UNDERWATER PILE REPAIR USING FRP – STATE OF THE ART

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ABSTRACT

Fiber reinforced polymers were first used for repairing corrosion damage in a prestressed concrete bridge spanning the Bay of Tokyo, Japan in the 1970's. Twenty years later when the bridge was replaced and selected girders examined it was discovered that FRP had prevented further intrusion of chlorides. Subsequently, research studies were undertaken to quantify the benefits of using FRP in chloride-induced corrosion repair. This paper provides an overview of the findings from long term laboratory studies and several field demonstration projects undertaken by the University of South Florida over the past decade to explore the use of FRP for repairing corroding piles in tidal waters. The findings are presented in the form of answers to questions that are of interest to highway authorities considering using FRP for corrosion repair.

1. INTRODUCTION

Corrosion of reinforced or prestressed concrete piles driven in tidal waters is a world-wide problem. Chlorides from salt water permeate through the concrete and destroy the passive layer that forms a protective layer over steel in concrete's alkaline environment. Oxygen and moisture present inside the concrete allows simultaneous oxidation and reduction reactions to take place that result in the formation of rust. Unlike bridge decks, where corrosion can extend over the entire deck, in piles driven in tidal waters, corrosion is limited to the splash zone, the region of the pile subjected to periodic wetting and drying under tidal cycles. The repairs are also concentrated over this region.

Since chloride-induced corrosion is electro-chemical, it can only be stopped by using cathodic protection. In cathodic protection, the electrons required for sustaining the electrochemical reactions are provided either by an impressed current or by another material such as zinc or magnesium attached to the steel that corrodes preferentially. While successful cathodic protection repair systems are available, they can be expensive. Recent data from the Florida Department of Transportation indicate that pile repair costs range from $437-$874/m; when repairs incorporate cathodic protection they increase to $1,577/m for *non-structural* and $1,990/m for *structural repairs.* These figures do not include mobilization and other overhead charges. Thus, the total cost of the corrosión repair is much higher.

Fiber reinforced polymers (FRP) are lightweight, high strength, corrosion resistant materials that have become the material of choice in the repair and rehabilitation of concrete structures. In fabric form, they offer unprecedented flexibility and since fibers can be oriented as required they can provide strength in any desired direction. Independent research studies undertaken in US and elsewhere have conclusively demonstrated that while FRP slowed down corrosión [8], it was unable to stop it as can be expected given the electro-chemical nature of corrosion.

Over the past decade the University of South Florida (USF) has undertaken laboratory studies and field demonstration projects to advance the use of FRP for repairing corrosing piles. Aside from answering the basic question regarding the effectiveness of FRP in corrosión repair, the goal of the studies was to provide answers to the following questions:

1. What is the optimal surface preparation required for best performance?
2. Can FRP be used to repair partially submerged elements?
3. How can FRP-concrete bond be improved?
4. Why does FRP slow down the corrosion rate?

This paper provides a brief description of the research projects focusing primarily on the findings. It also attempts to identify the frontiers of research in FRP pile repair.

2. RESEARCH PROGRAM

USF's research into the use of FRP for corrosion paper started more than a decade ago. They were principally in two areas: laboratory investigations [11,13] and field demonstration studies [6,7,9,10,12]. It is evident that field implementation was a very important consideration in the research.

In laboratory investigations, one-third scale, instrumented prestressed pile specimens (Fig. 1) were cast in a commercial prestressing facility with built in chlorides to simulate the splash zone (Fig. 2). Subsequently, selected specimens were wrapped using FRP and exposed to simulated tidal cycles for extended periods. Their corrosion performance was assessed from gravimetric test methods in which prestressing strands were retrieved and the metal loss measured. Complete details may be found in [11].

Fig. 1 Specimen with chloride

Fig. 2   Completed specimens

Similar specimens were also used to evaluate optimal surface preparation. In this case, specimens were first corroded to a targeted 25% metal loss, repaired and then exposed to simulated tidal cycles at elevated temperature. The performance of the FRP was determined by gravimetric tests and also by periodic ultimate strength tests. Details may be found in [13].

The first field applications were carried out in 2003 [6]. Subsequently there were three other applications [7,9,10]. A typical photo from a field demonstration project is shown in Fig. 3. These repairs were carried out on reinforced or prestressed piles located in aggressive environments. In all cases, piles were instrumented to allow corrosion performance of the FRP to be monitored. Complete details may be found in [12].

Field measurement of the FRP-concrete bond indicated the bond was variable and dependent on the type of resin used. As a result, additional laboratory studies were undertaken to develop methods that could improve bond even when the concrete surfaces were wet. Techniques used by the composites industry such as vacuum or pressure bagging were successfully adapted and employed in field demonstration projects. Complete details may be found in [1,14].

Fig. 3 FRP repair of corroding pile, Tampa Bay, FL

More recently, studies were carried out to understand the role of FRP as a barrier element. To this end, research was undertaken to determine the oxygen permeation coefficient of epoxy, FRP and FRP-concrete systems. The studies showed that FRP bonded to concrete significantly reduced its oxygen permeability [3-5]. A method of design that takes into consideration the permeability of the concrete was developed and its application illustrated.

3. FINDINGS

In this section, the findings from the research are presented in the form of question and answers on subjects that are of interest to highway authorities. The basic question relating to effectiveness of FRP repairs has been independently investigated by several researchers and is described in considerable detail in a state-of-the-art paper [8] that showed FRP slowed down but did not stop corrosion. This was also confirmed by our studies in which twenty two FRP wrapped and unwrapped one-third scale models of prestressed piles cast with built-in chloride were exposed to simulated tidal cycles under outdoor ambient conditions for nearly three years. All specimens were instrumented using embedded titanium reference electrodes to monitor the corrosion rate and thermocouples to record the corresponding temperature. The corrosion rate was monitored throughout the exposure and at the end of the study, all prestressing strands and ties were extracted and the metal loss measured from gravimetric testing. The findings showed that the metal loss in FRP wrapped specimens was only about one-third that in the unwrapped controls. Complete details may be found in [11].

What is the optimal surface preparation required for best performance?

A multi-year study was conducted to evaluate the role of pre-wrap substrate preparation on corrosion mitigation in a marine environment. Seventeen one-third scale prestressed piles were corroded to a targeted 25% metal loss to simulate severe corrosion. Subsequently, two types of pre-wrap substrate preparation were carried out (1) full repair in which the delaminated concrete was removed and the section re-formed and (2) epoxy injection repair in which the cracks were sealed and the surface cleaned. Specimens were then wrapped using CFRP and exposed to simulated tidal cycles at 60°C for 28 months. Post-exposure wrap performance was evaluated from gravimetric testing in which the metal loss in extracted strands and ties from all the exposed specimens was measured. Results showed that the performance of the full repair and the epoxy injection were comparable with relatively minor increase in steel loss despite the severity of the exposure. In contrast, the steel in unwrapped controls exposed to the same environment was totally corroded in several regions. The findings provide compelling evidence that epoxy sealing of cracks followed by FRP wrapping is effective even when corrosion damage is severe. Complete details may be found in [13].

Can FRP be used to repair partially submerged piles?

The intent of the research project throughout was to explore the feasibility of field repairs. As a result, several demonstration projects were undertaken to demonstrate that it was feasible to carry out field repairs. In the initial application, piles in shallow waters were repaired [6]. Subsequently, piles located in deeper waters were repaired (Fig. 3). These required scaffolding that was suspended from the pile cap [7,9,10]. In all the field applications, selected piles were instrumented Data from instrumented piles indicated that FRP was slowing down the corrosion rate [12].

In successive demonstrations, the efficiency of the field repairs was improved by employing easy-to-install movable scaffolds, hydraulically operated equipment for surface preparation and using innovative techniques for improving the FRP-concrete bond. Such developments pave the way for making repairs longer lasting and more cost effective.

How can FRP-concrete bond be improved?

Surface preparation is always the key for good bond. However, even if recommendations in guidelines are met, bond can be poor unless there is continuous, intimate contact of the saturated FRP material and the concrete substrate while the resin is curing. Such contact may be lost in repairs involving vertical elements such as columns or the horizontal soffits of slabs, because gravity effects create tendencies for the resin-saturated FRP to separate.

Fig. 4 Current practice vs pressure bagging

The problem with the FRP-concrete bond was solved by employing vacuum / pressure bagging techniques widely used by the composites industry for fabricating specimens. Though both systems were demonstrated to improve bond in piles, pressure bagging was selected since incorporating a vacuum in a cracked pile can be problematic in the field. Fig. 4 shows full sized pressure bagged piles in an outdoor tank. Two other controls are shown in the same photo that were used for comparison. A comprehensive series of pullout tests were conducted and this showed that there was significant improvement in the FRP-concrete bond. This system was successfully implemented in field demonstration projects. Complete details in [1].

Why FRP lowers the corrosion rate

FRP is a barrier element that slows down the ingress of deleterious materials such as chlorides, oxygen and moisture. As the size of the oxygen molecule is smaller than that of the water or chloride molecule, its diffuses faster because the larger the molecular diameter, the stronger the interactions and the smaller its diffusion coefficient. A new diffusion cell was developed by USF researchers and a technique developed that permitted the measurement of the oxygen diffusion coefficient for epoxy, FRP laminates and FRP-concrete systems. These results indicated that the oxygen permeability of FRP was orders of magnitude lower than that of concrete. However, it was not zero and this explains why properly bonded FRP can slow down but cannot stop chloride-induced corrosion steel. Complete details may be found in [3-5].

4. RESEARCH FRONTIERS

4.1. Cathodic Protection System

Though FRP serves as a barrier to the ingress of deleterious substances it cannot stop the corrosion of steel. This can only be stopped using cathodic protection. A study was recently concluded in which an embedded anode cathodic protection system was used inside a wrap. The system was implemented for repairing full-scale piles. The results after over 12 months of monitoring showed that the cathodic protection system was effective. Moreover, the consumption of anodes was lower in FRP wrapped piles compared to unwrapped controls [2]. This study provides additional field data that indicates the effectiveness of FRP repair. USF researchers are currently investigating how this system can be modified and improved.

4.2 FRP Materials

The findings from the oxygen permeation measurement study provide a simple method for assessing the efficiency of FRP materials for corrosion repair. Using this technique it should be possible to develop new systems and procedures that can make the material less permeable and thereby improve the efficiency of the corrosion repair.

4.3 Field Installation

The routine implementation of the recently developed pressure bagging technique will ensure good bond between FRP and concrete that is a requirement for good corrosion performance. The USF research team is currently exploring new methods for improving and simplifying pressure bagging that can result in further efficiencies in the corrosion repair of piles.

CONCLUSIONS

This paper provides a brief overview of various research studies undertaken by the University of South Florida to improve the state of practice for pile repair. Research included laboratory studies with a focus on field implementation. The findings from applications are very promising. Measurement of the corrosion rate in field demonstration projects indicates that FRP slows down corrosion that can lead to more durable repair. Advancements are in progress make it possible to incorporate a cathodic protection system inside a FRP repair. New developments in field application and new materials and systems such as pressure bagging are likely to lead to greater efficiencies in the future.

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