2018. Figure 12 shows these details for an 18x18 in square piles.

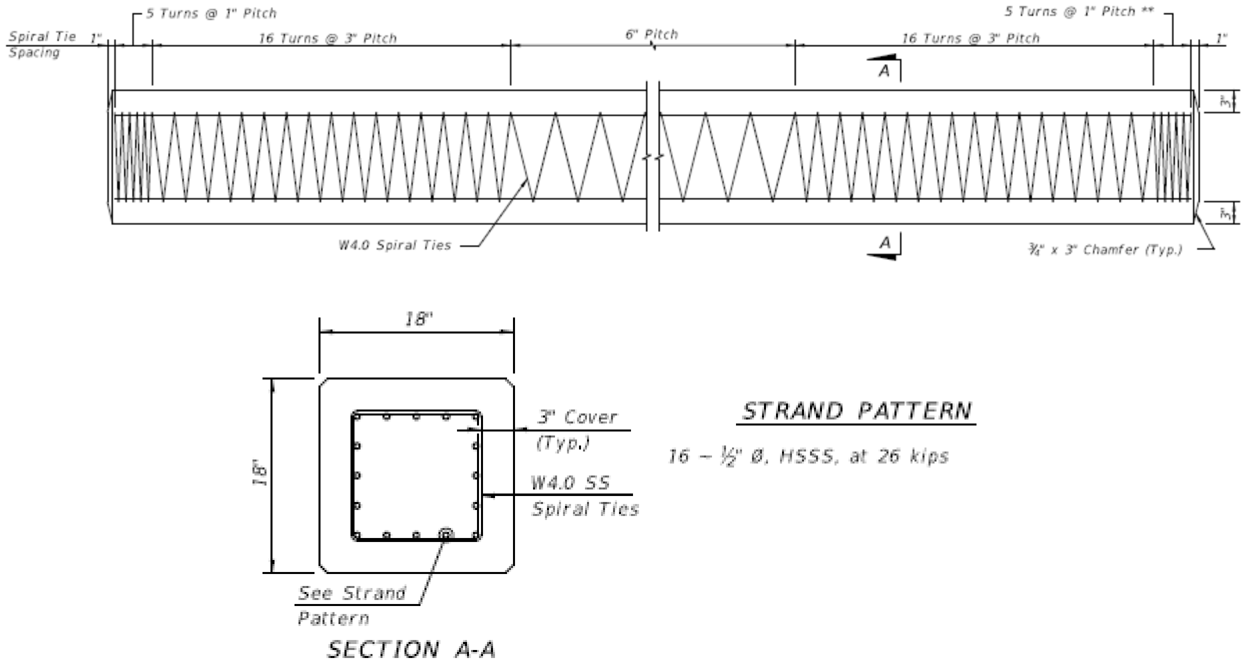

Figure 12: Details of prestressed concrete pile using HSSS strands and SS ties (FDOT Standard Drawings Index Series 455, 2018)

The conventional prestressing steel has been compared with strands made of HSSS by Nürnberger (2001). The comparison in Figure 13 illustrates that the HSSS strands have a better fatigue performance than conventional carbon steel strands (considered in their study) under various exposure conditions.

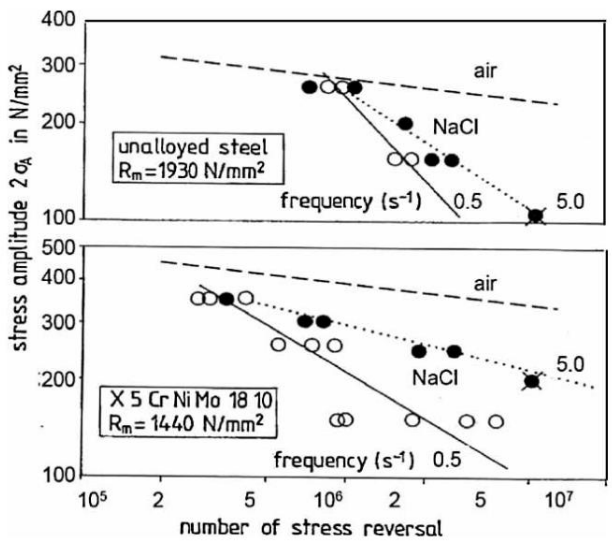

Figure 13: Results of comparing HSSS strands with conventional cold- drawn prestressing steel strand (Nürnberger 2001)

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 that predicted by both ACI-318 and AASHTO LRFD, and the stress loss was smaller than that predicted by AASHTO LRFD refined method. Prestress losses and transfer lengths were not affected by pile driving and extraction.

2.2 Pile Splice

Prestressed Precast Concrete Piles (PPCP) often require splicing for one or more of the following (i) shipping and transportation length limits, (ii) limited headroom that will force planned splicing, (iii) unplanned splicing when the required capacity is not achieved with the piles existing lengths,. There are various means for establishing bearing-type splices as illustrated in Figure 14 including wedge, pinned, welded end plates, post-tensioned, sleeve, connecting ring, mechanical and finally dowel splices. While more variation of splice types and alternatives are available (Cook and McVoy, 2003), this project makes specific focus on the dowel-type splicing using epoxy grout in accordance with FDOT Specification 926 Type AB.

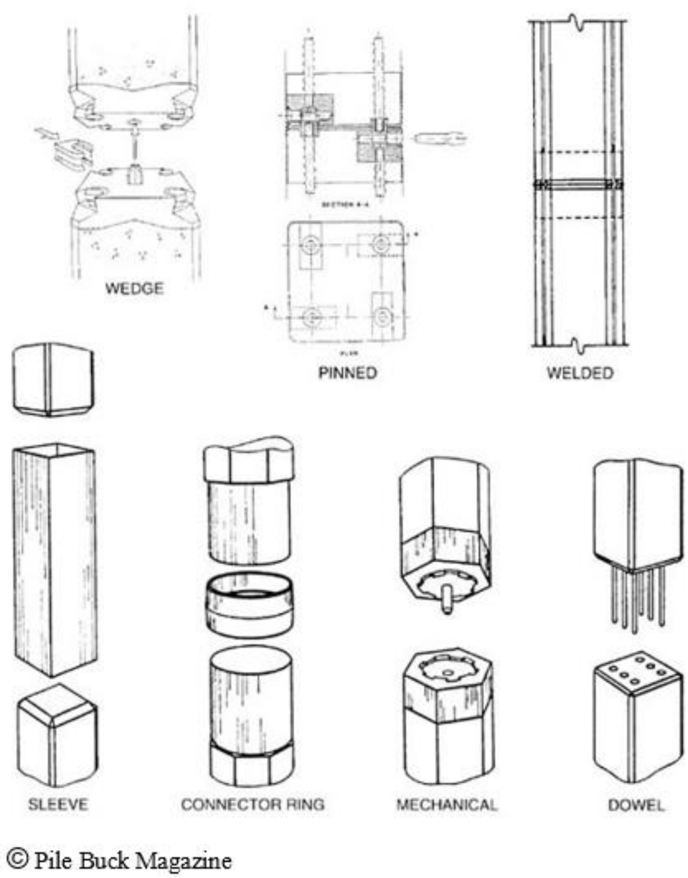

Figure 14: Various types of pile splicing

One of the earlier works conducted to investigate the existing methods for concrete pile splices is by Bruce and Hebert (1974). They categorized pile splices as follows:

- Welded Splices
- Bolted Splices
- Mechanical Locking Splices
- Connector Ring Splices
- Wedge Splices
- Sleeve Splices
- Dowel Splices
- Post-Tensioned Splices

Table 2 shows a summary of twenty types of pile splices from all over the world (Bruce and Hebert, 1974) in terms of size range, field time for splicing, approximate cost of splice, availability, construction usage, structural integrity, and structural performance.

Table 2: Summary data on different pile splices (Bruce and Hebert, 1974)

Name of Splice	Type	Origin	Approximate Size Range, in. (cm)	Approximate Field Time, min.	Strength		
					Percent Compressive	Percent Tensile	Percent Flexural Cracking
Marier	Mechanical	Canada	10-13 (25-33)	30	100*	100*	100*
Herkules	Mechanical	Sweden	10-20 (25-51)	20	100**	100**	100**
ABB	Mechanical	Sweden	10-12 (25-30)	20	100**	100**	100**
NCS	Welded	Japan	12-47 (30-119)	60	100**	100**	100**
Tokyu	Welded	Japan	12-47 (30-119)	60	100**	100**	100**
Raymond Cylinder	Welded	USA	36-54 (91-137)	90	100**	100**	100**
Bolognesi-Moretto	Welded	Argentina	Varied	60	100*	55*	100*
Japanese Bolted	Bolted	Japan	Varied	30	100**	90**	90**
Brunsplice	Connector ring	USA	12-14 (30-36)	20	100**	20*	50*
Anderson	Sleeve	USA	Varied	20	100*	0*	100*
Fuentes	Welded sleeve	Puerto Rico	10-12 (25-30)	30	100**	100*	100*
Hamilton Form	Sleeve	USA	Varied	90	100*	75**	100**
Cement Dowel	Dowel	USA	Varied	45	100**	40**	65**
Macalloy	Post-tensioned	England	Varied	120	100*	100*	100*
Mouton	Combination	USA	10-14 (25-36)	20	100*	40*	100*
Raymond Wedge	Welded wedge	USA	Varied	40	100*	100*	100*
Thorburn	—	Scotland		No information available on this splice			
Pile Coupler	Connector ring	USA	12-54 (30-137)	20	100**	100**	100**
Nilsson	Mechanical	Sweden	Varied	20	100*	100*	100*
Wennstrom	Wedge	Sweden	Varied	20	100*	100*	100*
Pogonowski	Mechanical	USA	Varied	20	100*	100*	100*

*and ** based on data furnished by proponent   *Calculated   **Observed

It is of importance to note that the information in the Table 2 mostly has been gathered from general correspondence with the manufacturer or designer of the splice. Regarding the strengths provided for each of the pile splices, the presented data is dependent on suitable procedures in establishing the splice and close quality control. Data on the strength of the pile splices has been obtained from the experimental tests conducted by Bruce and Hebert (1974), experiences and tests conducted by others, and the theoretical and analytical investigations.

2.2.1 Dowel Splice

In the dowel-type splice, holes are cast or drilled into the top of the lower pile to receive dowel rebars protruding out of the lower end of the upper pile. Dowel rebars can be made of carbon steel as in conventional splicing, or of Stainless Steel (SS), Carbon Fiber Reinforced Polymer (CFRP), or Glass Fiber Reinforced Polymer (GFRP) bars. Grouting/epoxy is used to fill the holes and interface. Despite occasional use of alternate dowel splicing and their apparent corrosion resistance advantages, the understanding of the performance of splices using alternate dowels and comparison with the splices using conventional bars is not adequate. Many investigations have covered the behavior of piles reinforced with alternate prestressing strands and bars, however, experimental and analytical investigation on the splices is scarce. In the lower section of the piles at splice location, the dowel bars need to cover a sufficient anchorage length (Navaratnarajah 1981). Based on drawings by Transport Roads and Maritime Services of New South Wales (2012), at the joint location, a splice sleeve needs to be used that is made of hot-dip galvanized steel (Figure 15). And, the lower edge of the splice sleeves needs to be sealed against pile. Alternatively, plywood pieces can be used to build a dam around the lower pile segment to contain the epoxy.

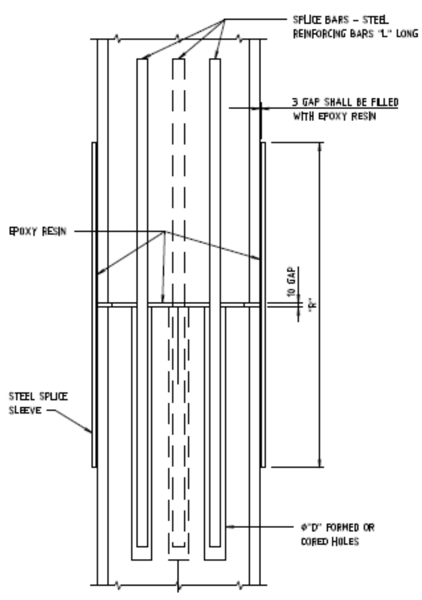

Figure 15: Galvanized sleeve at splice location

2.2.1.1 *Filler or bonding material*

Different types of resin and cement can be used as filler and bonding material to connect the two segments of pile at the splice. In precast prestressed concrete pile splice, epoxy is commonly used to fill the interface and sockets of the lower segment so that the dowel bars of the upper segment can be fully enveloped with the epoxy. The curing time for the epoxy can be accelerated with heating methods such as enclosing the joint with a steam jacket (Navaratnarajah 1981). Moreover, dowel splice using cement filler like Florok Plasticized Cement, manufactured by the Chargar Corporation of Hamden, Connecticut, has been studied by Bruce and Hebert (1974). CONCRESIVE® 1420 (currently known as MasterEmaco ADH® 1420) as a general-purpose gel epoxy adhesive has been used in prestressed concrete piles spliced with steel pipes investigated by Canner (2005). The investigation found, for the splice mating surface, CONCRESIVE® 1420 seemed to be the best product because of its high strength and ability to seal the mating surface, initially. However, in the field test, the plan for using CONCRESIVE® 1420 general purpose gel epoxy adhesive changed because the product was inconveniently supplied in two-part tubes with a mixing gun to apply it. The proper and more convenient way to apply the epoxy is to be able to mix them in larger containers and pour large volumes quickly to avoid setting of the epoxy before completion of the process. FDOT is frequently faced with the same problem of short setting time of epoxy adhesive in epoxy dowel splice projects (Canner 2005). It is also realized that some cement and resin materials that are very effective in anchoring dowels may require an excessive setting time, and vice versa. This motivates consideration of other filler material for establishing effective dowel anchorage within an acceptable setting and hardening time frame.

Among epoxy products available in the market, SEALBOND PILE SPLICING EPOXY (458-PE) is a two-component fast setting epoxy designed primarily for bonding concrete piles (Seal bond Chemicals 2019). The cured resin provides high compressive and flexural strength to the joint when used with fine aggregates as filler. EPIWELD® 580 (2011) is another epoxy product that has been used as filler for pile splices mixed with sandblasting sand 16-40.

2.2.1.2 *Dowel*

According to drawings by Transport Roads and Maritime Services of New South Wales (2012), dowels can be made of steel reinforcing bars, grade D500 to AS/NZS 4671. Apart from the conventional splicing dowels, Stainless Steel (SS) rebars, Carbon Fiber Reinforced Polymer (CFRP) bars, and Glass Fiber Reinforced Polymer (GFRP) bars are other alternatives for dowels. FDOT Standard Drawings Index Series 455 (455-002) include details and designs for conventional steel, CRFP and SS dowels (455-102), but does not cover GFRP dowel application.

Following describes some of the features of dowel splice details prescribed in these drawings for 18x18 in. square drivable prestressed precast concrete pile. For a conventional dowel splice in 18x18 in. pile, 8 No. 10 dowel bars are used. Three bars are used on each face spaced 3 ½ in. center to center at an edge distance of 5 ½ in. on center from the sides of the pile section. These dowels are cast in the upper pile segment (pile extension) for a length of 10'- 6". For unforeseen splice detail, dowels extension is projected out of the top segment (pile extension) only by 2'-6", whereas for preplanned splice detail, this extension length is 4'. For the case of preplanned splices, a set of 8 No. 9 bars, 10'-6" long are cast in the lower pile segment as auxiliary reinforcement. Spiral ties of W3.4 is used along the pile segments in accordance with the standard requirements of the prestressed precast concrete piles with smaller 1" pitch for 5 turns followed by 3" pitch for 16 turns and 6" pitch afterwards from both ends. For CFRP and SS dowel types, the FDOT Standard Drawings Series 455 details for SS dowels are identical to the conventional splices with SS dowel bars replacing the conventional bars at the same size and lengths. However, for CFRP dowel splices, 9 No. 6 CFRP bars are used as dowels, 3 on each side and one at the center, with the same spacing and edge distance as the conventional dowels. Also, the length cast in the upper pile segment is shorter for CFRP at 4' 6" for both unforeseen and preplanned splices. Dowel bar extension length from the upper segment for CFRP dowels is the same as conventional dowel for unforeseen splices (2'-6") and is slightly (6") longer than conventional dowel for preplanned splices at 4'-6". According to these drawings, auxiliary bars are not used in the lower pile segment for the case of CFRP dowel splices in CRFP prestressed pile option. Spiral ties of 0.2" diameter CFRP strand are used for piles with CFRP detail with the same spacing and pitches as conventional piles.

One of the major goals in this study is to investigate the performance of the different types of dowel bars for splicing prestressed precast concrete piles. The conventional carbon steel reinforcing bars are corroded when salts penetrate through concrete (and contaminations present in the material) and form electrochemical reactions resulting in corrosion inside the pile which induce high tensile stresses in the surrounding concrete causing cracking and spalling, and therefore higher exposure. Apart from salts, the variation of temperature, freezing and thawing are other sources for degrading the concrete (Iskander 2002). GFRP bars are expected to provide a more economic option to other corrosion resistant dowel materials.

Dowels made of carbon steel reinforcing bars have low durability and high maintenance cost because of high potential of degradation due to corrosion. Therefore, taking advantage of corrosion resistant materials for dowels (SS, CFRP) in pile construction has attracted attention of researchers and manufacturers as a practical alternative. Although the cost of using these advanced materials for foundation is greater than conventional carbon steel, it is a relatively small percentage of the overall cost of the bridge. In this study, the use of GFRP dowel bars as replacement for SS and CFRP dowels for epoxy splice for prestressed precast concrete piles will be investigated.

2.2.1.3 *Experimental Investigations*

With reference to the literature review carried out by Bruce and Hebert (1974), it has been concluded that the cement-dowel splice (using Florok Plasticized Cement manufactured by Chargar Corporation of Hamden, Connecticut) is effective and acceptable for splicing precast prestressed concrete piles. This plasticized cement is a fast-setting material allowing pile driving to resume within 15 minutes (Bruce and Hebert, 1974). Figure 16 shows the details and fabrication of the pile splices used by Bruce and Hebert (1974) in accordance with Louisiana Department of Highways specifications.

Bruce and Hebert (1974) selected cement-dowel splice for an actual test to evaluate the performance of the pile splice under field conditions and the structural capacity of the splice. For the experimental test, six prestressed concrete specimens grouped in two series of “A” and “B,” were fabricated by them. Series A and B were comprised of three 14-in. (35.6 cm) piles, and of three 24-in. (61 cm) piles, respectively. All of the pile splices were manufactured in square shape. Table 3 shows the arrangement for section and length of each pile splice.

Table 3: Size information for six tested pile splices (Bruce and Hebert, 1974)

Pile	Size Square Pile		Length					
			Bottom Section		Top Section		Total	
	in.	cm.	ft.	m.	ft.	m.	ft.	m.
A-1	14	35.6	45	13.7	15	4.6	60	18.3
A-2	14	35.6	45	13.7	15	4.6	60	18.3
A-3	14	35.6	40	12.2	38	11.6	78	23.8
B-1	24	61.0	45	13.7	35	10.7	80	24.4
B-2	24	61.0	45	13.7	35	10.7	80	24.4
B-3	24	61.0	40	12.2	20	6.1	60	18.3

For the field tests, firstly, the bottom sections of piles were driven and seated firmly in the soil. Then, the top sections were spliced to the bottom sections. Tensile capacity for Pile A-1 and flexural capacity for the remaining five piles were tested, respectively. Un-spliced pile specimens were used as control cases in the experimental evaluation, and the loads-deflections data was recorded for both spliced and un-spliced sections in the tests to failure. Bruce and Hebert (1974) stated there was no visible damage to the pile splices throughout all of the driving operations, and results of the tensile and flexure tests were considered to be favorable. They mentioned that the pile splice number A-1 withstood a tensile pull of 60 tons (54,431 kg) up to bond failure between two sections of the pile where the dowels of the top section pulled out of the bottom section. Apart from that, the splice withstood tensile forces and ultimate moments comparable to 40 percent of the cracking tensile load and 65 to 100 percent of the flexural cracking moments of the un-spliced pile, respectively.

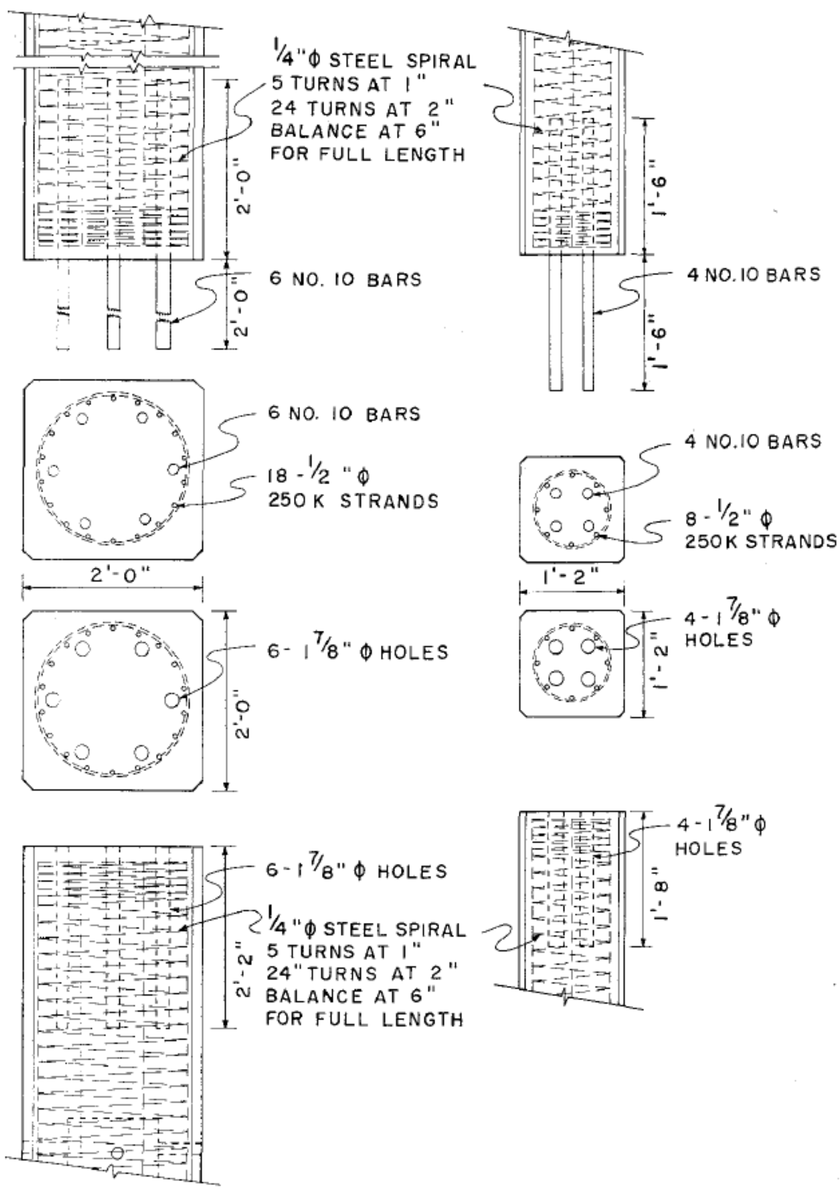

Figure 16: Details of cement-dowel splice

As it is shown in Figure 17, load-deflection measurements also were carried out by Bruce and Hebert (1974) to conclude that the spliced sections for cement-dowel pile splice are more flexible than the un-spliced sections.

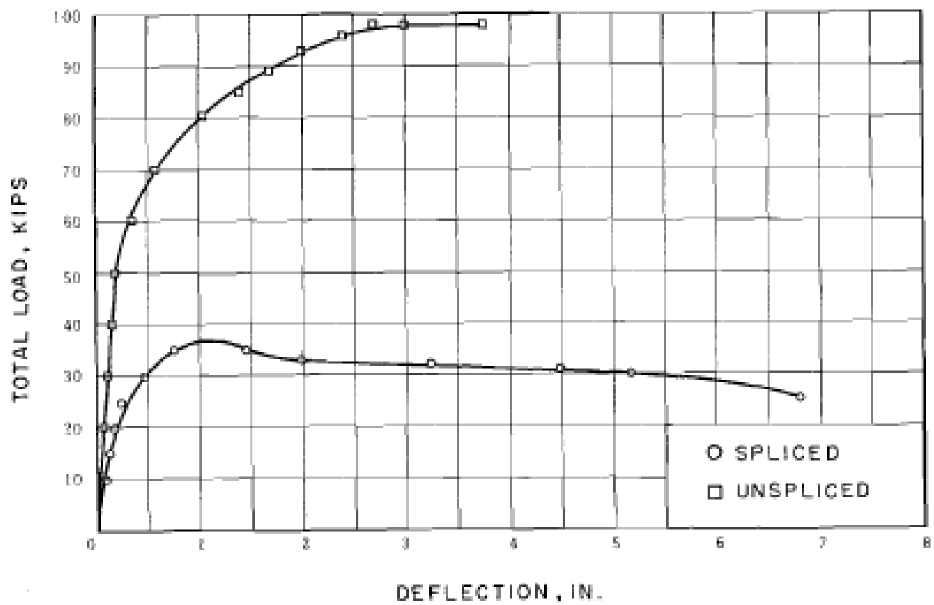

Figure 17: load deflection analysis of spliced and nonspliced pile

Figure 18 shows the details of the tests on epoxy pile splice performed by Navaratnarajah (1981). In this figure, the parameters of L, HT, HY, and MS are the length of pile varied 9m -18m (~30-60 ft) , high tension, high yield, mild steel (all dimensions in mm), respectively. The piles were prestressed with 16 ×7 mm (~ 0.6 × 0.3 in) diameter high-tensile (strength) wires arranged in a 300 mm (~ 12 in) diameter circular pattern. The secondary reinforcement was comprised of 6 mm (~ 0.2 in) diameter mild steel spirals at a pitch of 150 mm (~ 6 in) . In addition, for reinforcing at the pile ends, 4×20 mm (~0.2 ×0.8 in) mild steel bars were used extending, in length, 900 mm (~36 in) into the pile with closer spacing of the secondary reinforcement spirals at a pitch of 25 mm (~1 in) over 300 mm (~12 in) from the end. At the joining sections, the upper section used four 25 mm (~1 in) high yield deformed bars 1.2 m (~ 4 ft) long as dowels, and the other section used four holes with 32 mm (~1.3 in) diameter corrugated sheaths to receive the dowels. The holes were deeper than the length of dowels for better fit.

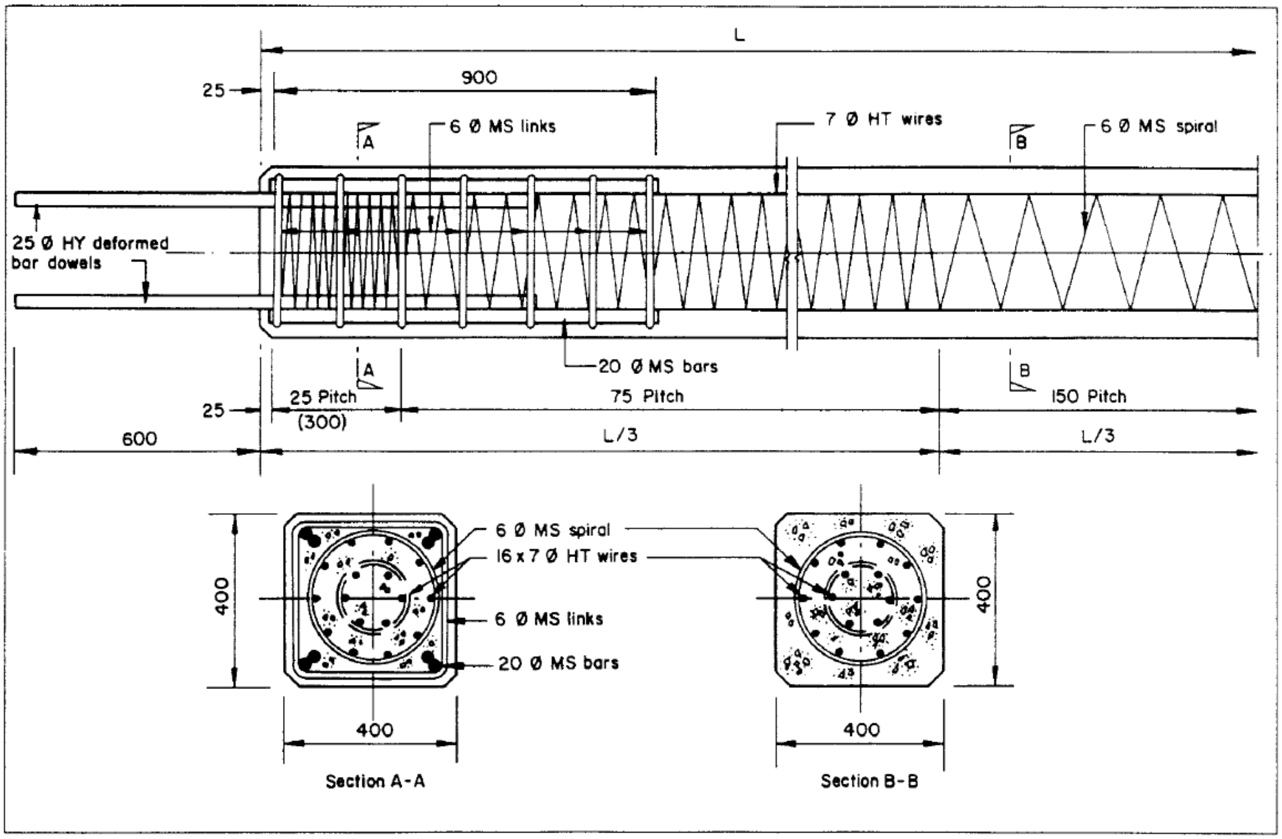

Figure 18: Details of test piles (Navaratnarajah 1981)

For establishing the pile splice, the bottom segment of the pile was held in a vertical position and the top segment including dowels projecting at the tip was positioned over the holes in the bottom segment. The detail of this epoxy dowel splice is shown in Figure 19. The sockets were filled with a proprietary brand two-part epoxy.

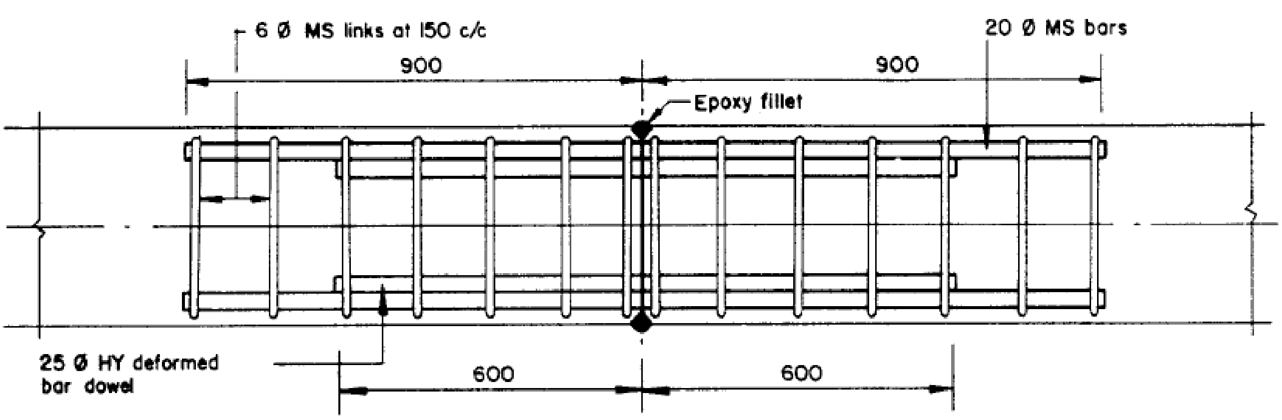

Figure 19: Details of epoxy splice (Navaratnarajah 1981) - dimensions all in mm (25.4 mm = 1 in.)

Figure 20 shows experimental set-up used by Navaratnarajah's for the epoxy dowel spliced prestressed precast pile. The pile was supported on a rocker and roller support at the two ends, respectively, over a span of 5.4 m (~ 213 in) . A steel spreader beam was used to apply the loads in increments of 1000 kg. (~ 2205 lb) For measuring the deflection of the pile, a steel indicator was vertically fixed to the center of the span so that observations can be made with a telescope focused on the indicator. Five dial gauges (Dl, D2, D3, D4 and Ds) were also set against the bottom of the pile at 900 mm (~ 36 in) intervals to record the deflected shape of the pile at different loading steps.

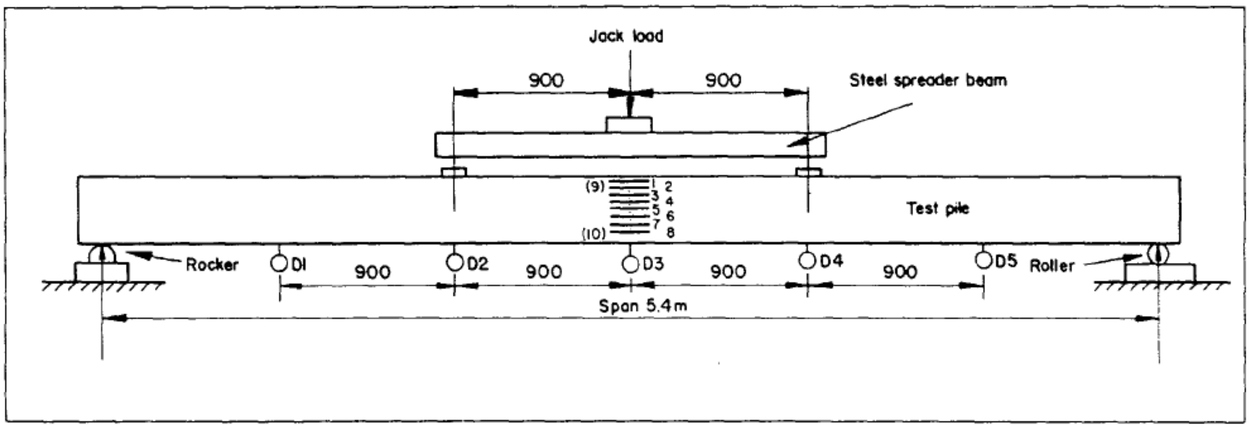

Figure 20: Experimental set-up (Navaratnarajah 1981) - dimensions in m/mm (25.4 mm = 1 in.)

In the experimental test, the first crack was noticed outside the joint and the maximum size of crack was recorded to be 4.0 mm (~ 0.16 in) (Figure 21). According to Navaratnarajah, the epoxy dowel splice pile failed as a result of the pull-out of the dowel bar due to local shear effects at the location of termination of the dowel rebars.

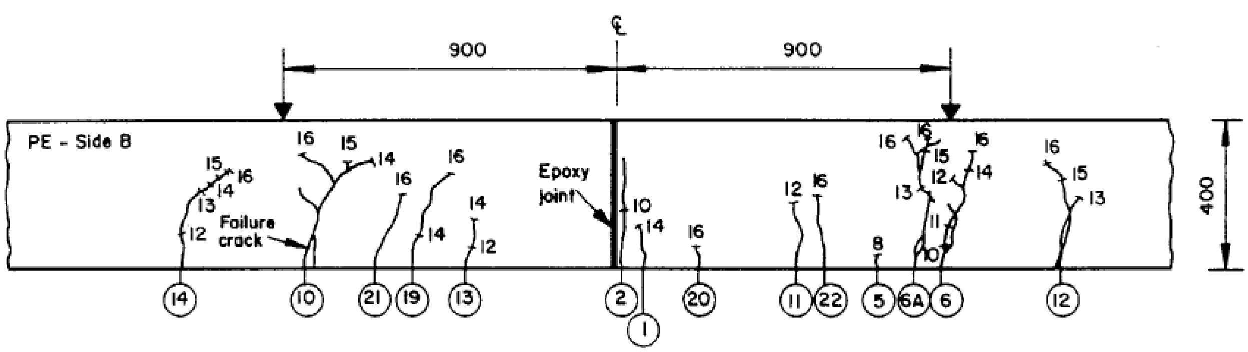

Figure 21: Cracking pattern in the epoxy-jointed pile (Navaratnarajah 1981) - dimensions all in mm (25.4 mm = 1 in.)

The flexural behavior of an epoxy dowel splice for precast prestressed concrete pile with a 400 ×400 mm (~16 ×16 in) cross-section and concrete strength of 45 N/mm^2 (~ 6527 psi) at 28 days was compared with the performance of an un-spliced pile and welded- joint pile. Figure 22 shows the load-deflection of three tested specimens at the center of the span or at the location of the splice. The results show that the pile using the epoxy joint failed at a higher ultimate load compared to the unjointed pile. This investigation also proved that the stiffness of the pile with epoxy joint was comparable to un-spliced pile and higher than the welded type.

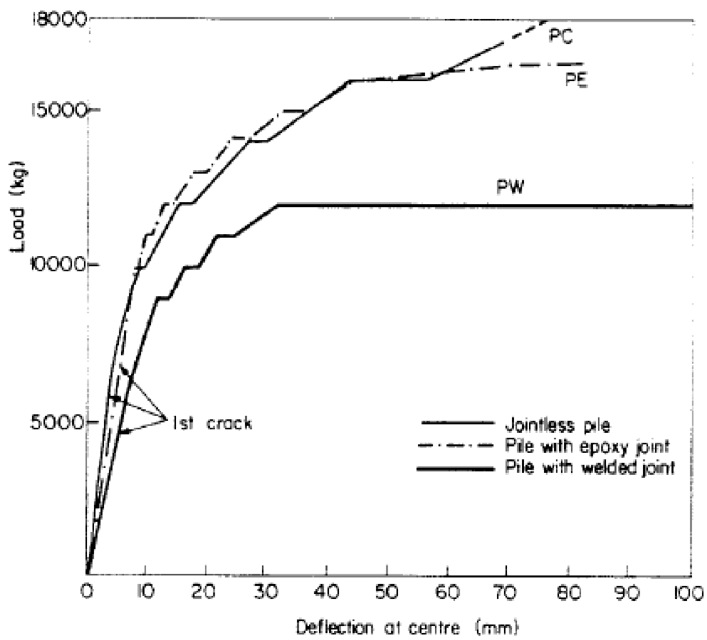

Figure 22: Load/deflection characteristics at the span center of the epoxy-jointed pile (Navaratnarajah 1981) (25.4 mm = 1 in, 1 kgf = 2.2 lbs)

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