Chapter 8
Quality Assurance

8-1. Test Methods

a. ASTM standards.

(1) Compounding the design issue is the fact that not all of the mechanical tests required for determining structural capacities for composite materials have been standardized. ASTM provides test methods for steel which provide all of the necessary capacities for different grades of steel as well as test methods for determining concrete mechanical properties. Currently methods are being developed for the testing of composite materials, but all the methods being developed have not yet been standardized nor have all the tests needed been developed. The lack of proper tests makes designing with composites difficult since there is not a standard to use as a reference.

(2) ASTM standards have been developed for a number of tests that are used to evaluate mechanical properties of composite components. Among the more important ones are the ones listed below:

ASTM D 638	Standard Test Method for Tensile Properties of Plastics
ASTM D 790	Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulation Materials
ASTM D 1242	Standard Test Methods for Resistance of Plastic Materials to Abrasion
ASTM D 2344	Standard Test Methods for Interlaminar Shear Test
ASTM D 3039	Standard Test Method for Tensile Properties of Fiber-Resin Composites
ASTM D 3171	Standard Test Method for Fiber Content of Resin-Matrix Composites by Matrix Digestion
ASTM D 3410	Standard Test Method for Compressive Properties of Unidirectional Crossply Fiber-Resin Composites
ASTM D 3479	Standard Test Methods for Tension-Tension Fatigue of Oriented Fiber, Resin Matrix Composites
ASTM D 3518	Standard Practice for In-Plane Stress-Strain Response of Unidirectional Polymer Matrix Composites
ASTM D 4255	Standard Guide for Testing Inplane Shear Properties of Composites Laminates
ASTM D 5229	Standard Test Method for Moisture Absorption Properties and Equilibrium Conditioning for Polymer Matrix Composite Materials

(3) ASTM D 638 has been used extensively by the plastics industry, but may not be the best choice for some composite materials. ASTM D 3039 was originally developed for thin sectioned composite structures, such as those common in the aerospace industry.

(4) Standards that still need to be developed are for various types of fracture toughness testing, such as delamination fracture testing, free-edge fracture testing, and end notch flexure test fracture testing. There are also two fracture test methods that were developed for use with metallic materials that are commonly being used for composite materials. They are:

ASTM E 399	Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials
ASTM E 813	Standard Test Method for J_{IC}, A Measure of Fracture Toughness

b. SACMA standards. Another set of test methods is available in the Suppliers of Advanced Composite Materials Association's (SACMA) SRM Manual. The SACMA Standards may be used in combination with other standardized tests.

c. Military specifications. Numerous military specifications exist with respect to testing of composite materials. Since FRP composite materials have been utilized for some time in the military, an extensive list of the specifications used in these applications is available and can be accessed as needed.

d. State-of-the-art report from ACI. Acceptance of FRP materials within the civil engineering community will depend on the recommendations of code- and standard-writing authorities such as the ASTM and the American Concrete Institute (ACI). These organizations currently have committees devoted to bringing these materials into the engineering community. The ACI Committee 440, on FRP Reinforcement, is currently writing a state-of-the-art report on FRP materials. This report includes chapters on history of FRP's, composite materials and processes, mechanical properties and test methods, behavior of nonprestressed structural elements, external reinforcement, field applications, and research needs. This text will have many good references and will contain many appropriate answers for people interested in knowing more about FRP materials for civil engineering applications. This publication will be available from ACI before the end of 1995.

8-2. Inspection and Performance Monitoring Methods

a. Background.

(1) The acceptance of FRP composites in civil engineering applications has been slow in growth, in part because of limited performance history of composite materials in civil-engineering-type applications. Performance monitoring of composite structural elements is important for several reasons: (a) to identify any problems with the FRP composite component before catastrophic failure occurs, (b) to designate where repairs are needed to avoid premature failure and/or extend useful life, and (c) to help establish a database of performance history in actual use situations.

(2) Defects (e.g., voids) and damage (e.g., delaminations) to FRP composite materials are not always easy to detect as these conditions are not always evident on the surface. A number of inspection techniques are available for use with composite materials. Most of these methods have been used extensively in the aerospace industry. Currently there are no consensus standard practices established within the construction industry for the inspection and quality assessment of FRP composite materials. Little information is available regarding the type and extent of the defect or damage relative to any change in properties of the composite component. The following information may be used, however, to help determine the suitability of using one or more of the inspection and performance monitoring techniques described below.

b. Visual inspection.

(1) Visual inspection is a very valuable technique for monitoring performance and should not be overlooked. Many defects can be detected visually. Defects readily detected visually include: discoloration, cracking, blistering, pitting, cuts and dents, and other surface damage problems. Under certain conditions, porosity, voids, and delamination may also be detectable by visual inspection.

(2) Visual inspection is most effective in detecting defects that are at or near the surface. Internal defects are not as easily detected by visual inspections unless the system is translucent or the defect is extensive enough to show as a surface flaw. ASTM D 2563, "Classifying Visual Defects in Glass Reinforced Laminates and Parts Made From These," will provide some help in visual inspections. No matter what, if any, other methods are used, performance monitoring of the composite structure by visual inspections should be performed on a routine, periodic basis.

c. Instrumental nondestructive evaluation (NDE) methods. A variety of common NDE methods used for or originally developed for other materials have been adapted for use with FRP composites. Some of the most widely used methods include sonic testing, ultrasonic testing, radiography (X-ray), and infrared detection. Each method has its strong points as well as limitations. Table 8-1 shows the type of defects that can be detected using the different NDE methods.

(1) Sonic methods. Although electronically controlled and instrumented sonic methods now exist, they were basically derived from the simple method of tapping the item with a small tool and listening to the sound. By simply tapping the surface of the composite with a small tool or even a coin, delaminations and large voids may be detectable. A composite component free of voids and delaminations will produce a clear, sharp ringing sound. A hollow or dull sound indicates the presence of delaminations and/or voids. The effectiveness of such a technique, of course, depends a great deal on the experience of the inspector. In a more sophisticated sonic test method, the tapping apparatus is electronically controlled and the produced sound is picked up by a microphone. The wavelengths used in the sonic methods limit the detection of defects to relatively large sized defects.

Table 8-1
Types of Composite Defects Detected by Various NDE Methods[1]

Type of Defect or Variation	Sonic	Ultrasonic	X-ray	Infrared Detection
Debonding	X	X	X	X
Delamination	X	X	X	X
Undercure	X	X		
Fiber misalignment			X	
Damaged filaments			X	
Variation: in thickness,	X	X	X	
in density		X	X	
Voids	X	X	X	X
Porosity	X	X	X	
Fracture	X	X	X	
Contamination			X	

[1] From *Materials Engineer*, March 1978, page 69.

(2) Ultrasonics. The detection size limitations of sonic methods can be overcome by using ultrasonic frequencies in the range of 100 kHz to 25 mHz. Three basic ultrasonic techniques applicable to composite materials include: pulse echo, through-transmission, and resonant frequency. Although each of these methods differs in how the test is set up and conducted, they all involve the conversion of electrical energy to sound energy and back again for detection. Through-transmission techniques require access to both sides of the item being analyzed. Besides detecting blisters, voids, and delaminations, through-transmission ultrasonic techniques may be used to indicate changes in strength, modulus, and density along the cross section. Resonant ultrasonic techniques may be used to assess the quality of adhesive bonds used in the composite system. For the most accurate assessment of the data output from any of these ultrasonic techniques, specimens of the same type of material with known properties or defects must be used as standards. Baseline readings of the composite structure should be made on areas where the material is known to be sound. For most accurate results, follow the manufacturer's operational instructions for each type of equipment.

(3) Radiography (X-ray). X-ray analysis techniques used for metals and ceramic materials are applicable to FRP composite materials as well. Although almost any defect normally found in FRP composites may be detected by X-ray techniques, the method does have some limitations. Cracks, voids, and delaminations that lie perpendicular to the ray path may go undetected unless such defects are so large that they would probably be readily detectable by visual means anyway. Cost, difficulties in performing the analyses in the field, and worker safety limit the use of this technique.

(4) Infrared detection. As a composite material cools from being heated (e.g., by using a heat source such as heat lamps or from being in the sun all day), internal defects such as delaminations or voids will slow the dissipation of heat causing a temperature gradient at the surface above the defect. This resulting temperature gradient can be measured using an infrared detector called a radiometer or an infrared camera. Typical radiometers are sensitive to temperature differences as small as 0.1 °C (0.18 °F). Infrared cameras are capable of detecting temperature differences in the order of 1 °C (1.8 °F). The method has the advantage over ultrasonic techniques in that there is no need for direct contact (including coupling agents, etc.) with the item being measured. A limitation, however, is that the infrared detection method is useful mainly for detecting delaminations and relatively large voids and then only if these defects are near the surface.

d. Remote sensing and smart systems. The NDE methods described above for monitoring performance require ready, direct access to the composite component or structure being evaluated. This is not always convenient or possible for submerged components or structures in remote locations. It may also be desirable for some critical structural components to have continuous monitoring of the system to warn of possible property changes that could catastrophically affect system structural performance. Such remote performance monitoring may be accomplished by incorporating external and/or internal sensors as part of the FRP composite structure. Strain gages, fiber optics, and piezo-polymer materials may be used as remote sensors. Strain gage sensors have been routinely used to monitor and proof-test FRP composites. However, the use of fiber optics and piezo-polymers for performance monitoring of FRP composites is not yet common practice. Such systems are still undergoing considerable development and refinement in the research community. The term "smart" composite is sometimes used to describe a composite system with a built-in sensor. [By strictest definitions, a "smart material" is a material that "can sense changes in its environment and make useful or optimal response by either changing its material properties, geometry, mechanical or electromagnetic response" (Varadan, Chin, and Varadan 1992).] Research is also ongoing to develop "smart" composites using embedded particles or "tags."

(1) Strain gages. The use of bonded strain gages to measure induced strain dates to the early thirties. Today's resistance strain gages consist of a grid of strain-sensitive metal foil that has been bonded to a plastic backing material. The gage is adhesively bonded to the item to be measured. When the item is stressed, a change in electrical resistance occurs which is proportional to the strain. Strain gages may be mounted at areas of known or anticipated high stress or other locations where critical strains may occur and need to be monitored. Gage length, width, and type of gage material must be matched to the application. Gages that will be exposed to the elements must be appropriately sealed from the environment. Gages are mounted on the surface of the component to be measured. The component, along with the strain gage, may then be embedded into another material--for example, placing strain gages on reinforcement bars which are then embedded in concrete. Strain gages provide strain-related information for the item only at the point of attachment. Therefore, the placement, number, and orientation of the gage is critical for optimum information output. Strain gage manufacturers are very willing to help determine the gage type, number, recommended locations, orientations, etc., to be used for a particular application and should be consulted as needed.

(2) Fiber optics. Considerable effort is being expended in the research communities (academia, industry, and government) to develop fiber optic systems to provide mechanical property data on structural systems, especially critical structures such as aircraft components. Fiber optics can function as sensors because the light channelled through the optical fibers is altered by the state of stress around the fiber. Such fiber optic sensors can provide information regarding: (a) changes in stress, strain, or pressure, (b) excessive vibration or deflections, (c) fracture crack growth, and (d) changes in the exposure (chemical) environment. Application of fiber optics in FRP composites is still in its infancy. Guidance on location and density of fibers needed and how to interpret the data output is not yet highly refined. Although the technique has a disadvantage regarding the cabling and connections necessary, fiber optic sensors are expected to find considerable future application in FRP composite structures.

(3) Piezo-polymers. Another "smart" technology undergoing further development within the research communities is piezo-electric materials. When a piezo-electric material is deformed a voltage is produced. Such materials can act as sensors when connected to instrumentation monitoring voltage and voltage changes. When stretched, polyvinylidene fluoride (PVDF) polymer film converts from an alpha phase to a beta phase, with the beta phase exhibiting piezo-electric properties (Andreshak and Bergman 1990). As a sensor material, PVDF has several advantageous properties. It is lightweight, flexible, can be fabricated into any shape or size, and possesses a high piezo-electric voltage output. Not only will a piezo-electric material emit a voltage when deformed, it will also conversely deform when an applied voltage is induced. The output of the PVDF sensor could be used to actuate another piezo-electric material that would deform in a controlled manner. For example, a piezo-polymer sensor detects unwanted vibrations which actuates another piezo-electric material system in a cyclic manner to dampen the unwanted vibrations. Such a system would truly be a "smart" system as previously defined. As with the fiber optics, use of these piezo-electric technologies is expected to provide definite future benefits for FRP composites used in civil engineering applications. However, the technology still needs some further development and demonstration before it will find widespread use in FRP composites.

(4) Other smart systems. Given the potential benefits of employing "smart" composite systems in civil engineering applications, a great deal of interest and effort is being focused in that direction. The Corps of Engineers is currently working cooperatively with the composites industry and academia participants on the research and development of smart FRP composite systems using embedded particle "tags." This tagging technique involves embedding micron-sized particles into the composite material. The particle material is selected so that

when the component is analyzed with suitable instrumentation, a measurable signature is produced. The signatures are then correlated with material and structural conditions. A state-of-the-art report has recently been completed as part of this cooperative effort (Rogers, Zhou, and Chaudhry 1994).