A New Tool for Concrete and Masonry Repair

Strengthening with fiber-reinforced cementitious matrix composites

by Antonio Nanni

In 1995 and 1997, *CI* articles documented early commercial development of what is now known as fiber-reinforced polymer (FRP) repair and strengthening technology.\(^1,2\) At present, about 15 years later, the industry is applying a new class of materials: fiber-reinforced cementitious matrix (FRCM) composites. As compared with FRP composites, FRCM composites offer greater resistance to high temperatures and ultraviolet radiation as well as superior compatibility with a concrete substrate. The objective of this article is to briefly introduce this additional tool for the concrete and masonry repair industry by presenting five repair projects completed using FRCM.

**Background**

FRCM composites have been identified using various monikers. Textile-reinforced concrete (TRC) is the term generally applied to thin shells, cladding panels, and other manufactured products made using woven textiles and concrete or mortar.\(^3,4\) Other terms in the literature include textile-reinforced mortar (TRM),\(^5,6\) mineral-based composites (MBC),\(^7\) and fiber-reinforced cement (FRC).\(^8\)

FRCM systems are not presently covered in North American building codes, but the International Code Council Evaluation Service (ICC-ES) recently published “Acceptance Criteria for Masonry and Concrete Strengthening Using Fiber-Reinforced Cementitious Matrix (FRCM) Composite Systems (AC434).”\(^9,10\) This document provides guidance for characterization and design of FRCM systems and establishes requirements for recognition of FRCM systems in an ICC-ES evaluation report under the 2009 and 2012 International Building Codes.\(^11,12\) As any other ICC-ES acceptance criteria, AC434 was developed by ICC-ES technical staff in consultation with and using input from industry, academia, and interested parties and was approved in a public hearing.

**FRCM Characterization**

Two key components of FRCM are the cementitious matrix and the fiber network or grid. The former is typically a grout system based on portland cement and a low dosage of dry organic polymers (less than 5% by weight). The organic compounds are necessary to ensure proper workability, setting time, and mechanical properties. The mechanical effectiveness of FRCM is strongly influenced by the ability of the cementitious matrix to saturate dry fiber rovings,\(^13,14\) the bond between the matrix and fibers,\(^15,16\) and the bond between the matrix and the substrate.\(^17,18\) Even though some interesting field applications have been recently undertaken, ongoing research is helping to characterize FRCM and quantify its mechanical effectiveness based on parameters such as type and arrangement of fibers, type of cementitious matrix, conditions of the substrate, and bond characteristics.\(^19\)

Cognizant of the wide variety of fibers and cementitious matrices potentially available on the market, field applications described in this article concentrate on two FRCM systems:

- Carbon fiber balanced network with fiber rovings disposed along two orthogonal directions at a nominal spacing of 10 mm (0.4 in.) (6 mm [0.2 in.] clear opening between rovings) and an equivalent nominal fiber thickness of 0.047 mm (0.002 in.) in both directions. The matrix comprises pozzolanic cement, selected silica aggregates, polycarboxylate water-reducing admixtures, and an adhesion promoter (hydroxymethylcellulose); and
• Polyparaphenylene benzobisoxazole (PBO) fiber unbalanced network with fiber rovings spaced at 10 and 20 mm (0.4 and 0.8 in.), respectively (5 and 15 mm [0.2 and 0.6 in.] clear openings between rovings), and an equivalent nominal fiber thickness in two directions of 0.046 and 0.011 mm (0.002 and 0.0004 in.). The matrix comprises high-fineness cement, an adhesion promoter, inorganic nanoparticles, microaggregates, and a polycarboxylate water-reducing admixture. This matrix was designed to achieve a chemical bond with the PBO fibers.

Example Projects

**Strengthening unreinforced concrete vaults**

This FRCM application comprised strengthening a bridge along the Rome-Formia-Naples railway in Italy. The 10.5 m (34.4 ft) wide bridge deck is supported by six semicircular plain concrete vaults supported by masonry abutments made of blocks of tuff. The thickness of each vault varies from 0.7 m (2.3 ft) at the crown to 1.0 m (3.3 ft) at the skewback.

The strengthening project was preceded by a field investigation to characterize the bridge geometry and material mechanical properties. Limit state analyses identified possible collapse mechanisms with formation of hinges under factored loads. The strengthening design was aimed at changing the collapse mechanism and consequently increasing the safety against collapse.

The final design called for strengthening of the soffit of each vault by an application of two layers of PBO-FRCM. This intrados strengthening prevents the formation of extrados hinges, modifying the ultimate behavior of the vault without affecting its behavior under service loads.

The technical choice to work on the intrados rather than the extrados was driven by the need to not interrupt the use of the bridge, which would have been necessary if strengthening of the extrados had been used.

Application of the FRCM composite was preceded by thorough cleaning of the concrete surface followed by removal and reconstruction of portions of deteriorated concrete. Then, a first layer of cementitious matrix (about 5 mm [0.2 in. thick] was applied on the concrete surface. The initial fiber network was pressed into the matrix to ensure good impregnation (shown in Fig. 1); a second, thinner matrix layer was applied; and a second fiber network was pressed into the second matrix layer. Figure 2 shows fiber network rolls freely hanging from the vault as the scaffolding is moved to the next location. The strengthening is completed with the application of a final top layer of the matrix. Because train traffic was not interrupted and strengthening proceeded as soon as concrete cleaning and patching was completed, the project execution was fast and relatively easy.

**Strengthening a reinforced concrete bridge pier**

This FRCM application involved strengthening of a reinforced concrete bridge pier in Novosibirsk, Russia. Significant cracking had appeared since the pier had been reconstructed in 1958 (Fig. 3(a)). In 1991, the cracks were epoxy-injected, but inspections in 1997 indicated that the cracks had reopened, with widths ranging from 2 to 5 mm (0.1 to 0.2 in.).

A repair and strengthening project was completed in 2007. The project consisted of:

- Sand-blasting the concrete surface;
- Rounding the corners to a radius of 30 mm (1.2 in.);

![Fig. 1: Strengthening of a bridge on the Rome-Formia-Naples railway in Italy. A worker installs PBO-FRCM composite on the soffit of a concrete arch. In this image, the initial fiber layer can be seen to the right of the scaffolding. Immediately to the left of the scaffolding, the worker advances rolls of the fiber network](image1)

![Fig. 2: The second layer of PBO fiber is installed over the first layer. Rolls of the fiber network material hang from the vault as the scaffolding is advanced to the left](image2)
Repointing the cracks (Fig. 3(b)) and resurfacing with single-component polymer-modified cementitious mortar; strengthening with PBO-FRCM composite; and applying a two-component, polymer-modified, cementitious waterproofing and protective slurry. Heated curing tents were used to maintain an air

Fig. 3: Reinforced concrete bridge pier in Novosibirsk, Russia: (a) the numerous cracks had been repaired using epoxy injection; and (b) workers repoint the cracks prior to application of PBO-FRCM composite strengthening.

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temperature of about 15 to 18°C (59 to 64.4°F) during application of the cementitious mortars and slurries and for 7 days after completion of the work (Fig. 4).

**Repair of trestle pedestals**

In this installation, FRCM composite was used to provide confinement and protection to concrete pedestals supporting a Metro North Railway trestle over a valley in northern New York (Fig. 5(a)). The pedestals have a truncated pyramid shape and vary in size depending on the configuration of the ground. The pedestal shown in Fig. 5(b) measured about 2.4 x 2.4 m (7.9 x 7.9 ft) at the base and was 2.4 m (7.9 ft) in height. Over the years, weathering had led to significant cracking and spalling (Fig. 5(b)). Even in this condition, the pedestals were still adequate to carry the loads for which they were designed. A repair was deemed necessary, however, to restore some of the initial strength and, more importantly,
ensure long-term performance. Confinement and protection of the concrete called for encapsulation of the entire pedestal, so a PBO-FRCM system was chosen because its cementitious matrix is breathable.

The repair was conducted according to International Concrete Repair Institute (ICRI) guidelines, ICRI 310.1R, starting with removal and replacement of deteriorated concrete. After deteriorated concrete was removed, the cavities were filled with an engineered mortar compatible with the FRCM system (Fig. 6(a)). The substrate surface was then prepared by grinding to remove sharp projections and round corners to an acceptable radius. Then, a layer of the cementitious matrix was troweled onto the substrate and sheets of cut-to-size PBO network were pressed into the matrix such that the mortar pushed out through the grid openings to encapsulate the fibers (Fig. 6(b)). A second layer of the cementitious matrix completed the repair.

**Strengthening a reinforced concrete tunnel lining**

In this application, FRCM composite was used for strengthening of a concrete lining for a vehicular tunnel along the Egnatia Odos Motorway in Greece. PBO-FRCM composite was used to overcome a deficiency of internal steel reinforcement in the 650 mm (26 in.) thick lining. As installed, the lining was reinforced with two steel bar mats, each with 50 mm (2 in.) cover.

Calculations indicated that the addition of a single PBO fiber network increased the circumferential flexural strength of the lining by 14% and 4% at the top and side portions of the tunnel, respectively. Calculations showed that the addition of two PBO networks increased the longitudinal flexural strength by 100% in the longitudinal direction on the top portion of the tunnel lining. The concrete surface was prepared using hydrojetting prior to installation of the PBO-FRCM fibers and application of a finish coat of the matrix (Fig. 7).

**Strengthening a masonry chimney**

This project consisted of strengthening an unreinforced masonry chimney of a historic sawmill in the municipality of Gerardmer, France. Although the mill is no longer operating, the chimney has been preserved as a symbol of the region’s industrial heritage and is currently used to support several telephone antennas and their cabling.

The chimney has a height of about 38 m (125 ft), with a diameter ranging...
From a design perspective, the chimney was analyzed as a cantilever beam with wind as a primary load condition. The analysis indicated that strengthening of the structure with FRCM was needed, using a single carbon fiber network (Fig. 9(b)). The final composite thickness was 10 mm (0.4 in.). It provided strength equivalent to an application of a welded wire reinforcement with 6 mm (0.2 in.) diameter reinforcing steel bars (D4 according to ASTM A615, “Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement”) with spacing of 0.50 m (20 in.) in both the hoop and vertical directions.

An Expanding Tool Kit

The need to repair and maintain our infrastructure is ever-increasing. FRCM is rising as one of the possible tools.
in the concrete and masonry repair toolbox. Its advantages are similar to those of FRP (that is, strength, low weight, and ease of application), but also include greater compatibility with concrete and mortar substrates, greater resistance to heat, and better long-term durability.

Commercial projects undertaken in Europe (Italy, Russia, Greece, and France) and the U.S. have already demonstrated the potential for FRCM composite applications. Others will follow as designers become more aware of the technology. The term FRP has now permanently entered the lexicon of the technical community, and FRP is a common staple in many concrete and masonry repair projects in North America and worldwide. It’s highly likely that FRCM will follow that trend.

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