Figure 11—Poured FRP Bridge Deck

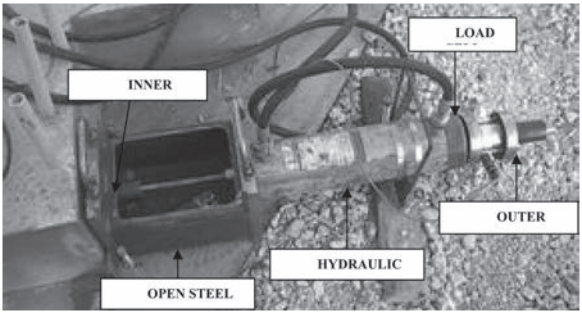

Figure 12—New Pulling Machine Ready for the Use

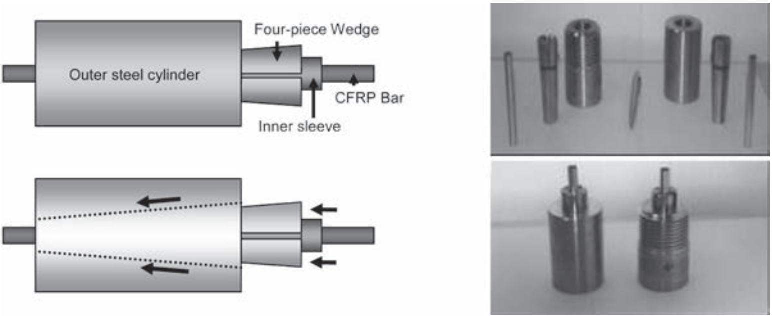

Figure 13—Steel Wedge Anchorage System

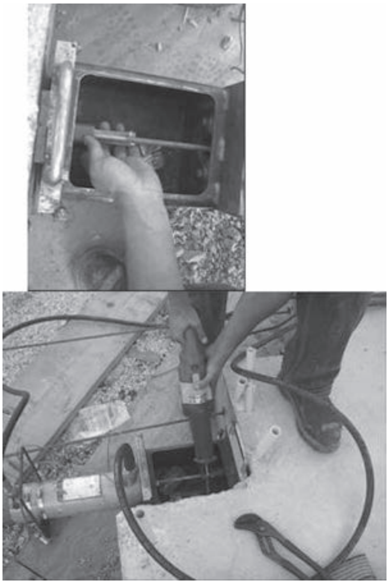

Figure 14—Wedges Insertion and Cutting of the Tendon

Figure 15—Southview Bridge-Deck Completed

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FRP Application in Underwater Repair of Corroded Piles

by R. Sen, G. Mullins, K. Suh, and D. Winters

Synopsis: The poor durability of conventional corrosion repairs has led to increased interest for its replacement by fiber reinforced polymers (FRP). Over the past decade, several highway agencies completed demonstration projects in which FRP was used to repair corrosion damage on surfaces that were dry. These repairs have held up well and show little sign of deterioration. The availability of resins that can cure in water has made it possible to explore the application of FRP for the underwater repair of corrosion-damaged piles. This paper presents findings from three demonstration projects in which corroding reinforced and prestressed piles at two contrasting locations were repaired using two different FRP systems. Several piles were instrumented to allow long-term corrosion monitoring. The projects confirm the feasibility of conducting underwater FRP repairs in tidal waters. Preliminary data suggests that the wrap leads to a reduction in the prevailing corrosion rate.

Keywords: corrosion; FRP; instrumentation; piles; repair; underwater

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INTRODUCTION

The high concentration of chloride ion in seawater allows it to penetrate to the level of steel even in high-quality concrete. As a result, the passive layer that normally protects steel is destroyed making corrosion of reinforcing or prestressing steel inevitable. This problem is particularly severe in tidal waters in sub-tropical environments where the combination of wet/dry cycles and high temperature/high humidity can lead to rapid deterioration that necessitate costly repairs.

Corrosion repairs are only durable if the conditions responsible for the original deterioration are removed. This means that all chloride-contaminated concrete including the concrete behind the steel must be removed[1]. Since the boundaries of the chloride contaminated region are not known with any precision this is daunting task even under dry conditions. For half-submerged piles in salt water this is a near impossibility.

Not surprisingly, corrosion repair of piles is seldom durable with the exception of the Life Jacket system[2-3] developed through the pioneering efforts of the Florida Department of Transportation[4-7]. In this system, corrosion is stopped by integrating a sacrificial cathodic protection system within the repair. Unfortunately, the Life Jacket system may not always be affordable. In such instances there is a need for alternative, cost effective “temporary” repairs that are more durable than conventional ‘chip and patch’ type of repairs.

Fiber reinforced polymers (FRP) offer the prospect of such a cost effective repair. Its lightweight, high strength and resistance to chemicals offer obvious cost advantages. In fabric form, it offers unprecedented flexibility in construction. Moreover, as fibers can be oriented as required they can provide strength in any desired direction. This versatility has led to several research studies to investigate if FRP's strength and durability can be harnessed to successfully repair corrosion damage.

It should be noted that the use of FRP for corrosion repair is deemed controversial. For example, ACI 440 Committee Guidelines[8] states "*The application of FRP systems will not stop ongoing corrosion ...If steel corrosion is evident ....placement of FRP reinforcement is not recommended without arresting the ongoing corrosion and repairing any degradation to the substrate*".

Economics has been largely responsible for disregarding this valid warning. When faced with the prospect of closing a bridge or a temporary FRP repair, highway authorities have usually opted for the latter. However, the performance of these "temporary repairs", in some cases extending over ten years of service, has been exceptional[9].

It should be noted that the vast majority of the studies attempted were carried out under dry conditions that are favorable for applying FRP. With the emergence of resin systems that can cure in water it has become possible to conduct corrosion repairs under water[10-11].

This paper describes three field demonstration studies in which FRP repairs were carried out on corroding, partially submerged piles in tidal waters. An important element in all these applications was that several piles were fully instrumented to allow the corrosion rate to be monitored. Thus, these studies have the potential to yield data on the role FRP plays in slowing down the corrosion rate. Complete descriptions may be found elsewhere[12-15]. This paper provides a brief overview to highlight some of the more important lessons learnt relating to the underwater application of the wrap.

RESEARCH SIGNIFICANCE

This paper summarizes information from three separate field demonstration projects relating to an emerging new application of fiber reinforced polymers, namely underwater corrosion repair of piles. Corrosion of piles in tidal waters is a common problem and this information will be helpful in advancing the state of practice.

PROBLEM STATEMENT

The application of FRP for corrosion repair of piles serves the dual purpose of enhancing flexural strength and providing confinement to withstand expansive forces set up by corrosion products. Thus, this application is part bond-critical and part contact-critical.

As with any bond-critical application, surface preparation is important; good bond requires the substrate to have an open pore structure to assure capillary suction of the epoxy. In underwater application, however, pores will be saturated with water or small marine organisms or algae. This is likely to adversely affect bond and alternative measures, e.g. bonding agents, may be required to ensure satisfactory performance.

The logistics of saturating FRP with resin and installing it in underwater applications are more complex given unpredictable environmental conditions. Wind, waves and tides play a critical role and unless they are factored in, wrapping is unlikely to be successful. New techniques have to be established for installation that minimizes the impact of these unfavorable conditions.

As stated earlier, FRPs are only viable for corrosion repair if they are cost effective. Given the high material cost, pile repairs must be properly engineered. Unfortunately, not all relevant information is available, e.g. relationship between corrosion and expansion.

Safety is of paramount important issue and must be factored in all operations. Normal as well as extraordinary measures need to be taken to avoid potentially unfavorable conditions. Meticulous planning and coordination is required to prepare for unexpected situations.

DESIGNING CORROSION REPAIR

The role of FRP in pile repair is twofold: first to restore lost flexural capacity due to steel corrosion; second to provide resistance to withstand expansive forces caused by corrosion of steel. The former requires fibers to be oriented parallel to the direction of the reinforcing or prestressing steel, i.e. along the length, while the latter requires fibers in the transverse or hoop direction, i.e. perpendicular to the steel. This can be met either by using two different sets of uni-directional fibers one for each direction or preferably, by using bi-directional FRP material that requires less labor.

An estimate of the required strength in the longitudinal direction may be made based on the steel cross-section that was lost by corrosion. A large body of laboratory test data relating ultimate capacity to metal loss is available in the published literature and this provides a means for developing a rational procedure. Alternatively, a conservative capacity loss may be assumed. This was the case in the demonstration projects where capacity loss was assumed to be 20%.

Currently, there is a lack of reliable information on transverse expansion caused by corrosion. Most available experimental transverse expansion data was obtained from accelerated corrosion tests that resulted in symmetric cracking. In practice, the combined action of wind and waves result in uneven chloride penetration that inevitably results in asymmetric cracking. More importantly, the solubility of corrosion products from accelerated testing may be different. Thus, laboratory data may not be appropriate. In view of this, a simplified procedure was developed[12, 16]. In design, the expansion strain was assumed as 0.1% (approximately 3 times the ultimate concrete tensile strain assumed to be 10% of the ultimate concrete failure strain).

Using the above assumptions, a two step design procedure was developed that was used in all the demonstration projects. In the first step, strain compatibility analysis was used to develop interaction diagrams to determine the number of FRP layers required to make up for the assumed shortfall in flexural capacity due to corrosion. In the second step, the confining lateral strain provided by this strengthening was checked to ensure that this did not exceed an assumed expansion strain of 0.1%. Results obtained using this method were found to be reasonable. For the bi-directional carbon fiber, only two FRP layers were required. Twice as many layers were required for fiberglass because of its lower strength and stiffness.

DESCRIPTION OF DEMONSTRATION PROJECTS

Three field demonstration studies were conducted at two contrasting sites. The first, Allen Creek Bridge, Clearwater is in shallow, relatively calm waters; the remaining two studies were carried out on piles supporting Gandy Boulevard bridges spanning Tampa Bay. The first of these two bridges is the Friendship Trails Bridge that is now a recreational trail for pedestrians and cyclists. The second is the Gandy Bridge. The waters of the Tampa Bay are much deeper and more turbulent than those of Allen Creek.

These sites were selected because the environment is extremely aggressive. This was confirmed from chloride content analysis of concrete cores taken from the piles. The chloride content at the level of the reinforcement exceeded the threshold required for corrosion to be initiated.

FRP material

Two differing systems were used in all three demonstration projects. One was a pre-preg, the other a wet lay up. The pre-preg system was from Air Logistics in which all the FRP material was cut to size, resin saturated in the factory and sent to the site in hermetically sealed pouches (Fig. 1). The wet lay up system used for wrapping the piles under wet conditions was from Fyfe. An additional wet lay up system was also used but this was carried out under dry conditions inside a cofferdam. For this reason, it is not discussed in this paper. Both carbon and fiberglass were used. Details of the properties of the fiber and the resin as provided by the suppliers are summarized in Tables 1 to 4.

Allen Creek Bridge

Allen Creek Bridge is located on the busy US 19 highway connecting Clearwater and St. Petersburg, FL. The original bridge built in 1950 was supported on reinforced concrete piles driven into Allen Creek. In 1982, the bridge was widened and this new section was supported on 35 cm (14 in.) square prestressed piles.

The waters from Allen Creek flow east into Old Tampa Bay that in turn joins the Gulf of Mexico to the south. The environment is very aggressive; all the reinforced concrete piles from the original construction had been rehabilitated several times. At low tide, the water level in the deepest portion of the creek is about 0.76 m (2.6 ft). Maximum high tide is about 1.89m (6.2 ft). This shallow depth meant that the underwater wrap could be carried out on a ladder.

Preparatory work -- Pile surfaces were covered with marine growth (Fig. 2) that had to be scraped off. Additionally, two of the four corners that were not rounded but chamfered had to be ground using an air-powered grinder. This was a difficult operation particularly for sections that were below the water line. A quick-setting hydraulic cement was used to fill any depression, discontinuities and provide a smooth surface. Just prior to wrapping the entire surface was pressure washed using freshwater to remove all dust and marine algae.

Instrumentation -- Instrumentation was installed to allow linear polarization and corrosion potential measurements to be made. An innovative instrumentation scheme was developed that eliminated the need for wiring and junction boxes[14]. This was an important consideration since the piles were located in relatively shallow waters that were accessible on foot. Several piles supporting the structure had been defaced and the probability of vandalism was very real.

FRP wrapping -- Two different schemes using two different materials were evaluated. In each scheme four piles were wrapped with two other instrumented piles serving as controls. In the first scheme, cofferdam construction was used and the piles wrapped using a bi-directional FRP in a wet lay up under dry conditions. As this was wrapped under 'perfect' conditions, its performance provided a means for evaluating piles that were directly wrapped in water using a new water activated resin (Fig. 3). The latter scheme was a pre-preg system developed by Air Logistics.

The pre-preg was easy to install since all the material came in labeled hermetically sealed packets. After applying an initial epoxy layer, the packets were opened according to the layout scheme and the FRP material applied. A shrinkage wrap was applied at the end to allow the FRP to cure. On an average, it took between 30 minutes to 45 minutes to wrap a pile over a 1.5 m depth depending on the number of layers of material that had to be applied.

Friendship Trails Bridge

This is the oldest of the Gandy Boulevard bridges crossing Tampa Bay. It was originally constructed in 1956 and was slated for demolition in 1997. Thanks to community activists, the bridge was saved, refurbished and rehabilitated. In 1999, the bridge was re-opened as a pedestrian bridge and re-christened as the "Friendship Trails Bridge". The 4.2 km (2.6 mile) structure is now the longest over-water recreational trail in the world. The bridge has 275 spans supported by 254 reinforced concrete pile bents and 22 column type piers located at the main channel crossing. Seventy seven percent of the 254 piers supporting this bridge have needed to be repaired indicating that the environment is very aggressive.

Preparatory work -- All piles wrapped were 50.8 cm x 50.6 m (20 in. x 20 in.) reinforced concrete piles and wrapped over a depth of 1.5 m that extended all the way to the underside of the pile cap. The waters are approximately 4.88 m (16 ft) deep. This meant that ladders could no longer be used to apply the FRP in this situation. An innovative scaffolding system was designed and fabricated. It was lightweight, modular yet sufficiently rigid when assembled to support 4-6 people. The scaffolding was suspended from the pile cap and extended 2.74 m (9 ft) below. Its mesh flooring provided a secure platform around the pile that allowed the wrap to be carried out unimpeded in knee deep waters (Fig. 4).

Instrumentation -- Unlike the Allen Creek Bridge where vandalism was a real concern, the piles of the Friendship Trails Bridge are located in deeper and more turbulent waters. Moreover, as the majority of the piles supporting this bridge had been repaired and some were instrumented, the element of novelty was absent making vandalism less likely. In view of this, an instrumentation system developed by the Florida Department of Transportation was selected. This required both wiring and junction boxes. The scheme uses rebar probes (Fig. 5) that are installed at different elevations close to the reinforcing steel. Changes in the direction of the corrosion current between these locations can indicate if the FRP is working as expected. Reductions in the measured current compared to unwrapped controls were also expected to provide an index of the efficacy of the FRP wrap. The drawback with this system is that it takes time for the equilibrium state around the probe to be attained. Until this time, data may not be meaningful.

FRP wrapping -- Two different FRP systems were used. One was the same pre-preg system with a water-activated resin used in the Allen Creek Bridge. The other was Fyfe's system that used resins that cure in water. The pre-preg system was used to wrap four piles – two using carbon and two using glass. The wet-lay up system from Fyfe required on-site saturation of the fibers. Two piles were wrapped with fiberglass using this system. Of the two, one was an experimental FRP system that combined wrapping with a sacrificial cathodic protection system. Two other unwrapped piles in a similar initial state of disrepair were used as controls to evaluate the performance of the wrapped piles. Application was facilitated through the use of a scaffolding system mentioned earlier (Fig. 6).

The pre-preg system was applied as in the Allen Creek Bridge and posed no problems. The Fyfe system was more challenging since the FRP material had to be saturated on-site. Access to foundations of an adjacent bridge provided a convenient staging post for the on-site impregnation (Fig. 7). On an average the operation took 90 minutes to complete.

Gandy Bridge

The Gandy Bridge built in 1970's connects St. Petersburg to Tampa. The bridge has approximately 300 piers comprising five or eight prestressed concrete piles with 50.8 cm x 50.8 cm (20 in x 20 in.) cross section. The original plan was to just wrap one heavily corroded pile (Fig. 8). Later, the scheme was revised to include three piles. An additional unwrapped but instrumented pile served as control (Fig. 9).

Preparatory work -- Though the scaffolding system used at the Friendship Trail Bridge provided a safe and stable working space, it required at least four to five people to install and move because of its large size and weight. In view of this, a new scaffolding system was developed that was geared towards wrapping individual piles. This was in