Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures

Reported by ACI Committee 440

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Applications of fiber-reinforced polymer (FRP) composites as reinforcement for concrete structures have been growing rapidly in recent years. ACI Committee 440 has published design guidelines for internal FRP reinforcement, externally bonded FRP reinforcement for strengthening, prestressed FRP reinforcement, and test methods for FRP products. Although these guidelines exist, new products and applications continue to be developed. Thus, this report summarizes the current state of knowledge on these materials and their application to concrete and masonry structures. The purpose of this report is to act as an introduction to FRP materials in areas where ACI guides exist, and to provide information on the properties and behavior of concrete structures containing FRP in areas where guides are not currently available. If an ACI guide is available, the guide document supersedes information in this report, and the guide should always be followed for design and application purposes. ACI Committee 440 is also in the process of developing new guides and thus the current availability of guides should be checked by the reader. In addition to the material properties of the constituent materials (that is, resins and fibers) and products, current knowledge of FRP applications, such as internal reinforcement including prestressing, external strengthening of concrete and masonry structures, and structural systems, is discussed in detail. The document also addresses durability issues and the effects of extreme events, such as fire and blast. A summary of some examples of field applications is presented.

Keywords: aramid fibers; blast; bridges; buildings; carbon fibers; composite materials; corrosion; design; dowels; ductility; durability; external reinforcement; fatigue; fiber-reinforced polymer (FRP); fibers; fire; glass fiber; masonry; mechanical properties; polymer resin; prestressed concrete; seismic; stay-in-place forms; structural systems; test methods.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

The purpose of this report is to present the current state of knowledge with regard to applications of fiber-reinforced polymer (FRP) materials in concrete. This report summarizes the fundamental behavior, the most current research, design codes, and practical applications of concrete and masonry structures containing FRP. This document is intended to complement other reports (for example, standards and design guidelines) produced by ACI Committee 440, either by summarizing the research that supports those documents or by providing information on future developments of those documents. If an ACI guide is available, the guide document supersedes information in this report, and the guide should always be followed for design and application purposes. ACI Committee 440 is also in the process of developing new guides; thus, the current availability of guides should be checked by the reader.

FRP materials are composite materials that typically consist of strong fibers embedded in a resin matrix. The fibers provide strength and stiffness to the composite and generally carry most of the applied loads. The matrix acts to bond and protect the fibers and to provide for transfer of stress from fiber to fiber through shear stresses. The most common fibers are glass, carbon, and aramid. Matrixes are typically epoxies, polyesters, vinylesters, or phenolics.

1.2—Historical perspective of FRP composites

While the concept of composites has been in existence for several millennia (for example, bricks made from mud and straw), the incorporation of FRP composite technology into the industrial world is less than a century old. The age of plastics emerged just after 1900, with chemists and industrialists taking bold steps to have plastics (vinyl, polystyrene, and Plexiglas) mimic and outdo natural materials. Spurred on by the needs of electronics, defense, and eventually space technologies, researchers created materials with properties that seemed to defy known principles, such as bullet-stopping Kevlar. The first known FRP product was a boat hull manufactured in the mid-1930s as part of a manufacturing experiment using a fiberglass fabric and polyester resin laid in a foam mold (ACMA MDA 2006). From this modest beginning, FRP composite applications have revolutionized entire industries, including aerospace, marine, electrical, corrosion resistance, and transportation.

FRP composite materials date back to the early 1940s in the defense industry, particularly for use in aerospace and naval applications. The U.S. Air Force and Navy capitalized on FRP composites' high strength-weight ratio and inherent resistance to the corrosive effects of weather, salt air, and the sea. Soon the benefits of FRP composites, especially its corrosion resistance capabilities, were communicated to the public sector. Fiberglass pipe, for instance, was first introduced in 1948 (ACMA MDA 2006) for what has become one of its widest use areas within the corrosion market, the oil industry. FRP composites proved to be a worthy alternative to other traditional materials even in the high-pressure, large-diameter situations of chemical processing. Besides superior corrosion resistance, FRP pipe offered both durability and strength, thus eliminating the need for interior linings, exterior coatings, and cathodic protection. Since the early 1950s, FRP composites have been used extensively for equipment in the chemical processing, pulp and paper, power, waste treatment, metal refining, and other manufacturing industries (ACMA MDA 2006). Myriads of products and FRP installations help build a baseline of proven performance in the field.

The decades after the 1940s brought new, and often revolutionary, applications for FRP composites (ACMA MDA 2006). The same technology that produced the reinforced plastic hoops required for the Manhattan nuclear project in World War II spawned the development of high-performance composite materials for solid rocket motor cases and tanks in the 1960s and 1970s. In fact, fiberglass wall tanks were used on the Skylab orbiting laboratory to provide oxygen for the astronauts. In 1953, the first Chevrolet Corvette with fiberglass body panels rolled off the assembly line (ACMA MDA 2006). Now, high-performance race cars are the proving ground for technology transfer to passenger vehicles. In the 1960s, the British and U.S. Navies were simultaneously developing FRP-based minesweeper ships because FRP composites are not only superior to other materials in harsh marine environments, they are also nonmagnetic. It was also noticed at that time that one of the features of FRP is the ability of the materials to reduce the radar signature of the structure, such as a ship or an aircraft. High-performance composite materials have been demonstrated in advanced technology aircraft such as the F-117 Stealth Fighter and B-2 Bomber. Currently, FRP composites are being used for space applications and are involved in several NASA test initiatives (ACMA MDA 2006).

While the majority of the historical and durability data of FRP composite installations comes from the aerospace, marine, and corrosion-resistance industries (ACMA MDA 2006), FRP composites have been used as a construction material for several decades. FRP composite products were first demonstrated to reinforce concrete structures in the mid-1950s (ACMA MDA 2006). In the 1980s, a resurgence in interest arose when new developments were launched to apply FRP reinforcing bars in concrete that required special performance requirements such as nonmagnetic properties or in areas that were subjected to severe chemical attack.

Composites have evolved since the 1950s, starting with temporary structures and continuing with restoration of historic buildings and structural applications. Typical products developed were domes, shrouds, translucent sheet panels, and exterior building panels. A major development of FRP for civil engineering has been the application of externally bonded FRP for rehabilitation and strengthening of concrete structures.

During the late 1970s and early 1980s, many applications of composite reinforcing products were demonstrated in Europe and Asia. In 1986, the world's first highway bridge using composite reinforcing tendons was built in Germany. The first all-composite bridge deck was demonstrated in China. The first all-composite pedestrian bridge was installed in 1992 in Aberfeldy, Scotland. In the U.S., the first FRP-reinforced concrete bridge deck was built in 1996 at McKinleyville, West Virginia, followed by the first all-composite vehicular bridge deck (The No-Name Creek Bridge in 1996) in Russell, Kansas. Numerous composite pedestrian bridges have been installed in U.S. state and national parks in remote locations not accessible by heavy construction equipment, or for spanning over roadways and railways (ACMA MDA 2006).