

EVALUATION OF EXTERNALLY BONDED FIBER-REINFORCED POLYMER SYSTEMS TO CONCRETE STRUCTURES

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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 U.S. 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.

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 lightweight, 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.

Described herein are 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, refer to ACI 440.2R, “Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures.”¹



Fig. 1: Externally bonded FRP to a concrete beam

INSTALLATION OF FRP SYSTEMS

There are a few approaches for installing externally bonded FRP systems, including either a pre-cured (that is, prefabricated) or 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 (for example, material properties, environmental conditions, and 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—that is, pull-off testing is the least subjective approach, but has higher costs (refer to Fig. 2).

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 inspector (Fig. 3).

Acoustic sounding (that is, a 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 of 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 D4541²; ASTM D7522/D7522M³; 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 (that is, until 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 (that is, 0.25 to 0.50 in. [6.4 to 13 mm])—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. (50 mm) diameter test dollies should be used. 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 (for example, large aggregate, weak paste, and so on).

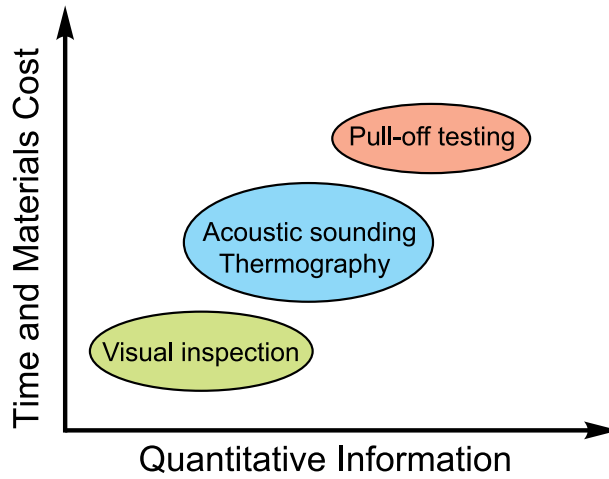


Fig. 2: Graph showing the relative costs and quantitative information for inspection techniques



Fig. 3: Inspector examining the FRP concrete system

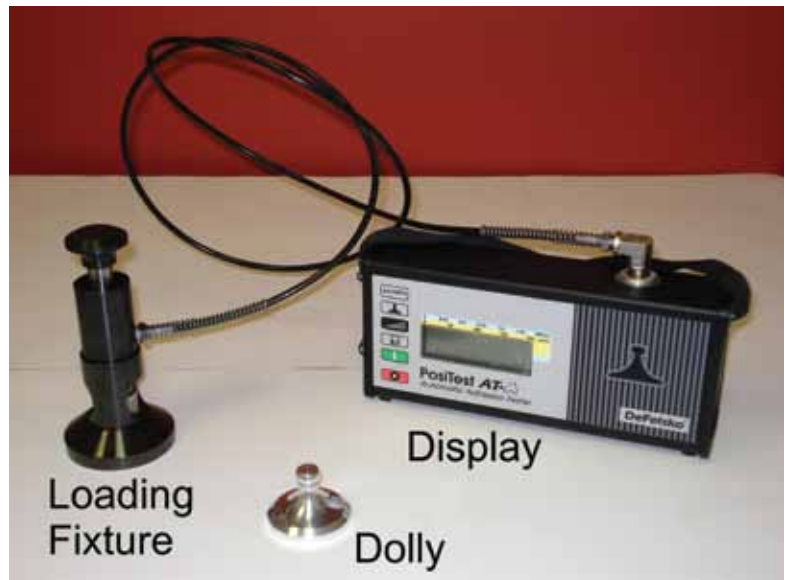


Fig. 4: Pull-off adhesion test equipment

In addition to the bond strength of the system, the specific failure mode should be noted (for example, failure in the concrete substrate or failure between the layers of the FRP). Ideally, the failure should occur in the concrete substrate (refer to Fig. 6 and 7), 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 (that is, minimally invasive). Alternatively, this test method can be modified to make it purely nondestructive by only loading the dolly to a predetermined amount of stress (that is, not until it fails). In this modification of the test method, the FRP would not be scored.

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 (1290 mm²) are permissible as long as the defect area is less than 5% of the total area and there are no more than 10 such delaminations per 10 ft² (0.93 m²). Any delaminations that do not follow these guidelines (that is, greater than 2 in.² [1290 mm²]) 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 (1.4 MPa) and should exhibit failure within the concrete substrate (refer to Fig. 6 and 7). 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 (92.9 m²) 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 (that is, apply FRP to a 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 and 200 psi (17.2 and 1.4 MPa), respectively.¹ This is an important although often overlooked aspect of the installation process and illustrates the importance of testing the concrete strength prior to applying the FRP system.

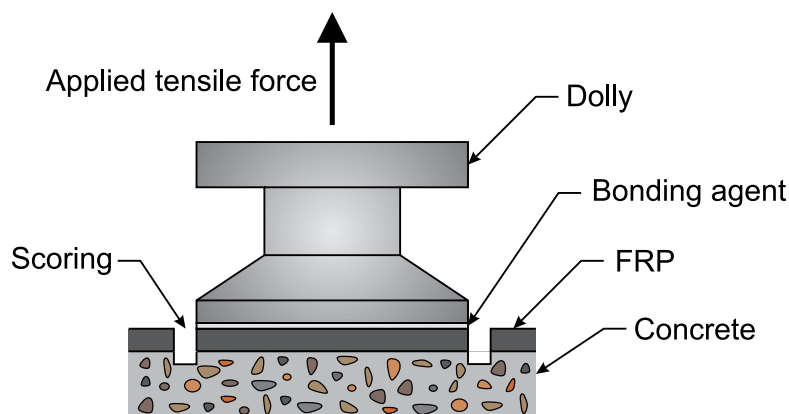


Fig. 5: Schematic diagram showing application of a tensile force to the dolly

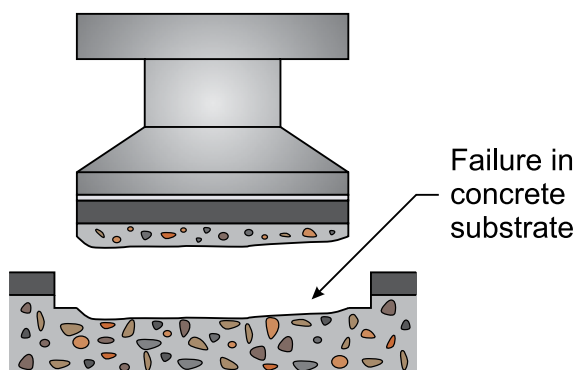


Fig. 6: Schematic diagram showing cohesive failure of the concrete substrate



Fig. 7: Dolly showing cohesive failure of the concrete substrate

TABLE 1: CHALLENGES OF PULL-OFF ADHESION TESTING

| Challenge | Potential cause |
|--|---|
| Delaminations between FRP layers or between FRP and concrete | Improper curing of resin (for example, low ambient temperature) |
| | Air trapped between sheets during application |
| Dolly detaches at FRP surface | 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 | Improper scoring process caused weakened concrete substrate |
| | Concrete tensile strength is low |

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 (1.4 MPa), one can encounter failing pull-off test results, even if the actual bond strength is greater than 200 psi (1.4 MPa). Table 1 provides a summary of typical challenges that are encountered when evaluating externally bonded FRP to concrete structures.

REFERENCES

1. ACI Committee 440, “Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures (ACI 440.2R-08),” American Concrete Institute, Farmington Hills, MI, 2008, 76 pp.
2. ASTM D4541-09e1, “Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers,” ASTM International, West Conshohocken, PA, 2009, 16 pp.
3. ASTM D7522/D7522M-09, “Standard Test Method for Pull-Off Strength for FRP Bonded to Concrete Substrate,” ASTM International, West Conshohocken, PA, 2009, 6 pp.
4. ACI Committee 440, “Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures (ACI 440.3R-04),” American Concrete Institute, Farmington Hills, MI, 2004, 40 pp.



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