Development of Vacuum / Pressure Bagging System for FRP Repair

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Abstract
Fiber reinforced polymers (FRP) are widely used in the repair and rehabilitation of structures. Recently, their application has extended to the repair of damage caused by corrosion of steel in concrete. In any strengthening application, the bond between FRP and its substrate is of paramount importance for ensuring proper load transfer. This requires continuous intimate contact between the resin-saturated fibers and the substrate as the resin cures. Such contact is generally maintained except in situations where gravity effects create tendencies for separation. This occurs in the repair of vertical elements such as columns or soffit regions of slabs. Traditional methods of ensuring contact utilize plastic shrink wrap or duct tape. However, the pressure is variable and bond can be poor. Tests have shown that sustained, uniform external pressure can improve FRP bond. Pressure bagging and vacuum bagging are well established techniques routinely used in the fabrication of FRP parts by the aerospace and automotive industry. Their extension to infrastructure applications has been limited. Indeed, no applications of pressure bagging had been reported in the literature until last year. This paper provides an overview of the development of pressure bagging and vacuum bagging systems intended for the repair of piles in tidal waters. The system is inexpensive, easy to use and versatile and can be used for both above and below water applications. Results from destructive pullout tests show that bond is significantly improved by these systems.

Keywords
FRP, Repair, Pressure bagging, Vacuum bagging, Underwater

1. Introduction

The lightweight, high strength and corrosion resistant characteristics of fiber reinforced polymers (FRP) make it the ideal repair material. Not surprisingly, it is increasingly becoming the material of choice for the repair and rehabilitation of structures.

The ACI 440.2R-08 guideline for externally bonded FRP systems defines two broad categories of repairs (1) *bond-critical* and (2) *contact critical*. Bond critical applications are exemplified by flexural repairs of beams and slabs where the bond between the FRP and the substrate is crucial since loads are transferred to the FRP by shear. *Contact-critical* applications are exemplified by seismic retrofit of columns where the FRP material is wrapped completely around the perimeter of a section to provide confinement, not strength. Such systems are passive since the FRP material only provides the needed ductility in the event plastic deformations result from an earthquake.

Aside from the two applications mentioned in the ACI guideline, there are hybrid applications with a dual requirement of strength and confinement as exemplified by the repair of corroding piles in tidal waters. In this application, the FRP material serves the twin functions of strengthening to make up for metal loss due to corrosion and also confinement to withstand expansive forces generated due to corrosion of steel. Thus, there is a need for good bond between the FRP material and its substrate.

2. Why Bond Can Be Poor

The bond between FRP and its substrate is of course dependent on the quality of the surface preparation. The ACI 440-2R-08 guideline stipulates that for concrete surfaces, the concrete surface profile (CSP) should at least meet be a '3' in accordance with the ICRI-surface-profile chips. In addition, all laitance, dust, oil, curing compound and other matter that can interfere with bond must be removed. Even if all these requirements are satisfied, bond can be poor unless there is continuous, intimate contact of the saturated FRP material and the substrate as the resin cures. This is because the resin is initially a liquid with no shear strength. Therefore, if the curing time of the resin is long, the weight of the saturated FRP material will create a tendency for it to slide down or separate from the substrate. It should be noted that applications where gravity effects are present are quite common, e.g. repair of the bottom surface of flexural members such as beams or slabs or the strengthening of vertical elements such as columns.

3. Why Pressure Improves Bond

Concrete has a porous structure that reflects the space unoccupied by the cement and its hydration products. Good bond requires the concrete surface to have an open pore structure that is not clogged. The application of pressure forces the resin into the open pores thereby improving bond. As a result, bond failures will be *cohesive* (in the concrete), not bond-line *adhesive* failures. Not surprisingly, pressure is commonly used to improve bond whether to ensure continuous contact as in attaching strain gages, sun roofs in automobiles or in segmental construction where a minimum 276 kPa pressure is used to join epoxied match-cast concrete segments (AASHTO 1999).

4. Techniques for Improving Bond

Two alternative means have been used by the composites industry for maintaining constant contact between the saturated FRP material and its substrate. These are (1) pressure bagging and (2) vacuum bagging. The extension of these techniques for enhancing bond in underwater FRP repairs had not been attempted prior to the author's recent studies (Winters et al., 2008; Aguilar et al., 2008)

4.1 Pressure Bagging

Pressure bagging FRP repairs on piling or columns is relatively simple in concept and in application. Therein the surrounding geometry of the repaired section allows the pressure bag to develop restraint from its tensile capacity unlike a flat surface repair where an external reaction system would be required.

The pressure bag incorporates an air-tight bladder (low tensile strength) contained within a restraining structure which can be either rigid or flexible. Flexible restraints are more desirable as they can be fitted and adapted as necessary to accommodate multiple pile sizes. The restraining pressure to assure proper contact is limited to the hoop strength of the pressure bag.

4.2 Vacuum Bagging

Vacuum bagging applies pressure by creating a vacuum (limited to a maximum of 1 atmosphere - 760 mm of Hg). It is particularly advantageous for large flat surfaces where hoop strength is difficult to develop or where adjacent structures are not available to provide a reaction force. No special strength considerations arise concerning the bag tensile strength but rather a puncture resistant membrane material is sought. The maintenance of an air tight seal is critical and difficult to sustain since the concrete to be repaired is likely to be cracked.

5. Development of Pressure / Vacuum Bagging for Pile Repair

A limited number of vacuum bagging applications relating to infrastructure repair have been reported in the literature (Stallings et al., 2000; Nazier et al., 2005). No studies describing pressure bagging were reported prior to those conducted by the authors. Since the original development (Winters et al., 2008), much progress has been made (Aguilar et al., 2008) and this is reported here.

5.1 New Pressure Bag Design

Changes were made to the design of the pressure bag compared to the one used in the earlier study. These were to the design of both the outer bag that is wrapped around the pile and the inner bladder that fits inside the outer bag. The outer bag prevents bursting of the inner bladder by providing structural support. The inner bladder provides a sealed, conformable system for applying air pressure to the outside surface, the FRP wrapped region of the pile.

5.1.1 Outer bag

The bag was made from rubberized nylon 1.45m long by 1.14m wide (4.75ft long by 3.75ft wide) (Figure 1). The design was refined to incorporate double stitched edges, a zipper enclosure, cinch straps for securing the bag, and a reinforced region for the flange.

Figure 1: Pressure Bag Used in Laboratory Study

5.1.2 Internal bladder

The internal bladder of the pressure bag was made using a 0.2mm (0.008in) thick roll of clear PVC. It was necessary to produce a slightly oversized bladder to ensure full expansion when placed and inflated inside the outer bag. A 3.66m x 1.37m (12ft x 4.5ft) PVC sheet was cut, folded crosswise, then glued with a 0.15m (0.5ft) overlap to produce a 1.37m (4.5ft) wide ring. The ring was laid flat, and prior to sealing the edges, a metal flange was installed to provide a means of attaching a hose and inflating the bag. The edges were sealed, folded inward, and taped, resulting in a bag that was 1.75m x 1.37m (5.75ft x 4.5ft). The bladder was placed inside the outer bag and held using Velcro strips. The Velcro maintained the proper orientation of the bladder within the outer bag to prevent bunching prior to inflation.

5.1.3 Testing

The bag was expected to safely maintain a pressure of 48 kPa (7 psi) with an ultimate design pressure of 70 kPa (10 psi). This was verified by a full-scale test. In the test, the bag was attached to a concrete pile and the bladder inflated (Figure 2a).

As the pressure increased, the cinch straps in the center of the bag were removed to assess the tensile capacity of the zipper alone (Figure 2b). The bag exceeded the design requirement of 48 kPa (7 psi) (Figure 2c) and a total pressure of 70 kPa (10 psi). After 70 kPa (10 psi) was achieved, the zipper failed. The design was deemed acceptable. However, the number of cinch straps was increased from 3 to 4 in the bags that were later fabricated for testing. This can be seen by comparing the number of straps in Figure 2 (3 straps) with those in Figure 1 (4 straps).

(a) (b) (c)

Figure 2: (a) Pressure Bag Partially Inflated; (b) Bag after Cinch Strap has been Removed; (c) Pressure Gage Reading

5.2 New Vacuum Bag Seal

Unlike pressure bagging where net pressure is obtained by increasing the external pressure, vacuum bagging applies net pressure by decreasing the internal pressure. Entrapped air is evacuated within the wrap using a system consisting of a sealing bag, breathing material and a vacuum pump. An advantage of using vacuum is that no special consideration must be given to the tensile strength of the bag, since the pile itself provides the structure to prevent the bag from collapsing. Rather, consideration is given to the puncture resistance of the material.

5.2.1 Vacuum bag

Vacuum bags used in this study were made from a roll of 0.2mm (0.008in) thick clear PVC. A 1.37m x 1.42m (4.5ft x 4.7ft) sheet was cut and wrapped lengthwise around the pile with a 76.2mm (3in) overlap. After gluing the overlap, a flange was installed in a similar fashion to those used for the pressure bag. The flange served as the means for connecting the bag to the vacuum pump.

5.2.2 Air tight seal
One of the most critical aspects of the vacuum bag system is the formation of an airtight seal between the vacuum bag and the pile specimen. To provide an air-tight seal at the upper and lower ends of the bag, it was determined that a flexible intermediate material was needed which would contour to the dimensions of the pile as well as be flexible enough to contract under vacuum. After multiple trial attempts at creating a seal with putty, silicone, and tar in a previous study failed, a suitable intermediate was found in ½ in. thick closed-cell foam.

The foam was cut and glued into 0.15m x 1.17m (0.5ft x 3.83ft) rings using contact cement. The rings were stretched over the pile and positioned at the upper and lower extents of the vacuum bag. Details of the foam pad and the flange assembly for the vacuum bag are shown Figure 3.

Figure 3: Closed Cell Foam about to be Glued and Vacuum Port in Bag

After the rings were in position between the pile surface and vacuum bag, a duct tape was wrapped around the outside of the vacuum bag within the region of the rings to provide confinement for initial sealing. Once vacuum was applied, the upper and lower rings became self-sealing, thereby eliminating the need for additional confinement.

6. Application of Pressure / Vacuum Bagging for Pile Repair

The application of pressure bagging and vacuum bagging in underwater pile repair using FRP was tested in a laboratory experiment using twelve, 0.305m (12in) square pre-stressed concrete piles (4 controls, 4 pressure bag, & 4 vacuum bag). Figure 4 shows the (a) pressure bag and (b) vacuum bag applied to the laboratory specimen. The steps for installation of pressure and vacuum bagging are as follows:

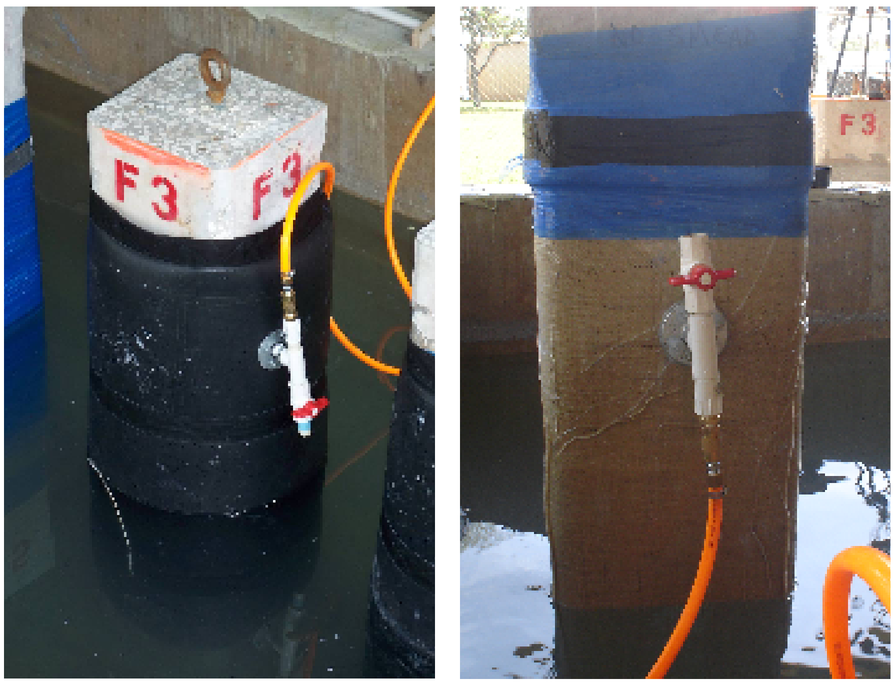
Installation of Pressure Bags

Step 1: Place a protective layer over the final FRP application to separate the pressure bag from the FRP during curing. This is typically a plastic stretch-wrap.
Step 2: If necessary, place a breathable layer over the stretch-wrap. This is for gas-generating resins.
Step 3: Wrap the pressure bag around the pile (un-inflated).
Step 4: Zip the two ends of the pressure bag together and connect the air source.
Step 5: Connect the buckle cinch straps and begin to inflate the bag. The cinch straps must work with the zipper enclosure; therefore the cinch straps should be kept loose until minimal pressure is achieved and then tighten prior to full pressurization.

Step 6: Inflate the pressure bag to the desired pressure (safe working loads of the bag design).

Installation of Vacuum Bags

Step 1: Place a protective layer over the final FRP application to separate the vacuum bag from the FRP during curing. This is typically a plastic stretch-wrap.
Step 2: Place a breathable layer over the stretch-wrap. This is to allow the air to escape around the pile during vacuuming.
Step 3: Slide the closed cell foam bands to the outside of the FRP repair area.
Step 4: The vacuum bag is then slipped over the pile and positioned over the foam bands.
Step 5: Cinch the plastic bag down to the closed cell foam ensuring an air-tight seal of the system.
Step 6: Connect the vacuum source to the desired pressure.



(a) (b)

Figure 4: (a) Pressure Bagging; (b) Vacuum Bagging

7. Results of Pressure / Vacuum Bagging for Pile Repair

The effect of pressure bagging and vacuum bagging on bond was evaluated in tests conducted on full-size pile specimens. Since the application was for piles in tidal waters, the specimens were placed in a tank containing water so that half the FRP wrapped region was completely submerged while the other half was completely dry. The results from pressure / vacuum bagged specimens were compared against those for identically prepared controls where no pressure was used.

Pullout tests were conducted using an Elcometer 106 adhesion tester. A total of 422 pullout tests were conducted on 12 specimens. Figure 5 summarizes the results of the tests from 4 controls, 4 pressure bagged, and 4 vacuum bagged piles.

Results show an average increase in bond of 71% for pressure bagging above waterline (dry region) and 75% increase in strength below waterline (wet region). Vacuum bagging showed improvements of 56% and 33% increase in strength above and below waterline, respectively.

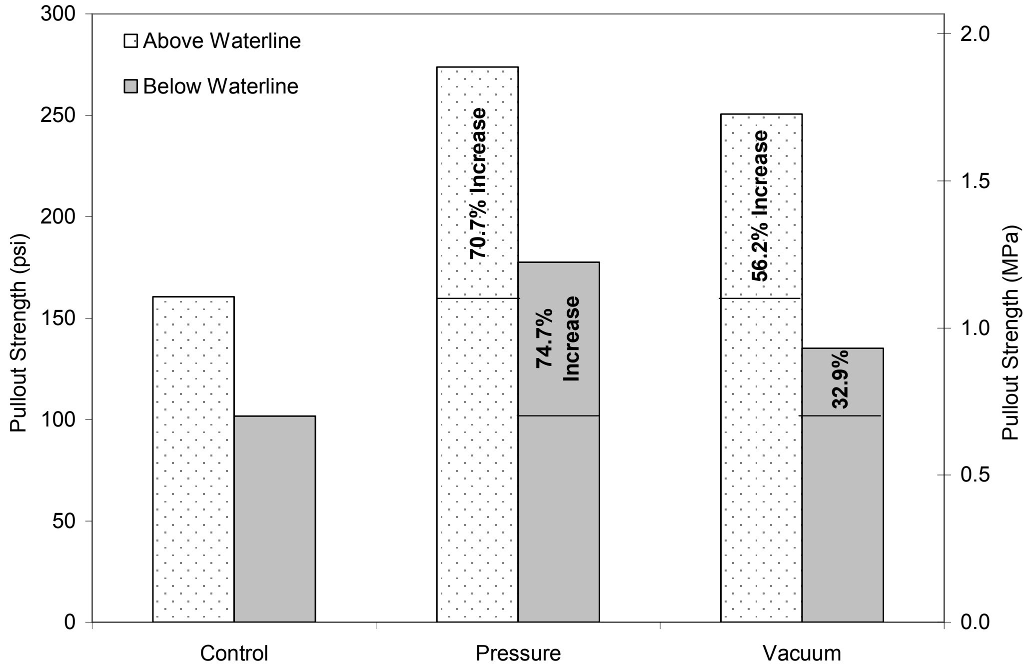


Figure 5: Average Pullout Test Results

8. Summary and Conclusions

This study shows that the techniques used by the composites industry can be readily adapted for infrastructure repair. Two new, inexpensive systems were developed that permitted repairs to be conducted using pressure or vacuum bagging.

The results of the laboratory testing confirm that external pressure, either by pressure or vacuum bagging, significantly enhances the bond between FRP and concrete both above and below the waterline. From the practical standpoint, pressure bagging is simpler for concrete structures since there is no requirement for an airtight seal as in the case of vacuum bagging. An air tight seal is problematic when the concrete is cracked. The pressure bagging system developed in the laboratory was successfully implemented in field repairs of piles supporting the Friendship Trail Bridge located in tidal waters of the Gulf of Mexico (Winters et al., 2008).

The developments reported provide the construction industry with a simple, practical method for improving concrete-FRP bond in repairs of piles and columns both above and below the waterline.

9. Acknowledgements

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