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Application of FRP composites for underwater piles repair

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Abstract

The lightweight, high strength and corrosion resistance of fiber reinforced polymers (FRP) make them ideally suited for quick and effective structural repairs. As a result, they have been favoured for conducting emergency bridge repairs where speed is of essence. The availability of resins that can cure under water has made it possible to similarly extend its application to substructure elements such as partially submerged damaged piles. Such repairs can be carried out using the same strategies that were successfully used in recent demonstration projects in which FRP was used to repair and rehabilitate corrosion-damaged piles. In the projects two disparate FRP systems – a pre-preg and a wet layup – were used and both carbon and glass evaluated. Access to the piles in the deep waters was provided by a custom-designed, lightweight modular scaffolding system that was assembled around the piles. An overview of the project is provided with particular emphasis on changes that would allow its adoption for emergency repairs.

Keywords: A. Carbon fibre; A. Glass fibres; A. Prepreg; B. Strength

1. Introduction

Fiber reinforced polymers (FRP) have long been used for the repair and retrofit of concrete structural elements. Their lightweight, high strength and resistance to chemicals offer obvious benefits. In fabric form, they provide unparalled flexibility. Moreover, as fibers can be oriented in any direction, their use can be optimized. This makes FRP particularly suited for emergency repairs (Fig. 1) where damage can be multi-directional and speed of strength restoration critically important.

The emergence of new adhesives [1] that allow FRP to be bonded to wet concrete surfaces makes it possible to economically conduct emergency repairs on sub-structure elements. Fig. 2 shows impact damage that led to both cross-section loss and breakage of the spiral ties. Conventional repairs will require the cross-section to be enlarged to accommodate new ties. If instead, FRP were used it would only be necessary to re-form the cross-section and apply bi-directional layers that could restore lost tensile capacity while providing equivalent lateral support to the longitudinal steel. Moreover, the application of a protective UV (ultra-violet) coating on the wrap of the right color will render the repaired pile indistinguishable from other undamaged piles. The aesthetics of FRP repair is one of its unheralded benefits.

The techniques developed recently for underwater FRP corrosion repair of piles [2–4] are equally applicable for repairing other types of damage. This paper distils relevant information from recently completed demonstration projects [5,6] in which two disparate FRP systems were used for repairing corroding reinforced concrete piles. In the projects both carbon and glass were used and the piles instrumented to monitor performance. Additionally, bond tests were carried out after two years to evaluate the residual bond. An overview of the studies is presented with particular emphasis on changes that will be needed for emergency repairs. Recommendations are also made regarding strategies that were found to be the most effective.

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Fig. 1. Damage to prestressed girder due to vehicular collision (*Courtesy A. Alvi*).


Fig. 2. Damage to pile requiring emergency repair (*Courtesy FDOT*).

2. Problem statement

The application of FRP wrap for underwater repair and rehabilitation of piles is problematic for the following reasons:

1. Surface preparation suitable for dry conditions cannot be directly used for wrapping partially submerged elements. New methods and equipment may be required.
2. All round access to the pile in deep waters poses many logistic problems. Meticulous planning is required and safety issues must be carefully addressed.

Moreover, even if the application is perfect, there may be unexpected bond problems. For example, since the FRP material is a barrier element it can trap moisture that is already inside the pile. Evaporation of this water by heat generated during curing may trigger localized debonding. While bond is not as critical for applications where the FRP material is wrapped completely around the pile, it can accelerate corrosion in the debonded region.

It is however unrealistic to expect satisfactory resolution of all potential problems given the limited number of field studies that have been completed to date. Some of the solutions that have evolved are described with particular reference to a recently completed field study [5].

3. Field demonstration project

The friendship trails bridge, formerly the "old" Gandy Bridge, is one of four bridges spanning Tampa Bay, the most famous being the Sunshine Skyway Bridge. Originally built in 1956, it was scheduled for demolition in 1997 following the construction of the new Gandy Bridge. Instead, it was rehabilitated and converted into a recreational trail that is closed to vehicular traffic.

The 4.2 km (2.6 mile) bridge is supported by 254 piers and 22 columns numbered 1–276 extending east from St. Petersburg in Pinellas County to Tampa in Hillsborough County. Seventy seven percent of the 254 piers have needed to be repaired indicative of a very aggressive environment. As a result, the site provides a rich history of the various attempts made over the years to repair piles.

The piles selected for this study were identified following a detailed survey of the site. Its aim was to locate piles on the Hillsborough side of Tampa Bay (Hillsborough County funded the study) that were in the same general state of disrepair. Piers 99, 100, and 101 were found suitable for this purpose. Pier 99 was a six pile bent while piers 100 and 101 were both four pile bents.

Details of the eight piles selected for the study are summarized in Table 1. Piles are identified by the Pier Number followed by the letter N or S signifying 'north' or 'south'. Six of the eight piles were instrumented. Instrumentation consisted of special rebar probes developed by the Florida Department of Transportation that were installed at two locations along a pile length to provide a measure of the corrosion current. Details on the performance of these probes and results obtained may be found elsewhere [5].

The four piles in Pier 100 were wrapped using a pre-preg system developed by Air Logistics referred to subsequently as System A [7]. Two were wrapped with carbon and two others with glass. The glass wrap required a greater of number of layers to compensate for its lower strength. The two piles in Pier 101 were wrapped with a wet layup system developed by Fyfe referred to subsequently as System B [8]. Both piles were wrapped using glass. One of the piles used an experimental zinc mesh sacrificial cathodic protection system. The other was a regular glass wrap.

The wrap length extended to the underside of the pile cap excepting for instrumented piles that were 15 cm (6 in.) shorter to accommodate junction boxes needed for measuring the corrosion current. It extended 45 cm (18 in.) above the high water line and 15 cm (6 in.) below the low water line. The wrap length in non-instrumented

Table 1
Test pile details

Pier number	Repair system	Specimen type	Pile name	Instrumentation
Pier 99	None	Control	99-N	Yes
	None	Control	99-S	Yes
Pier 100	Aquawrap®	Carbon 1 + 2 layers[a]	100-N	Yes
		Carbon 1 + 2 layers	100-N*	No
		Glass 2 + 4 layers	100-S*	No
		Glass 2 + 4 layers	100-S	Yes
Pier 101	Tyfo® SEH-51A	Glass 2 + 4 layers	101-N	Yes
	Tyfo Zinc Cathodic Protection	Glass 2 + 4 layers	101-S	Yes

[a] Signifies number of layers in the longitudinal and transverse directions respectively.

piles was 1.83 m (6 ft) long. It was 1.68 m (5 ft 6 in.) in instrumented piles.

4. Material properties

System A: The Aquawrap® Repair system [7] uses a unique water-activated urethane resin in conjunction with custom woven FRP fabric that can be wrapped around the pile. Because it is water-activated, the FRP material must be pre-impregnated with the resin and sent to the site in hermetically sealed foil pouches. The pouches are opened just prior to application to prevent premature curing by atmospheric moisture. Properties of the uni-directional and bi-directional fibers used as reported by the manufacturer are summarized in Table 2. Note the higher capacity of carbon compared to glass.

System B: System B used Tyfo® SEH-51A [8] and was used to wrap two piles in Pier 101. Tyfo® SEH-51A is a custom weave, uni-directional glass fabric that is normally used with Tyfo-S Epoxy. However, for the underwater application, Tyfo® SW-1 underwater epoxy was used. The epoxy was mixed at the site and the FRP fabric impregnated just prior to use. Properties of materials as provided by the manufacturer are summarized in Table 3.

Table 2
Properties of Aquawrap® fabrics [7]

Fibers	Tensile strength (ksi)	Tensile modulus (ksi)	Load per ply (lb/in.)
Uni-directional glass fiber	85	5200	2400
Bi-directional glass fiber	47	3000	1200
Uni-directional carbon fiber	120	11,000	3400
Bi-directional carbon fiber	85	3200	2400

1 ksi = 6.895 MPa; 1 lb/in. = 1.75 N/cm.

Table 3
Properties of Tyfo® SEH-51 composite [8]

Properties	Quantities
Tensile strength	3.3 k/in.
Tensile modulus	3030 ksi

1 ksi = 6.895 MPa; 1 lb/in. = 1.75 N/cm.

5. Composite jacket design

The FRP wrap must restore the lost axial, bending and shear capacity due to damage, e.g. corrosion, impact, fire etc. Available ACI [9] and ISIS [10] guidelines provide design equations and worked out numerical examples. Design manuals for specific systems are also available, e.g. Fyfe Co., [11]. The provisions in all the guides are comparable though equations are more simplified for the proprietary systems. However, axial, flexural and shear strengthening are considered independently; their interaction, necessary for designing pile wraps, is not considered.

The low strain capacity of the FRP makes the maximum permissible strain, the critical parameter in design. For strengthening applications, ACI 440 guidelines [9] specifies strain limits for both "contact-critical" (FRP in intimate contact with the substrate with no specific adhesion requirement) and "bond-critical" (minimum adhesion required since load transfer is by bond) applications. For piles, the limit for contact-critical application applies as the FRP material is wrapped completely around the circumference. This is set as the lower of 0.4% or 75% of the FRP design rupture strain. The latter limit was established from tests to avoid loss of aggregate interlock that can occur at strains below the ultimate fiber strain.

As piles corrode, they expand in the lateral direction since the volume of the corrosion products can be as much 600% of the original steel [12]. To accommodate such a large potentially uniform increase, a lower maximum strain limit may be appropriate. This can be based on experimental data [13] or from other considerations.

A strain limit of 0.1% – approximately three times the maximum tensile strain leading to cracking – was selected for designing the FRP to withstand corrosion expansion [5,6]. This value was used since reported experimental strains, calculated from the total circumferential increase, tend to be on the high side because it includes unrestrained movement of the crack.

Interaction diagrams can be developed for FRP strengthening, as for reinforced concrete columns, by using strain compatibility analysis [14]. The only difference is that the equations incorporate the contribution of the FRP. Since FRP wrapping can provide increased tensile but limited compressive strength increase, only the tensile contribution was incorporated in the analysis. Also, as the confinement effect of concrete leads to modest increases in the ultimate axial capacity in non-circular sections, it was ignored. As with most strengthening applications, the role of the FRP is passive. That is, the FRP is unstressed except for additional load applied to the structure after it has been retrofitted.

Fig. 3 shows a typical interaction diagram for the design of the wrap used for underwater corrosion repair. In the applications, capacity loss was estimated to be 20%. It was found that this could be restored by using two transverse and one longitudinal carbon layer for the material properties outlined in Table 2. For the weaker glass, two longitudinal and four transverse layers were required to restore full capacity [6].

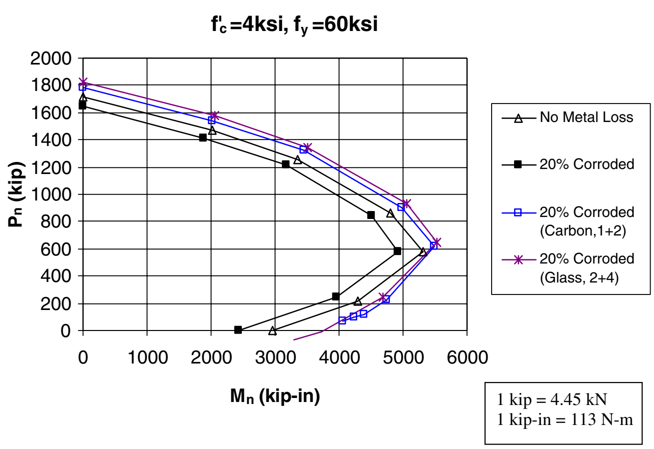

Fig. 3. Interaction diagram for corrosion repair of piles.

6. Access to piles

All around access to the pile is needed to allow the FRP material to be wrapped around the circumference expeditiously. In shallow waters, access is not a problem and ladders can be used. For deeper waters, a boat may be used to wrap the pile above water while divers can wrap the submerged region (Fig. 4). This solution can be economical where repairs are to be carried out on a single isolated pile.

In the field demonstration study however, several piles in the same bent were wrapped. For this case, a scaffolding system was more suitable since it allowed ready access to all the piles. The scaffold was built using 19 mm (3/4 in.) #9 expanded steel mesh on a 5 cm × 5 cm × 0.6 cm (2 in. × 2 in. × 1/4 in.) steel angle framework. The stiff but lightweight mesh helped minimize the forces from wave action while providing a secure working surface. Its modular design meant it could be placed around one or more piles depending on the application. Each framework consisted of two half-sections with cut-outs sized for the specific pile.

The four-part platform was 10 m (33 ft) long and 2.13 m (7 ft) wide when fully assembled. Advantage was taken of the overhead pile cap to suspend the scaffold at an appropriate elevation. In this case it was 2.74 m (9 ft) from the pile cap to allow piles to be wrapped over a 1.83 m (6 ft) length starting from the underside of the cap. Wood railing

Fig. 4. Underwater repair using a boat and divers (*Courtesy: Air Logistics*).

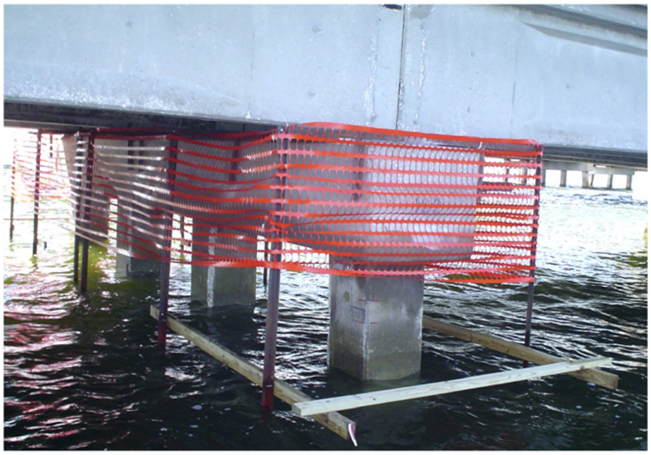

Fig. 5. Scaffolding system suspended from pile cap.

was bolted to the steel angles to delineate the extent of the underwater platform (Fig. 5).

7. Surface preparation

Surface preparation for contact-critical applications is defined as providing "continuous, intimate contact" [9] between the concrete substrate and the FRP material. In a marine environment this implies removal of all marine growth. As for dry conditions, depressions and voids on the concrete surface have to be patched using suitable material that is compatible with the concrete substrate. If there are corners, they need to be ground to a minimum of 19 mm (3/4 in.) [9] radius to avoid stress concentration in the wrapping material.

In case of emergency repairs, it may be necessary to re-form the concrete section. Advantage should be taken to insert appropriate cut-outs with the required radius inside the form so that the corners of the formed surface are automatically rounded. Otherwise, the sharp corners would have to be ground to the required 19 mm (3/4 in.) radius. This approach was successfully used in a recently completed study [6] that investigated the effectiveness of FRP in corrosion mitigation application for new specimens. Fig. 6 shows one of the wood trim cut-outs placed inside the form of the prestressing bed prior to concreting.

Fig. 6. Curved wood trim inserts at corners.

In the demonstration project, there was significant marine growth at the water line that was removed with a scraper prior to wrapping. Projecting parts of the concrete surface were chipped using a hammer and chisel. All four corners were chamfered and ground to a 19 mm (3/4 in.) radius using an underwater pneumatic grinder. To provide a smooth surface, quick setting hydraulic cement was used to fill surface voids. Finally, all surfaces were pressure washed using fresh water to remove all dust, debris, and remaining marine growth just prior to wrapping.

8. Pre-preg system

The pre-preg system was used for wrapping four piles in Pier 100. The two piles at the north end were wrapped using one layer of unidirectional carbon fiber and two layers of bi-directional carbon fibers. The two piles in the south end of the same pier were wrapped using two layers of unidirectional glass fibers and four layers of bi-directional glass fibers. As this was a pre-preg, all FRP material was pre-saturated in a factory and sent to the site in hermitically sealed pouches. The FRP material was removed from the packet just prior to the wrap, unrolled and was ready to be applied to the prepared surface.

Wrapping commenced from the pile top or 15 cm (6 in.) below the underside of the pile cap for the instrumented piles located in the north and south ends because of the presence of the junction box. The longitudinal layer was placed vertically followed by two transverse layers that were spirally wrapped around the pile without overlap (Fig. 7). In case of glass, this sequence was repeated since two longitudinal layers and four transverse layers were needed to provide the same strength.

A 25 cm (10 in.) wide glass fiber veil with a 5 cm (2 in.) overlap was used to consolidate the wrap and provide a better finish. This was covered by plastic stretch film to keep the wrap in place as it cured. On an average it took less than one hour to wrap a pile.

The FRP was allowed to cure for one day. After removal of the stretch film, all wrapped piles were painted

Fig. 7. Applying second transverse CFRP layer.

over the veil using the same base primer to provide protection against UV radiation.

9. Wet layup system

The Tyfo®SEH-51A composite system was used to wrap piles 101N and 101S. The original plan was to use two different epoxies one for the submerged region and the other for the dry region in the pile. This scheme was tried on pile 101N. However, because of wave action, the dry region was not dry and resulted in observable poor bond between the FRP and the pile. This wrap was later removed. As a result, the same underwater epoxy Tyfo® SW-1 was used for both piles along with Tyfo® SEH-51A fiberglass fabric.

Unlike System A that was a 'pre-preg', in System B the fibers had to be impregnated with resin on-site. This gave greater flexibility since wrap lengths could be adjusted but posed greater logistic problems since impregnation had to be done on-site in a timely manner. This required careful planning and system redundancies to avoid unexpected problems arising from equipment malfunction.

The FRP fabric for pile 101S was impregnated by hand. For pile 101N re-wrapped three months later, a resin impregnator was used (Fig. 8). Following the saturation of the FRP, the wrapping procedure was identical to that for System A. Complete details may be found in the final report [5].

Fig. 8. On-site saturation of fiberglass fabric.

10. Bond tests

For contact-critical applications there is a requirement for intimate contact but no specific requirement for adhesion of the FRP to the concrete substrate [9]. Nonetheless, on-site pullout tests were conducted to evaluate the FRP-concrete bond two years after the wrapping had been completed. An Elcometer106 adhesion tester and a 3.7 cm (1.456 in.) diameter dolly was used to evaluate the FRP/concrete bond. Two System A wrapped piles 100-N* (carbon) and 100-S* (glass), and one System B wrapped pile 101-N were selected. The tests were conducted on two faces per pile at two different levels – in the dry and the tidal region.

FRP witness panels created during the wrap on the east and west faces of the piles were used in the testing. Bond tests were carried out in accordance with established procedure. The FRP surface was scored using a 4.4 cm ($1\frac{3}{4}$ in.) diameter diamond core drill. The surfaces of the scored FRP were cleaned using coarse sand paper and dust removed. Fast curing epoxy (Power-Fast+) manufactured by Powers Fasteners, Inc. was used for bonding the dollies to the FRP. This took 15 min to dry and cured in 24 h. It can provide maximum bond strength of 20 MPa (3000 psi.).

Table 4 and Fig. 9 summarize the results of the pullout tests. The bond of FRP to the concrete substrate was found to be poor. Most of the wet layup wrapped piles showed epoxy failures where the dolly separated from the concrete at its interface (Fig. 10). All tests conducted on the pre-preg system were inter-layer failures (Fig. 11) indicating that the bond between the FRP layers was poorer than its bond to concrete.

Inspection of Table 4 shows that the bond from System B performed better in the wet region while System A was better for the dry region. Similar differences were not observed on laboratory specimens tested [6]. Therefore, the problem with bond can be attributed to the field techniques used for wrapping. On-going research is developing a new protocol to prevent such inconsistency.

Table 4
Summary of bond test result (unit: psi)

Name	Type	Face	Top	Bottom
#100-N*	Carbon AirLogistics	East	145.0 (layer)	58.0 (layer)
		West	116.0 (layer)	0.0 (layer)
		Average	130.5	29.0
#100-S*	Glass AirLogistics	East	0.0 (layer)	0.0 (layer)
		West	0.0 (layer)	0.0 (layer)
		Average	0.0	0.0
#101-N	Glass Fyfe	East	101.5 (epoxy)	58.0 (epoxy)
		West	29.0 (epoxy)	260.9 (concrete)
		Average	65.2	159.5

1 MPa = 145 psi.

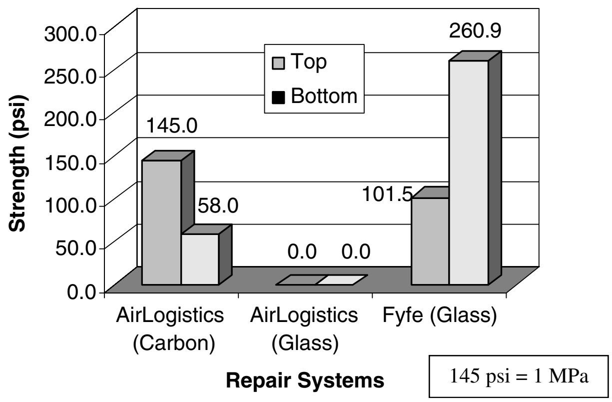

Fig. 9. Maximum residual bond strength after 2 years.

11. Discussion

This paper provides an overview of a demonstration project that explored the feasibility of using FRP to repair corroded reinforced piles in the tidal waters of Tampa Bay. In the study, two contrasting FRP systems were used and two different materials evaluated. Additionally, long term bond was also evaluated from on-site bond tests that were conducted two years after the wrap had been applied.

Of the two systems, the pre-preg was unquestionably the easier to use. The alternative wet layup system offered greater flexibility but required on-site saturation of the resin that requires much greater preparation. Though bond is not a requirement for contact-critical applications, the results from the bond tests showed that the wet layup system performed better particularly in the partially wet and submerged regions. The water-activated pre-preg system performed better in the dry regions.

While the demonstration project was for corrosion repair, the FRP system can be readily adapted for emergency repair. A combination of a boat and divers would allow the wrap to be easily conducted in both the dry and the submerged regions. However, a customized scaffolding system may be better since it can eliminate uncertainty associated with underwater currents and changing weather conditions that can complicate the wrapping operation. The light weight modular scaffolding systems used in the demonstration project can be readily and inexpensively fabricated. They were assembled around the pile and conveniently suspended from the pile cap. Its height was adjusted so that the walk way was below the lowest wrapping depth. In a second demonstration study, steel chains rather than angles were used to support the scaffold from the pile cap since it was deemed to be more convenient for the application [6].

The wrapping operation for the corrosion repairs was carried out at low tide. In case of emergency repairs, an adjustable scaffolding system can be designed to accommodate changing tides. Should repairs be carried out much below the water line, divers would also be needed. The economics of wrapping will require contractors to devise

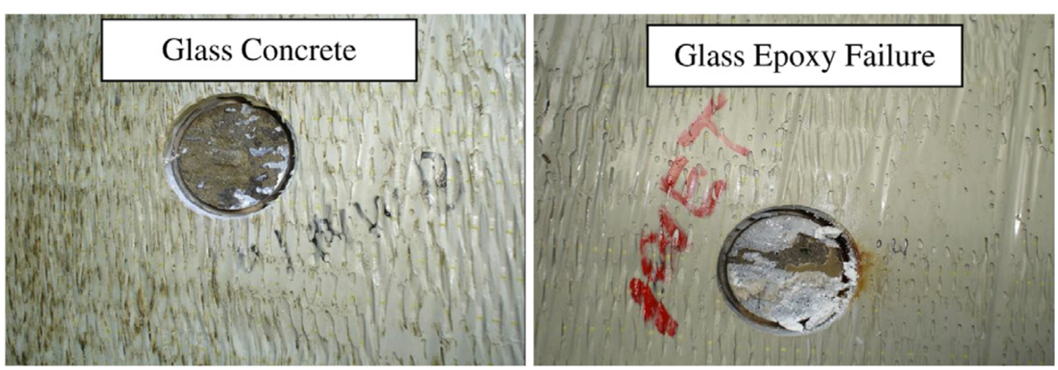

Fig. 10. Failure mode in wet lay up wrap system.

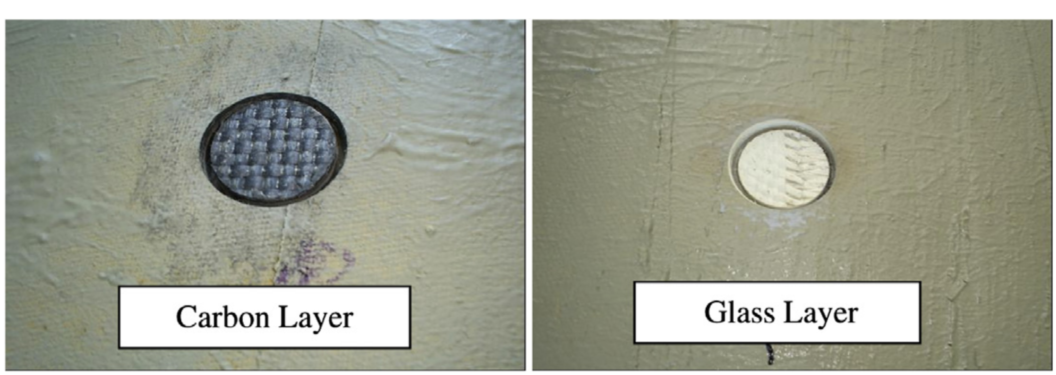

Fig. 11. Failure mode in pre-preg wrap system.

appropriate re-usable, modular, systems that can be used in a number of alternative applications.

The damage to the section needs to be repaired using low shrinkage materials compatible with concrete. Should the section be reformed, appropriate inserts should be used at the corners (Fig. 6). This will greatly reduce the surface preparation work needed to round the edges since sharp corners introduce stress concentrations that cannot be taken by thin FRP material.

Estimate of material cost for wrapping the piles was provided for both systems. This did not include the cost of mobilization or installing the system. Costs expressed per linear m (ft) of the 50 cm (20 in.) square piles ranged from \$670/m (\$204/ft) for glass to \$885/m (\$270/ft) for carbon. These costs compare favourably with alternative repair systems [5,6].

12. Conclusions

The use of FRP for repairing partially submerged concrete elements is relatively new. All applications reported to date relate to corrosion repair. However, given the lightweight, high strength and corrosion resistance of the FRP it is just as suitable for conducting cost-effective emergency repairs. The procedures described in this paper that were used for corrosion repair can be readily adapted for repair of piles damaged otherwise.

Based on the experience gained from the demonstration studies, the following recommendations are made:

1. Speed is of essence in emergency repairs. All around access to piles needed for the wrapping operation is best provided by using scaffolding systems that can be suspended from the pile cap. Should repairs be required significantly below the water line, divers may be needed for wrapping below the water line. If possible, operations should be scheduled for low tide.
2. The FRP wrap should be engineered to provide the required strength. Interaction diagrams need to be developed to allow the combined effect of axial and bending capacity to be considered. The design should seek to keep the number of FRP layers to a minimum. For this reason, bi-directional material should be preferred over uni-directional material and carbon over glass.
3. Both pre-pregs and on-site saturated FRP systems can be used. However, if repairs have to be carried out at very short notice, on-site saturation systems may be the more suitable.
4. If the section is to be re-formed, styrofoam or wood inserts with a curved profile should be placed in the corners so that surface preparation work is minimized and overall costs reduced.

The methods described in the paper were refined and improved with each new application. This will undoubtedly be the case for emergency repairs were similar improvements may be expected. The possibility of using FRP may provide highway authorities with a cost-effective alternative to conventional repair of damaged piles.

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