



Evaluation of externally bonded fiber reinforced polymer systems to concrete structures

A white paper by

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Introduction

Originally developed in Japan and Europe in the 1980s, the use of fiber reinforced polymer (FRP) to strengthen concrete is gaining increasing popularity in the United States. FRP systems can be used to retrofit and rehabilitate bridges, buildings, parking garages, and other concrete structures. Figure 1 shows a photograph of FRP applied to the tension face of a concrete beam.



Figure 1: Externally bonded fiber reinforced polymer (FRP) to a concrete beam

Fiber reinforced polymer, or commonly referred to as FRP, is a polymer matrix that is reinforced with high-strength carbon or glass fibers. FRP possesses a high tensile strength; in addition, it is light-weight, corrosion resistant, and generally easy to install. Because of these advantages, FRP has become a desirable approach for the repair, rehabilitation, and updating of existing concrete structures.

This paper briefly describes the test methods and acceptance criteria for evaluating the in-place adhesion strength of externally bonded FRP to concrete. For a full description of the design, installation, and application of FRP systems to concrete structures, the reader is directed to ACI 440.2R, *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures* [1].

This paper would be of interest to general contractors, repair contractors, inspection and testing agencies, FRP and adhesive manufacturers, engineers, architects, and owners.

Installation of FRP systems

There are a few approaches for installing externally bonded FRP systems, including either a pre-cured (i.e. prefabricated) or a wet layup application. The wet layup method involves saturating the fiber sheets with resin, applying the sheets to the concrete surface, and then

allowing the system to cure in-place. Conversely, pre-cured sheets (or shells) are manufactured in a controlled environment and then later adhered to the concrete structure.

Several different parameters (e.g. material properties, environmental conditions, loading) should be considered prior to the application of FRP to concrete members, and should be done with the guidance of a knowledgeable structural engineer. While the installation of FRP is generally considered to be a simple process, errors in the handling and application can occur. Therefore, it is critical to inspect and test the final installed system.

Inspection and testing of FRP systems

Prior to and during the installation of the FRP system, appropriate quality control measures must be applied to ensure that the FRP-concrete system complies with the performance criteria. Then, once the FRP system has been installed and adequately cured, it should be inspected and tested to verify conformance with accepted application procedures. Visual inspection should be performed in conjunction with nondestructive testing and evaluation (NDT&E) techniques, such as acoustic sounding, thermography, and pull-off adhesion testing. Of the different approaches, pull-off testing provides the best quantitative information, i.e. least subjective, but has higher costs (see Figure 2).

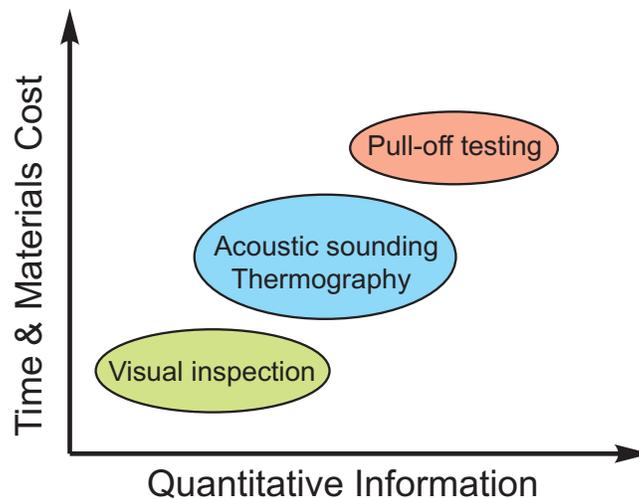


Figure 2: Graph showing the relative costs and quantitative information for inspection techniques

Visual inspection is the simplest and generally the first approach for the inspection of FRP systems. The inspector should look for evidence of any type of surface defects, such as cracking, wrinkling, and blistering (bubbles). While visual inspection can be an effective tool for assessing the quality of the FRP installation, it is subjective in nature and relies heavily on the experience and knowledge of the specific inspector.



Figure 3: Photograph of inspector examining the FRP-concrete system

Acoustic sounding (i.e. tap test) is used to determine if voids, delaminations, or bubbles are present between the FRP and the concrete. Typically, the inspector will use a hammer to tap the surface of the FRP-concrete system and will then listen for a dull hollow sound (imagine the sound of a loose ceramic tile on the floor). This technique is similar to the popular chain drag method that is used for detecting delaminations in concrete bridge decks. Alternatively, thermography can be used to detect delaminations. Thermography measures infrared radiation that is emitted from the structure. Because delaminations will cause variations in the heat flow along the structure, these *hot spots* can indicate locations where the FRP is improperly bonded to the concrete. The primary advantage of both these techniques is that they can be applied quickly and provide an overview of the system. Acoustic sounding and thermography can be used to identify delaminations; however, they are not able to quantify the bond strength between the FRP sheets or the FRP-concrete interface.

Pull-off adhesion testing, ASTM D4541 [2], ASTM D7522/D7522M [3], or ACI 440.3R Test Method L.1 [4], is used to determine the bond strength between the FRP layers and the FRP-concrete interface. Figure 4 shows an example of the pull-off testing equipment. The test method requires a dolly (pull stub) to be bonded to the surface of the FRP-concrete system. A tensile force, perpendicular to the surface, is applied to the dolly until it is detached (i.e. failure occurs). The maximum tensile stress or bond strength is calculated based on the applied load and the area of the dolly face. Figure 5 provides a schematic diagram of the test method. Typically, the surface of the FRP at the periphery of the dolly is cut into the concrete substrate (i.e., 0.25 to 0.50 in.), a procedure termed *scoring*. Scoring the surface ensures that the load is applied uniformly over the surface area of the dolly face and that the resulting stress is solely tensile. Because of the heterogeneous nature of concrete, 2 in. diameter test dollies should be utilized. While smaller dollies are commercially available, applying a load over a small surface area makes the test results more susceptible to be influenced by local anomalies (e.g. large aggregate, weak paste, etc.).

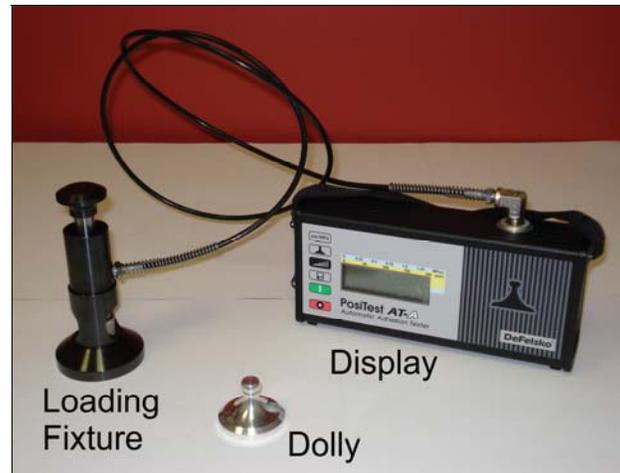


Figure 4: Photograph of pull-off adhesion test equipment

In addition to the bond strength of the system, the specific failure mode should be noted (e.g. failure in the concrete substrate, failure between the layers of the FRP). Ideally, the failure should occur in the concrete substrate (see Figure 5 and Figure 6), meaning that the bond between any layers of the FRP and between the FRP-concrete interface is greater than the concrete tensile strength.

While the pull-off adhesion test may be categorized as an NDT&E technique, it is not purely nondestructive; however, the affected surface area is relatively small compared to the whole system (i.e. minimally invasive). Alternatively, this test method can be modified to make it purely nondestructive by only loading the dolly to a pre-determined amount of stress (i.e. not until it fails). In this modification of the test method, the FRP would not be scored.

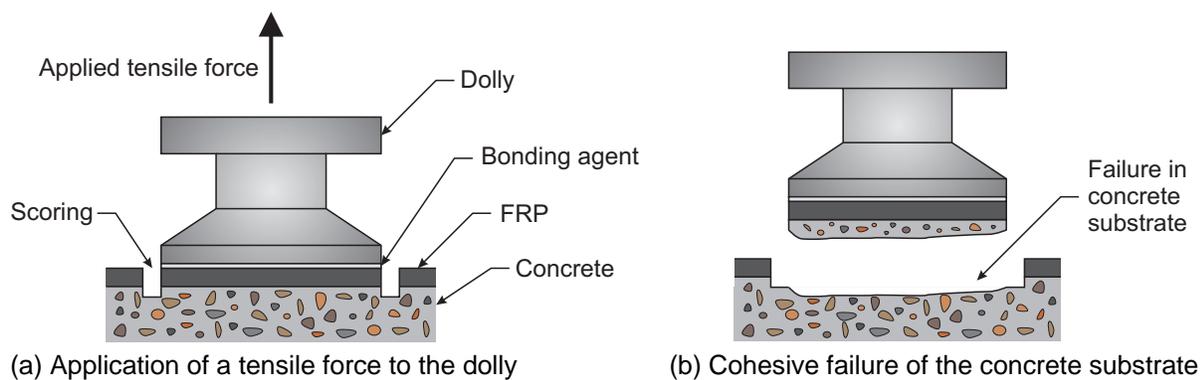


Figure 5: Schematic diagram of pull-off adhesion test



Figure 6: Photograph of dolly showing cohesive failure of the concrete substrate

Delaminations

If not carefully installed, delaminations can occur during the application of the FRP to the concrete surface. ACI 440.2R specifies that delaminations less than 2 in.² are permissible as long as defect area is less than 5% of the total area and there are no more than 10 such delaminations per 10 ft². Any delaminations that do not follow these guidelines (i.e. greater than 2 in.²) should be properly repaired.

Adhesion strength

It is important that the FRP materials are properly adhered to the concrete member. Furthermore, if multiple layers of FRP are applied, it is critical to ensure that the layers are properly bonded together. ACI 440.2R specifies that for bond critical applications, the tension adhesion strength should exceed 200 psi and should exhibit failure within the concrete substrate (refer to Figures 5 and 6). Currently, ACI 440.2R does not specifically address the pull-off testing locations and frequency, which highlights the importance of a properly developed test plan. Depending on the specific test standard that is being referenced, the number of recommended trials will vary from three to five trials per representative area. A typical test plan should require at least one trial per 1000 ft² with a minimum of three trials. Additional requirements may include testing for each day that the FRP was applied and/or for each concrete type. For complex projects, it may be advantageous to conduct a proof-of-concept (i.e. apply FRP to small section of concrete) to ensure that the FRP-concrete system achieves acceptable test results prior to the actual application.

It is important to note that the bond strength of the FRP system relies on the concrete substrate having acceptable compressive and tensile strength. For bond critical applications, the compressive strength and tensile strength of the concrete should be at least 2500 psi and 200 psi, respectively [1]. This is an important, although an often overlooked, aspect of the

installation process and illustrates the importance of testing the concrete strength prior to applying the FRP system.

Summary

While the application of FRP seems simple and the testing is relatively straight-forward, several problems can persist during the evaluation of the FRP-concrete bond strength. Weather, particularly temperature fluctuations, can cause improper curing of the epoxy resin. For the FRP system to be effective in enhancing the strength of the concrete member, the tensile strength of the concrete substrate must be sufficient. For example, if the tensile strength of the concrete is less than 200 psi, one can encounter failing pull-off tests results even if the actual bond strength is greater than 200 psi. Table 1 provides a summary of typical challenges that are encountered when evaluating externally bonded FRP to concrete structures.

Table 1: Challenges of pull-off adhesion testing

Challenge	Potential cause
Delaminations between FRP layers or between FRP and concrete	<ul style="list-style-type: none"> • Improper curing of resin (e.g. low ambient temperature) • Air trapped between sheets during application
Dolly detaches at FRP surface	<ul style="list-style-type: none"> • Dolly face not abraded to ensure good adhesion • Dolly face contaminated with oils • Improper cure of dolly adhesive
Failure in concrete substrate, but low pull-off strengths	<ul style="list-style-type: none"> • Improper scoring process caused weakened concrete substrate • Concrete tensile strength is low

It is critical that the acceptance criterion for the FRP system is clearly defined at the beginning of a project. There is a common misconception that the testing locations and frequency is outlined within ACI 440.2R; currently, this is not the case. The results (or lack of results) of a simple tensile test can delay a multi-million dollar project because the test plan was not clearly outlined in the contract or design documents.

References

- [1] ACI 440.2R (2008). Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures. In *ACI Manual of Concrete Practice*. Farmington Hills, Michigan: American Concrete Institute.

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