Repair of Wood Piles Using Prefabricated Fiber-Reinforced Polymer Composite Shells

Roberto Lopez-Anido, M.ASCE[1]; Antonis P. Michael, S.M.ASCE[2]; Thomas C. Sandford, M.ASCE[3]; and Barry Goodell[4]

Abstract: An effective method for combined environmental protection and structural restoration of wood piles in waterfront facilities is not available. The objective of the study presented in this paper is to survey the available methods for wood pile protection and structural restoration with the intent of developing an effective method. In addition to reviewing the available repair methods, a field inspection of a harbor in Maine was conducted to assess existing technologies. A wood pile repair method that utilizes bonded fiber-reinforced polymer (FRP) composite shells and a grouting material is proposed. Fiber, resin, adhesive, coating, and grouting materials are systematically analyzed to deliver the required system performance. Two fabrication methods for the FRP composite shells are discussed based on the experience gained in the fabrication of laboratory prototypes. Then a step-by-step procedure amenable for field installation is proposed, and a preliminary cost analysis is conducted to assess the feasibility of the proposed system.

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Introduction

Scope and Objective

No effective method for both protection and structural restoration of wood piles in waterfront facilities is discussed in the literature, nor is such a method available in practice. Understanding the cause and characterizing the extent of wood pile deterioration is the first step in designing a repair method for damaged piles, as well as in devising a protection strategy to prevent further attack from marine organisms (Lopez-Anido et al. 2004c). The objective of the study described in this paper is to survey the available methods for wood pile protection and structural restoration with the intent of developing an effective repair method.

Attaining this objective required both a literature review and a field inspection of a harbor. A wood pile repair method that utilizes fiber-reinforced polymer (FRP) composite prefabricated shells, shear connectors, and grouting material is proposed to address both the protection and the structural restoration needs. This repair system provides shear transfer capability between the wood pile and the encasing FRP composite shells, which strengthens the damaged pile portion (Lopez-Anido et al. 2003, 2004a). The FRP composite repair system can also reduce the rate of future deterioration by introducing a barrier that protects the wood pile from marine borer attack. In this method, prefabricated shells are bonded together in situ with an underwater-curing epoxy adhesive to form the FRP composite shield or jacket that encases the wood pile specimen. The performance of the underwater-curing epoxy after exposure to freezing and thawing cycles was investigated (Lopez-Anido et al. 2004b).

Two fabrication methods for the FRP composite shells are presented and compared based on the experience gained fabricating laboratory prototypes. Then a step-by-step procedure amenable for field installation is proposed, and a preliminary cost analysis is conducted to assess the feasibility of the proposed system.

Background

Marine borers cause extensive damage to wood piles used to support piers, marinas, or other waterfront structures, and in many cases replacement of these piles has been the only alternative (Goodell et al. 2003; Lopez-Anido et al. 2004c). Preservative treatments prolong the life of wood piles for many years and have previously been used extensively to protect piles in wooden waterfront structures. However, environmental concerns regarding the preservatives used for this purpose have resulted in restrictions on their use.

For this reason some states, such as Maine, have effectively banned the use of creosote in marine waters. Creosote has been one of the most common and effective preservatives used for the protection of wood piles from marine borers. The lack of an effective preservative to protect against marine degradation has aggravated the problem of wood pile deterioration. Another preservative chemical used in wood piles, chromated copper arsenate (CCA), contains heavy metals, and questions have been raised

[1]Associate Professor, Dept. of Civil and Environmental Engineering and Advanced Engineered Wood Composites Center, Univ. of Maine, Orono, ME 04469-5711 (corresponding author). E-mail: RLA@maine.edu

[2]Graduate Research Assistant, Civil and Coastal Engineering Dept., Univ. of Florida, Gainesville, FL.

[3]Associate Professor, Dept. of Civil and Environmental Engineering, Univ. of Maine, Orono, ME.

[4]Professor, Wood Science and Technology and Advanced Engineered Wood Composites Center, Univ. of Maine, Orono, ME.

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about its hazard to human health. The federal government has recently placed restrictions regarding the use of CCA preservative in residential applications, and some states have banned its use for noncommercial applications entirely. Some marina owners and state department of transportation officials have also expressed concern over the use of CCA-treated piles because of perceived brittleness of the pile after treatment. A study on CCA leaching of treated wood piles in seawater and fresh water estimated the long-term release of chemical elements (Lebow et al. 1999).

The service life of deteriorated marine wood piles can be prolonged in some instances by repairing the piles. Repair methods include encasing the damaged wood pile with some type of jacket or sheeting (e.g., plastic, steel, or concrete) or removing the damaged portion and replacing it with a new piece that is spliced with the old wood pile. For example, a method for repairing damaged creosote-treated wood piles using a wire-mesh reinforced shotcrete jacket has been proposed (Chellis 1961). A method for ground repair of wood poles has also been presented that involves screwing a metal sleeve around the base of the pole and filling the space between the sleeve and the pole with aggregates and resin (Douglas 1986; Shepard 1987).

The Unified Facilities Criteria (UFC) handbook for operation and maintenance of waterfront facilities presents six repair methods for damaged wood piles (USACE 2001). The first method discusses protection of wood piles by wrapping them with polyvinyl chloride or polyethylene wraps. A second method proposes partial posting of a damaged wood pile by joining a new pile butt with bolted pretreated timber fish plates. The third method discusses repair of wood piles by concrete encasement. Two types of concrete forms can be used: (1) flexible forms (sea form fabric form), and (2) split fiberboard forms. These forms have no structural significance but are used to keep the concrete contained until it hardens. The fourth method addresses the repair or retrofit of timber piles with an underwater-curing epoxy and fiber-reinforced wraps in which the fabrics are saturated with the epoxy and then applied to the wood pile. The fifth repair strategy considers replacement of the damaged wood pile with a new wood pile. Finally, the sixth repair strategy proposes replacing the damaged wood pile with a new concrete pile.

Available Methods for Protection of Wood Piles

One strategy for protection of wood piles from marine borer attack is encasing new piles with a plastic wrap or jacket (Baileys 1995; U.S. Navy 1987). Most of the available methods are suitable only for protection and provide no structural restoration capabilities, and therefore, can only be used to protect new piles or piles with minimal damage and adequate structural properties. Master Builders, Inc., of Cleveland, Ohio, developed a process (APE, advanced pile encapsulation) for protection of piles, risers, jackets, and other marine structures. This method employs a molded fiberglass outer jacket that is used as a form for containing the grout. The grout used in this process is an aggregate epoxy mix that is pumped through injection ports from the bottom of the form (ADCI 1996; Master Builders 2001). This method uses an epoxy grout that is usually expensive and a nonstructural fiberglass jacket that is expensive and offers no structural restoration.

Tapecoat Company, of Evanston, Illinois, has developed a modular encapsulation system that provides protection to marine structures. The product trade name is TC Enviroshield and the series T is used for wood piles. This system consists of a flexible outer jacket that wraps the pile and restrains the flow of water. The modular encapsulation system is reported to reduce the levels of dissolved oxygen content of the water inside the wrap by preventing the exchange of oxygenated water with that trapped in the jacket. Even though complete water exchange may not be prevented, use of the jacket is believed to kill existing borers in the wood pile and prevent new larval forms from settling on and attacking the pile (ADCI 1996; Tapecoat 2001). This product can only be used to protect structurally sound wood piles, since it cannot restore structural capacity.

Denso North America, of Houston, has also developed a line of products used for protection of wood piles. These include Denso's SeaShield Series 100, which encapsulates the pile and seals out oxygen and water, providing protection from marine borers for timber piles. Denso has also developed jackets that are used as forms for concrete or epoxy encasement to structurally restore wood piles (ADCI 1996; Denso 2000). These jackets and encasements have no structural significance and cannot be used to repair deteriorated wood piles.

Rockwater Manufacturing Corp. has developed a marine pile system for marine borer protection of wood piles that is similar to the other available systems in that it is reported to reduce the oxygen levels of the water inside the wrap. The company also provides fiberglass pile jackets that, when used with underwater grouts, can provide structural support (ADCI 1996; Rockwater 1999). The wraps and fiberglass pile jackets are nonstructural and cannot be used for wood pile restoration.

Osmose Marine, based in Griffin, Georgia, has developed a protection system for marine piles using a polyvinyl chloride (PVC) wrap with the trade name Pile-Gard, which has been described as producing an airtight seal. This product, which reportedly limits the oxygen supply to marine borers, was invented in the 1950s (U.S. Patent No. 3, 321, 924) and therefore has a long history of protecting piles (Liddell 1967; ADCI 1996; Osmose 2001). This method can only be used to protect undamaged wood piles or wood piles that have adequate structural capacity, since the method does not provide structural restoration.

Available Methods for Structural Restoration of Wood Piles

Hardcore Composites of New Castle, Delaware, has developed a method with the trade name Hardshell System, which is reported to protect as well as repair and restore timber piles. This system uses E-glass/vinyl ester composite shells fabricated by the vacuum-assisted resin transfer molding (VARTM) process. The shells are manufactured in two halves joined by using bonded H connectors. The H connector is a female-male type of connector in which one of the half shells has the female end and the other acts as the male. Adhesive is applied to the female portion of the seam, and straps are used to hold the two pieces together until the adhesive cures and the grout is pumped (Hardcore 1999, 2000). The fact that the bond area of the H connector is relatively small raises doubts about the ability of the system to provide structural continuity in the circumferential direction.

The second company with a system that rehabilitates wood piles is Fyfe Co. LLC, also known as the Fiberwrap Company, based in San Diego. This repair method uses a fabric reinforcement that is wrapped around the pile and then impregnated underwater with an epoxy resin providing a barrier against marine borers (Fyfe 1998). Since the fabric reinforcement impregnation is performed underwater, after the epoxy cures, the portion that is repaired is sealed from the surrounding environment. Impregnation of the fabric reinforcement underwater is difficult to execute

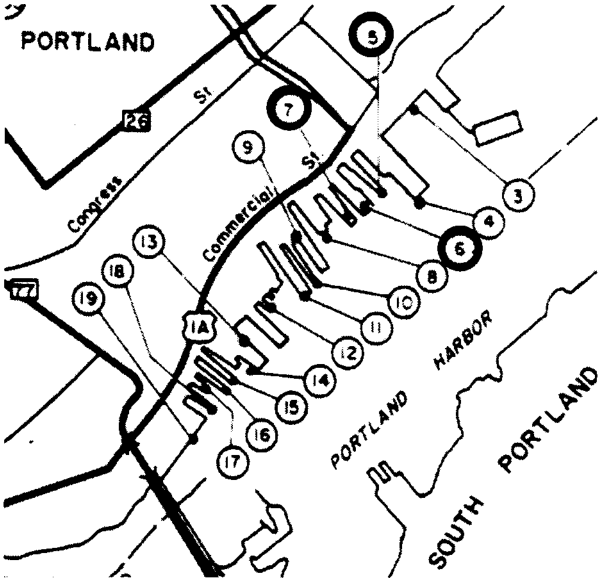

Fig. 1. Piers inspected in Portland Harbor, adapted from Maine DOT (1986)

and monitor. Even if the fibers are impregnated before they are introduced into the water, the resin may not cure properly.

Assessment of Existing Wood Pile Repair Methods in Portland Harbor, Maine

A harbor on the Northeast coast of the United States, a region where wood piles traditionally have been used, was selected to conduct a case study. The condition of structural wood piles repaired using various methods in Portland Harbor piers was determined by visual inspection in May 2000. The objective of the inspection was to assess methods currently used to repair damaged wood piles. Wood pile repair methods in three piers—Portland Pier (7), Custom House Wharf (6), and Maine Wharf (5)—were inspected during low tide, as depicted in Fig. 1. The Portland Pier had a timber-retaining wall with solid fill, wood piles, and a wood deck supporting a parking lot (Maine DOT 1986). The Custom House Wharf had an earth-filled pier structure with wooden timber and a steel crib bulkhead, wood piles, and an asphalt-paved wood deck; several marine-related businesses were operating on the pier (Maine DOT 1986). The Maine Wharf pier had wood piles with a concrete deck (Maine DOT 1986).

Inspection of Portland Pier

The wood pile repair method used in this pier consisted of a corrugated (profile wall) high-density polyethylene (HDPE) pipe encasing [Fig. 2(a)]. The corrugated HDPE pipe was split into two halves that were placed around the wood pile and held together with circumferential metal straps. The metal straps were spaced approximately 910 to 1,220 mm apart, and the space between the wood pile and the corrugated HDPE pipe was grouted with unreinforced concrete. Typical dimensions of the corrugated HDPE pipe used were 686 mm for the external diameter and 584 mm for the internal diameter. The thickness of the corrugated profile wall was 51 mm. Several problems with this repair method were observed in individual piles: (1) The steel straps were damaged and severed, and the corrugated HDPE pipe halves were

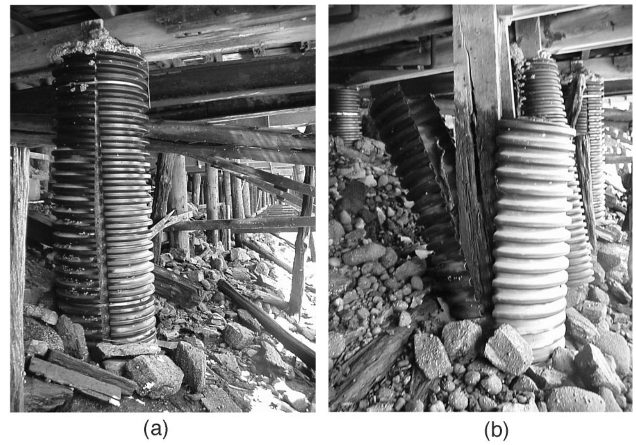

Fig. 2. Repair method using corrugated HDPE pipe encasing: (a) repaired wood pile; and (b) failure of HDPE pipe encasing

opened as shown in Fig. 2(b); (2) wood damage was observed at pile sections above the repaired area; (3) the concrete fill was deteriorated and disintegrated with relatively little effort; and (4) at the opened joint of the corrugated HDPE pipe, the concrete was spalling and exposing the interior wood pile.

Inspection of Custom House Wharf

Previous attempts to repair damaged wood piles were made on this pier as well, and the same repair method was used as at Portland Pier. However, some of the corrugated HDPE pipes were installed as a continuous section around the piles and not as two halves. This implied that the old pile was probably cut off and a new portion connected to the stub of the old pile. The corrugated HDPE pipe was then secured in place and grouted with concrete. The use of a continuous corrugated HDPE pipe eliminated the problem of concrete spalling observed at the joints. The wood piles at this structure were of smaller size and therefore a smaller size corrugated HDPE pipe was used (exterior diameter 533 mm, interior diameter 457 mm, and corrugated wall thickness 38 mm). According to one of the workers at a commercial facility on the pier, the wood pile repairs were performed 2 years earlier.

Another type of wood pile repair method observed was splicing. In this method the top portion of the old damaged pile was removed and a new wood pile portion was spliced using steel bolts, as shown in Fig. 3. For a wood pile with an approximate diameter of 254 mm, the steel bolts were spaced 203 mm apart. A

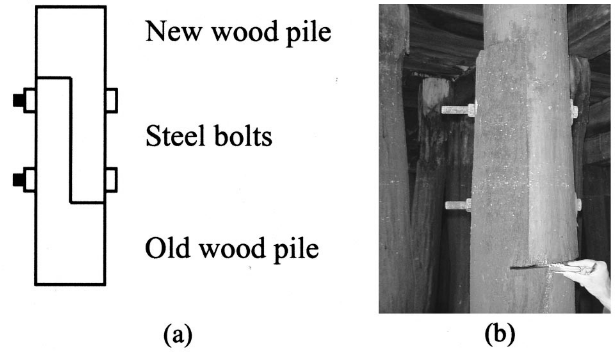

Fig. 3. Splicing of wood piles with steel bolts

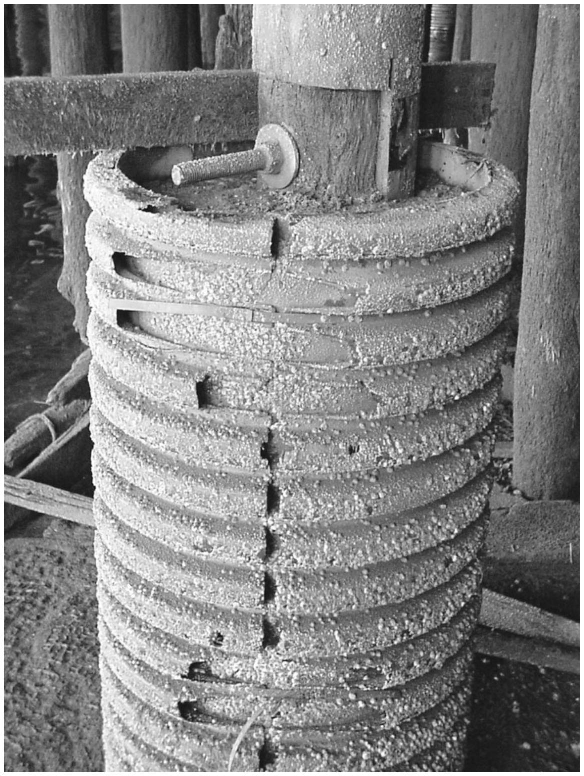

Fig. 4. Repair method using HDPE pipe encasing and splicing with steel bolts

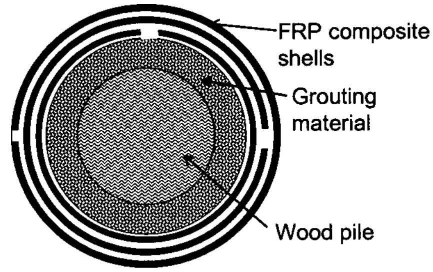

Fig. 5. Cross section of wood pile repaired with fiber-reinforced polymer composite shells

problem observed in the splices was a gap between the horizontal surfaces of the two wood pile portions, which does not allow for proper vertical load transfer by bearing. The splice also exposes the untreated center of the wood pile as pressure preservative treatments rarely extend all the way to the center of the impermeable heartwood region of a pile. In areas where gaps occurred in the splice, shipworm larvae could enter and attack the untreated wood.

Inspection of Maine Wharf

At the Maine Wharf, repair methods were also applied to several damaged wood piles. Several piles were repaired using splicing, as shown in Fig. 3(b). Corrugated HDPE pipes were also used at this facility. The pipes were placed around the pile in two halves and metal straps were used to hold them together. At the vertical joints metal plates were used to close the gap and contain the concrete. The concrete was in good condition. A combination of corrugated HDPE pipes and the splicing method with steel bolts was observed. Part of the splice length was buried in concrete and part was exposed, as shown in Fig. 4.

Proposed Repair Method Using Fiber-Reinforced Polymer Composite Shells

The available protection or restoration methods have limited applicability in most cases. Plastic wraps can protect against marine borers in some cases but cannot be used to restore structural capacity. Steel jackets can corrode, especially in the marine environment, and concrete encasement can develop problems with spalling. Fiber-reinforced composite jackets installed in halves with an H connector have bonded longitudinal joints, that may limit the ability of the pile encasement to deliver circumferential confinement. On the other hand, application of wet fabric reinforcement underwater can be difficult, and proper curing of the resin may not be achieved.

The wood pile repair method proposed in this paper utilizes an FRP composite encasement or shield that encapsulates and splices the deteriorated portion of the pile. The encasement was developed based on experience with appropriate technologies in the structural FRP composites field (Kshirsagar et al. 2000; Lopez-Anido and Karbhari 2000; Lopez-Anido et al. 2000; Lopez-Anido and Xu 2002) combined with the needs for wood pile protection and strengthening observed in the field inspection, survey, and literature review. The shield is made of bonded thin and flexible FRP composite prefabricated cylindrical shells that deliver the required strength to repair damaged wood piles. The shells are fabricated in a quality-controlled composites manufacturing facility. The cylindrical shells have a slit or opening along their length, which enables them to be opened and placed around the deteriorated wood pile. Since it is advantageous to encase the pile with a series of overlapping shells, the minimum number of FRP composite shells required is two; however, additional shells can be added, depending on the structural restoration needs. The slit in each cylindrical shell is staggered to avoid lines of weakness through the entire shield (Fig. 5).

In the proposed repair method, the space between the FRP composite shield and the wood pile is filled with a grouting material that does not provide a structural bond with the wood pile, but rather provides interlocking (friction) between the wood pile and the FRP composite shells. Since the grout is not expected to completely seal the wood core, seawater saturates the pile, creating a layer of stagnant water, potentially limiting the oxygen supply. Assuming a lack of oxygen, marine borers already inside the wood pile would be expected to die and new borers would be prevented from attacking the wood pile. A schematic of the proposed repair system is depicted in Fig. 6.

FRP composite shells need to be driven 0.3 to 0.6 m below the mud line to avoid secondary attack by marine borers; extending the FRP composite shells 0.6 m above the high-water level could prevent secondary attack by marine borers in the splash zone (Baileys 1995; Chellis 1961). However, caution should be exercised in extending the shell too far above the water line, as encapsulating the pile above the high-water line can trap fresh water in this zone. If the wood stays continually wet, the unprotected core and other poorly protected areas may then be subjected to more aggressive attack by decay fungi than would normally occur. The proposed structural restoration method utilizes the undamaged zone of the existing wood pile by encasing and splicing the damaged portion plus the required development length to en-

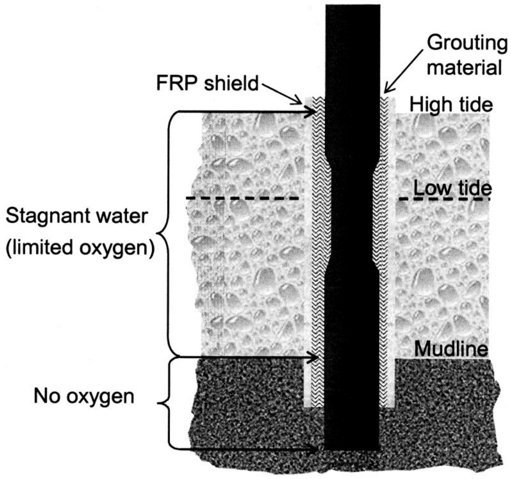

Fig. 6. Schematic of wood pile repair with fiber-reinforced polymer composite shells

sure reinforcement integrity (that is, partial length reinforcement of the pile).

Material Section—Prototype Development

Fiber-Reinforced Polymer Composite Shell

A unidirectional woven fabric (style VEW 260) (BTI 2000) with unit area weight of 880 g/m^2 was selected as the primary continuous reinforcement. The fabric reinforcement is provided by the manufacturer in rolls with a width of 1.22 m and an approximate weight of 105 kg. This type of fabric reinforcement was selected due to its adaptable directional properties (for example, continuous fiber reinforcement in selected orientations), ease of fabrication (for example, cutting and placement), and cost competitiveness. The number of fabric reinforcement layers in the longitudinal (axial) and hoop (circumferential) directions was selected based on the design loads and the extent of damage, and therefore the stresses imposed on the part. In addition, E-glass fiber chopped strand mat (CSM) with a unit area weight of 305 g/m^2 was used as secondary noncontinuous and randomly oriented reinforcement.

The proposed fiber architecture for the FRP composite shell consists of three layers of unidirectional continuous fabric reinforcement in the longitudinal direction (0°), one layer of unidirectional continuous fabric reinforcement in the hoop direction (90°), and two outer CSM layers (Fig. 7). The intent is to fabricate the final FRP composite shield from these shells in place on the pile using adhesive to bond the shells together. This is done because the individual shells have the required compliance to be opened wide enough along the seam to fit around the wood pile. The elastic nature of the shell would then allow it to return to its original fabrication dimensions. This design also allows the seams to be oriented so that overlapping of seams does not occur.

The fiber architecture design is based on maximizing fiber reinforcement in the axial direction with a minimum amount of fibers oriented in the hoop direction. Axial fiber reinforcement contributes to both the bending and axial stiffness and strength of the shell, which is required to splice the damaged portion of the wood pile. Hoop fiber reinforcement provides adequate integrity to the flexible shell, allowing the required shear strength and mechanical fastener support to be developed. One CSM layer is placed on each face of the shell laminate to provide improved bonding to the substrate and to develop a resin-rich area for environmental protection. The resulting laminate layup of the FRP composite shell is [CSM/0/90/0/0/CSM].

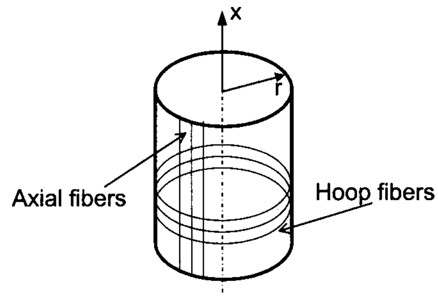

Fig. 7. Fiber reinforcement of fiber-reinforced polymer composite shell

A low-viscosity, epoxy-based vinyl ester resin, Derakane 411-C50, was selected as the matrix for the composite shells (Dow 1999). The epoxy-based vinyl ester resin was selected because of its high flexibility and impact resistance, its lower cost compared to other resin systems such as epoxies, and its good performance in harsh marine environments. This resin has a viscosity of 0.15 Pascal seconds (150 centipoise) and is well suited for resin infusion molding. The design outlined provides for high flexibility and impact resistance to allow the manufactured part to easily absorb impact loads from approaching vessels.

Grouting Systems

The criteria used to select the grouting system were (1) ability to be applied underwater, (2) pumping ability, (3) minimal shrinkage, (4) commercial availability, and (5) cost competitiveness. Research conducted on concrete columns suggested that the grout material used has fewer voids when pumped from the bottom rather than dropped from the top (Snow 1995). Two different types of grouting systems were selected and evaluated: (1) cement-based structural grout, and (2) expanding polyurethane chemical grout.

The cement-based grout can be pumped in place using conventional concrete pumps and cures underwater (Five Star 2001). This grout has minimal shrinkage and high compressive strength at early stages. The typical one-day compressive strength of this material at 23°C is 35 MPa, while at 28 days it reaches compressive strengths up to 52 MPa.

The expanding polyurethane chemical grout is a two-part material system: component A is the polyurethane, and component B is an accelerator (Sika 1998). This grout is a fluent material and can be easily pumped to place. The curing reaction is triggered when the grout comes in contact with moisture with less than 1 h curing time. The polyurethane grout system results in a flexible layer with high-energy absorption capabilities, but the polyurethane grout does not have any significant compression or bearing strength and therefore is nonstructural. The cost of polyurethane grout is relatively high compared to cement-based grout.

Shear Connectors

Shear connectors (steel-threaded rods) can be used to transfer shear forces between the FRP composite shield and the wood pile

(Lopez-Anido et al. 2004c). For example, four steel-threaded rods with a diameter of 19 mm were used at each end of the FRP composite shields as shear connectors to repair wood piles (Lopez-Anido et al. 2003). The steel-threaded rods were spaced along the pile axis at approximately 102 mm intervals and rotated approximately 30° in the circumferential direction. When a polyurethane chemical grout is used in wood pile strengthening, then shear connectors are required to develop the structural capacity of the FRP composite shield. For the cement-based grout, metal shear connectors are not required.

Underwater-Curing Adhesive

An underwater-curing adhesive is required to bond the FRP composite shells together and provide composite action. The selection criteria for the adhesive were (1) ability to cure underwater, (2) ability to be applied underwater, (3) ability to bond well to vinyl ester composites, and (4) durability in waterfront environments (Lopez-Anido et al. 2004b). The adhesive selected is an underwater-curing two-part epoxy adhesive. Part A is the epoxy resin and Part B is the hardener (Superior 2000). Part A, which is modified bisphenol-A polyglycidyl ether, is a viscous light amber liquid with mild odor that comes in various consistencies. Part B, which is a modified polyamine, is a viscous liquid with a fishy odor and comes in various colors and consistencies. Blue color was selected for the pile repair application because it is visible through the FRP composite shells and therefore would make it possible to visually inspect the adhesive spread area between shells. A paste consistency applied with a trowel is recommended for underwater applications. In the laboratory prototypes, the adhesive was applied around the circumference and along the length of the FRP composite cylindrical shells covering all the contact area between two shells.

Polymer Concrete Coating

A polymer concrete coating or overlay is required to develop friction between the FRP composite shell and the cement-based structural grout. The polymer concrete selected is a two-component, low-modulus polysulphide epoxy-based wearing course (TRANSPO 2000). Components A (resin) and B (hardener) are mixed in a 2:1 volume ratio. The selected polymer concrete is an impervious overlay typically used for restoring bridge decks and other pavements and applied with a thickness of 6 to 12 mm (TRANSPO 2000). In the wood pile repair application a polymer concrete layer with a thickness of 3 mm was applied on the interior surface of the innermost shell. First, the epoxy was applied using rollers, and then standard basalt sand was broadcast as the aggregate. The epoxy bonded well to the vinyl ester composite shell. The aggregate created a rough surface, which provided adequate interlocking with the cement-based grout. It was found that the shear strength at the interface between the cement-based grout and the innermost FRP composite shell was significantly increased due to the polymer concrete coating (Lopez-Anido et al. 2004a).

Fabrication of Fiber-Reinforced Polymer Composite Shells

The first manufacturing process used to fabricate the FRP composite cylindrical shells with the longitudinal slit was wet layup with vacuum bagging compaction. In this fabrication process the fabric reinforcement is impregnated with resin, placed on the mold, sealed using a plastic bag, and compacted by drawing a vacuum. The vacuum pressure also removes part of the excess resin from the part into the breeder/bleeder layers. One problem found with this fabrication method is the limited pot life of the resin used; that is, when long shells were manufactured, the resin gelled before all of the fabric reinforcement layers were impregnated. This fabrication process delivered a composite shell with relatively low-fiber volume content and a consolidated thickness of approximately 4.5 mm. The relatively high thickness of the consolidated part presents an obstacle to installation since the cylindrical shell lacks the required flexibility to let one worker open it around a wood pile.

Fig. 8. Dry fabrics and peel ply on PVC mold

To overcome the fabrication problems encountered, a variation of the VARTM process, the licensed Seemann Composites Resin Infusion Process (SCRIMP) (TPI 2001), was selected for fabricating the FRP composite cylindrical shells with the longitudinal slit. A PVC pipe rated for 900 kPa internal pressure was used as a mold or tool. The fabric reinforcement was placed on the cylindrical mold dry (Fig. 8), and then the fabric reinforcement was sealed with a tubular vacuum bag (Fig. 9). Vacuum pressure of −102 kPa was applied with a vacuum pump and resin was infused through a resin pot. The pressure differential between the atmosphere and the applied vacuum allowed infusion of the resin into the fabric reinforcement layup. Once the resin completely impregnated the fiber reinforcement, the vacuum pressure was reduced to −51 kPa until the resin gelled. The vacuum pressure debulked (compacted) the dry fiber reinforcement. After the resin gelled, vacuum pressure was removed and the part was allowed to cure. A cured, partially exposed cylindrical shell is shown in Fig. 10. The FRP composite shell was then removed by pulling open the longitudinal slit.

The VARTM/SCRIMP process produced FRP composite shells with a relatively high fiber volume content and a consolidated thickness of approximately 3.3 mm. The shells fabricated by the VARTM/SCRIMP process had adequate flexibility to be pulled open and placed around the wood pile prototypes.

The FRP composite shields are expected to be exposed to ultraviolet radiation (UV), where the weathering effects are expected to be more important in the piles located on the perimeter of the waterfront facility. Weathering and UV protection of the FRP composite shells can be efficiently attained with a surface layer containing a pigmented gel coat or by incorporating a UV

Fig. 9. Tube vacuum bag placed over system

inhibitor as an additive to the polymer matrix (Haeberle et al. 2002).

Laboratory Prototypes—Fabrication

The feasibility of the repair method was demonstrated in the laboratory by fabricating FRP composite shells and restoring "damaged" wood pile prototypes (Fig. 11). Marine borer damage was simulated by reducing the cross-sectional area of the pile. The space between the wood core and the FRP composite shells was filled with a grouting system. Two different grouting materials were used: (1) portland cement-based (inorganic) structural grout (Fig. 12), and (2) polyurethane-based (organic) nonstructural grout with shear connectors that transfer loads from the wood pile to the FRP composite shells (Fig. 13). Laboratory prototypes were fabricated for two types of experiments: (1) pushout tests by compression loading to characterize the interface response (wood/grout/shear connector/FRP composite) (Lopez-Anido et al. 2004a); and (2) full-size bending tests to characterize the overall structural response (Lopez-Anido et al. 2003).

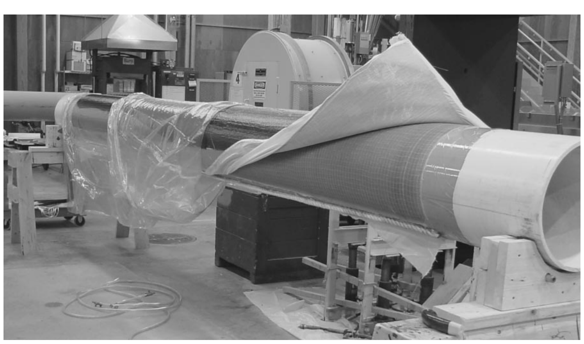

Fig. 10. Demolding of cured fiber-reinforced polymer composite shell

Fig. 11. Application of fiber-reinforced polymer composite shells to predamaged wood pile

Installation Procedure

To implement the repair method in waterfront applications, a possible step-by-step installation procedure was developed and is presented.

Step 1: Clean Existing Wood Pile

Wood piles usually have marine fouling organisms growing on them. Even though achieving good bonding between the grout and the wood core is not expected, cleaning will be helpful. The marine organisms are primarily organic matter, and their presence creates voids in the grout, making it weaker and reducing the interlocking that is required for the repair system to work efficiently. Cleaning can be performed using a water jet without excessive pressure (USACE 2001). Excessive pressure can cause more damage to the already vulnerable wood pile. Cleaning can also be achieved by scraping off the marine organisms with a modified scraper that conforms to the shape of the wood pile (Hardcore 1999).

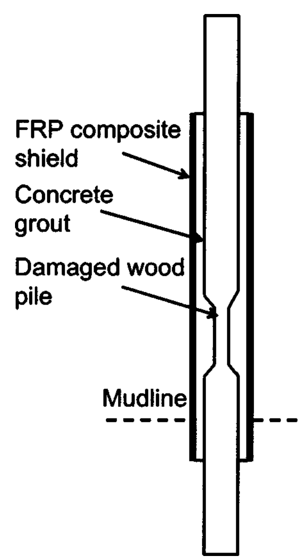

Fig. 12. Fiber-reinforced polymer composite repair system with cement-based grout

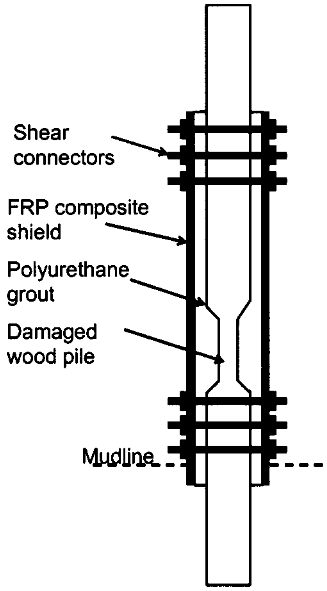

Fig. 13. Fiber-reinforced polymer composite repair system with shear connectors and polyurethane grout

Step 2: Place Shear Connectors at Wood-Grout Interface
If shear connectors, such as lag screws, are required at the wood-grout interface, they must be driven deep enough into the wood pile to be effective. The connectors need to extend as much as the thickness of the grout to serve as spacers.

Step 3: Position First Fiber-Reinforced Polymer Composite Shell Around Wood Pile
The longitudinal slit along the length of the FRP composite shell is opened and the shell is placed around the damaged wood pile.

Step 4: Apply Adhesive on First Shell
A coat of underwater epoxy adhesive is applied on the interior surface of the second shell and on the exterior surface of the first shell, if possible. The use of trowels is recommended to help spread the adhesive.

Step 5: Position Second Shell
The second shell is slid around the first one with the longitudinal slits or gaps staggered (preferably 180°) to avoid lines of weakness. This step is repeated for additional shells staggering the longitudinal slits.

Step 6: Strap Shells Together
It is necessary to use straps or other means to apply pressure on the FRP composite shells to hold them in place until the adhesive cures and also to force out any trapped water between them. Straps should be spaced at approximately 0.6 m intervals for satisfactory pressure to be applied to the adhesive contact area.

Step 7: Drive Fiber-Reinforced Polymer Composite Shield to Required Depth into Mud Line
After curing of the adhesive, the FRP composite shield can be driven into the mud line, which needs to be loosened. This can be achieved either by using a water jet that stirs and loosens the mud or by digging around the wood pile to the required depth and then backfilling the hole.

Table 1. Cost Items for FRP Composite Shells Fabricated in Laboratory

Item	Cost per fiber-reinforced polymer composite shell ($)
Fiber reinforcement	101
Resin	70
Catalyst	8
Fabrication supplies	114
Labor preparation	70
Labor application	15
Total	378

Note: Prices are for shells having a diameter of 394 mm and a length of 4.88 m.

Step 8: Drill Holes and Place Shear Connectors
If shear connectors are required for the transfer of loads from the wood pile to the FRP composite shield, then holes need to be drilled and the shear connectors placed before grouting. This will ensure that any possible voids are filled by the grout and no possible access points remain for marine borers to enter and damage the wood pile. If the holes are to be drilled underwater, then an air drill will be necessary. In the laboratory, regular steel threaded rods were used, but galvanized steel rods should be used in field applications to reduce corrosion.

Step 9: Prepare Grout and Pump it into Place
After the FRP composite shield is driven into the mud, then the grout material can be pumped. Grout should be pumped from the bottom to avoid segregation.

Cost Analysis

To assess the commercial feasibility of the wood pile repair method, a preliminary cost analysis was conducted. For this purpose, the cost of repairing full-size wood piles in the laboratory was calculated. The cost was divided among the following items: (1) materials, (2) fabrication supplies, and (3) labor for preparation and application. Material costs included the cost of the fiber reinforcement, resin, and catalyst. The fiber reinforcement cost for a typical composite shell, which has a diameter of 394 mm and a length of 4.88 m, was $101. The fiber reinforcement cost included the CSM mat cost, $17 per shell, and the woven unidirectional fabric cost, $84 per shell.

The resin cost for a typical composite shell was $70 and the catalyst cost was $8. The cost of fabrication supplies per shell included peel ply, $40; release film, $25; distribution media, $16; plastic tubing, $8.50; bagging film, $12; sealant tape, $7; and vacuum line, $5.50. The labor cost to prepare materials, supplies, and the mold for VARTM/SCRIMP fabrication of one shell was based on the time required, $3\frac{1}{2}$ h, for two student workers to complete the task at a wage rate of $10 per hour; therefore the total cost for labor application was $70 per shell. The labor application cost was based on the time required for one student worker to mix the resin and infuse the part. In the laboratory, $1\frac{1}{2}$ h were spent to complete the infusion process; therefore the total labor application cost was $15. The total cost for one shell was $378, where the cost items are summarized in Table 1.

The total cost for repairing a typical wood pile with a diameter of 335 mm using 4.88-m-long FRP composite shells can be determined by adding the cost of the underwater epoxy adhesive, $200, to that of the cement-based grout with a thickness of 50

Table 2. Cost items for wood pile repair with fiber-reinforced polymer composite shells

Item	Number of items	Cost per item ($)	Total cost ($)
FRP composite shell	2	378	756
Adhesive	4 gal	50	200
Grout	20 bags	11	220
Labor	10 hours	10	100
Equipment	—	—	200
Total			1,476

Note: Above prices are for wood piles with a diameter of 335 mm repaired with 4.88 m long FRP composite shells.

mm, or $220. The labor cost for the application of the adhesive and the grout, $100, was estimated assuming that $2\frac{1}{2}$ h are required for four student workers to complete these tasks. The cost of any equipment needed, such as concrete mixing trucks and pumps, is expected to exceed $200. The total cost for a typical wood pile repair is calculated to be $1,475 (approximately $1,500), where the cost items are summarized in Table 2. It is worth noting that additional cost items such as the shear connectors and polymer concrete coating are not included in this estimate. Some costs would be expected to decrease if multiple piles at the same site were reinforced. Actual worker rates will be higher than the student worker labor rates assumed in this study; however, it is expected that fabrication and installation time will be reduced with practice and expertise partially compensating changes in the overall labor cost.

In the cost analysis of the repair method, no cost item is needed for extraction of the existing damaged wood pile. This represents a cost saving compared to the alternative of pile removal since the cost of extracting and disposing of the old treated wood piles, including the disruption to the pier facility, is eliminated. The disturbance to the normal operation of the waterfront facility is expected to be minimal. Most of the repair work can take place beneath the pier facility; no heavy or large equipment is necessary to complete the task.

Conclusions and Recommendations

The study presented in this paper allows the following conclusions to be drawn:

1. Current methods of repairing marine piles were assessed and deemed problematic through literature review and field inspection.
2. The proposed repair of wood piles with prefabricated FRP composite has a dual function of marine borer protection and structural restoration. A method for fabrication of FRP composite shells based on the VARTM/SCRIMP processing technology was successfully implemented.
3. The proposed repair method is environmentally friendly since no new wood preservative chemicals are introduced to the surrounding marine environment. The encasement with the FRP composite shield is expected to attenuate further leaching of chemicals from treated wood piles.
4. The repair method has potential to be cost competitive compared to damaged pile extraction and new pile installation in cases where disruption to the waterfront facility (for example, pier or wharf) is of concern.

The following commentary and practical recommendations are proposed:

1. Modifications and improvements to the wood pile repair method are expected to take place when the technology is implemented in the field.
2. For extended protection of wood piles in service without marine borer damage, the use of the polymer grout with only two FRP composite shells may be advantageous.
3. For structural restoration of wood piles with damage (for example, necking with reduction in cross-sectional area), the use of the cement-based structural grout combined with polymer concrete overlay and the required number of FRP composite shells may provide the requisite load-bearing capacity (Lopez-Anido et al. 2004a).
4. It should be noted that the labor rate used for determination of labor cost is low ($10 per hour) since it is the rate for a student worker. In real applications the rate is expected to be approximately $40–$50 per hour. The total time for a typical repair to be performed by professionals is expected to be less, and therefore a portion of the cost will be balanced.

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