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Using Fabric-Reinforced Cementitious Matrix (FRCM) for Strengthening and Retrofit of Existing Structures

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Traditional Concrete Repair Methods

Using shotcrete has been a traditional method for repairing and strengthening concrete, masonry and brick structures. However, this method can present significant challenges with respect to time, labor, trade coordination and, of course, cost. Often, shotcrete repairs require two separate contractors — both a rebar contractor and a shotcrete application contractor. Rebar also takes several hours, if not days, to install, resulting in increased labor costs. Because rebar is susceptible to corrosion, it also needs 1.5 to 3 in (38 to 76 mm) of concrete cover to protect it from exposure to the elements. As a result, engineers need to factor the weight of the extra concrete into the building's total dead load.

Another familiar method for strengthening or repairing concrete and masonry structures uses a fiber-reinforced polymer (FRP) system, which can come with application challenges of its own. To install FRP systems, it is necessary to resurface any unevenness in the underlying substrate using a system-approved mortar or FRP paste before the FRP composite is applied. Afterwards, a finish coating is usually desirable to conceal the FRP. In addition, FRP systems can be challenging to install in damp areas or in areas exposed to higher temperatures.

What Is FRCM and What Is it for?

Used in Europe for the past decade and just now emerging in the United States, fabric-reinforced cementitious matrix (FRCM) systems combine high-performance sprayable mortar with a carbon-fiber grid to create thin-walled, reinforced concrete layers over existing masonry or concrete substrates. This system is similar to an FRP system, with the primary difference lying in the application methods. Instead of a carbon or glass fabric saturated with an epoxy, FRCM consists of a carbon-fiber grid embedded in a cementitious matrix. The function of the carbon grid is to carry tensile stresses.

Fig. 1: Cementitious matrix

So what is FRCM? In FRCM composite systems, the fabrics that are typically used in FRP are replaced with open carbon fabric grids in which the carbon fibers are oriented in two directions. The function of the cementitious matrix is to encapsulate and protect the fibers, and to transfer stresses from the concrete or masonry substrate to the fibers. Instead of relying on complicated rebar doweling, FRCM transfers stress through the bond between the substrate and the matrix, and through the mechanical interlock between the fabric and the matrix.
The cementitious matrix is typically a one-component, shrinkage-compensated, polypropylene-fiber-reinforced cementitious matrix (Fig. 1) designed to be field-installed with unidirectional (Fig. 2) and bidirectional carbon grids (Fig. 3). Benefits of the matrix include a 28-day compressive strength of 7,500 psi (52 MPa) and the ability to apply the matrix using a shotcrete pump on uneven surfaces. Typical mechanical properties of the cured FRCM composite are listed in Figure 4.

FRCM Installation Tips

Because FRCM accomplishes stress transfer through bonding between the substrate and the matrix, surface preparation of the substrate is crucial. First, prepare the surface and exposed reinforcement per ICRI Guideline No. 310.1R.[1] Prepare concrete surface to achieve a Concrete Surface Profile (CSP) 6-9 in accordance with ICRI Guideline No. 310.2R[2] by means of sandblasting, shotblasting or waterblasting. Substrate surfaces need to be clean, sound and free of standing water at time of application. All dust, laitance, grease, curing compounds and other foreign materials that might hinder the bond must be removed before installation. All corners to be covered with grid and matrix need to be rounded to a ¾ in (19 mm) minimum radius using a grinder. Finally, wet the substrate for at least 24 hours to a saturated surface-dry condition prior to FRCM application.

Once the surface is prepared as described above, layers of the carbon grid from a roll are pre-cut to the required dimensions of the area to be reinforced. Next, a shotcrete pump is used to spray the first layer of the matrix. The first layer should be minimum ½ in (13 mm) thick. The pre-cut carbon fiber grid is then wet-set in the first layer of the matrix, and a second layer of matrix sprayed at minimum ¼ in (6.4 mm) thick over it. Repeat this process for multiple grid applications, and finish the final layer to the desired smoothness. Overall, the minimum thickness of the system should be ¾ in (19 mm).

FRCM systems have certain advantages over typical shotcrete or FRP systems. Since this system does not have any steel rebar, only minimal concrete cover is needed. This reduces the overall thickness and weight, a crucial consideration in retrofit applications. Also, because no steel rebar dowels are needed to connect the system to the substrate, this system can be installed much faster than a conventional shotcrete method. An FRCM system also has a four-hour UL fire rating for its ability to withstand high temperatures.

Fig. 2: Unidirectional carbon grid

Fig. 3: Bidirectional carbon grid

Cured Composite Properties[1]

Property	Design Value[2]
Cracked Tensile Modulus	7.0×10^6 psi (48,300 MPa)
Ultimate Tensile Strain	1.1%
Ultimate Tensile Strength	143,000 psi (986 MPa)
Lap Tensile Strength	114,000 psi, 12" lap (786 MPa, 30 cm)
Thickness per Layer	0.5 in. (13 mm)

1. When installed with cementitious matrix and 2 layers of bidirectional carbon grid.
2. Average tensile strength and strain minus one standard deviation per ACI 549. Modulus values are average.

Fig. 4: Cured composite FRCM properties from a manufacturer technical datasheet

The design approach for flexure and shear strengthening considers an effective usable strain of FRCM, which represents a strain limit that globally accounts for the loss of bond. ACI 549.4R[3] identifies three different types of bond failures: cohesive failure in the substrate material; adhesive failure at the interface between the FRCM and the substrate material; and adhesive failure at the FRCM interface between the reinforcing fabric and the matrix.

FRCM Applications

Given its reduced preparation and installation time, FRCM is in many cases the most economical solution available for adding flexural, axial or shear strength to a range of structures. The lightweight, sprayable matrix is ideal for application on overhead or vertical surfaces in structures such as tunnels, mines, parking garages, silos, bridges, buildings and other structures with large surface areas. A single ¾ in (19 mm) layer provides sufficient structural strengthening without substantially constricting tight spaces or adversely affecting facility operations. Further strengthening can be obtained as necessary through the application of up to four additional ¼ in (6.4 mm) layers. Since FRCM systems can be successfully used to enhance the shear strength and ductility of structural members, they are a viable option for seismic retrofit of masonry and concrete structures. FRCM systems are also ideal for repairing existing concrete members without altering the existing substrate.

FRCM systems can be used to do the following:

- strengthen aging, damaged or overloaded structures;
- repair and strengthen surfaces in a single application;
- upgrade live-load ratings to accommodate changes of use;
- assist in seismic retrofits by adding shear strength and mitigating displacement and ductility;
- correct size and layout errors;
- match the finish of the existing substrate; and
- strengthen or repair damp substrates, or substrates in harsh environments that may expose the system to high temperatures, humidity, abrasion or ultraviolet (UV) radiation.

Case Study: Historic Napa Courthouse

FRCM is currently being utilized to strengthen and repair unreinforced masonry walls (Fig. 5, 6, and 7) on the historic Napa Courthouse building in Northern California, which was damaged in the 2014 Napa earthquake. The courthouse suffered structural damage to existing unreinforced masonry walls, plaster finishes, finish carpentry, HVAC, fire sprinklers and electrical systems.

Fig. 5: FRCM application over the prepared surface

Fig. 6: Laying out and wet-set of unidirectional carbon grid

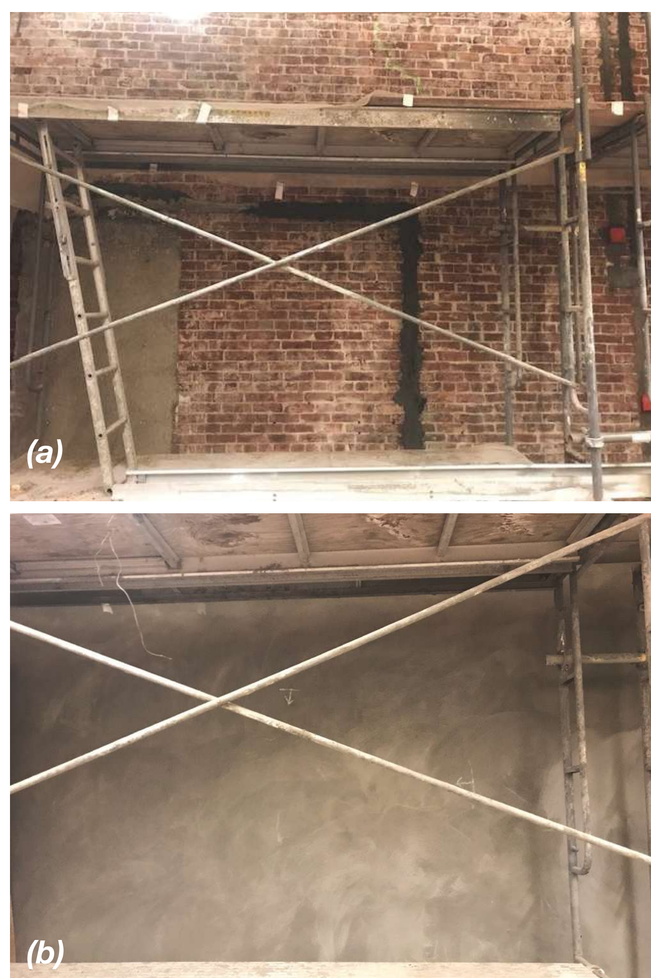

Fig. 7: Wall before (a) and after (b) installation of FRCM final finished layer

Construction methods considered for repair of the courthouse structure included shotcrete walls, fiber-reinforced polymer (FRP), FRCM, mortar repointing, grout injection, and replacement with concrete masonry unit (CMU) walls. The most heavily damaged masonry walls, those no longer in stable form, were removed and rebuilt implementing ductile reinforced CMU construction. Special detailing considerations were designed to achieve strength and flexibility compatible with the remaining historic brick construction.

FRCM was selected instead of the more traditional repointing or grout injection as the preferred repair solution for the less damaged walls with their countless small cracks. FRCM provided a homogenous interaction with the existing masonry and corresponding performance and stiffness. Furthermore, the matrix provided greater strengthening with a smaller investment of labor than crack injection. The structure was composed of walls with elevation differences of up to 1 in (25 mm), which allowed FRCM to be sprayed at different thicknesses as required to create an even surface without building out the original substrate.

FRCM provided in-plane and out-of-plane strengthening with minimum surface preparation beyond the removal of existing finishes. The FRCM was also detailed to engage and tie the historic masonry to the new CMU walls. Additionally, the cement based FRCM did not seal the historic walls and allowed the walls to breathe as they had for 150 years and provided a favorable surface for installation of plaster finishes.

To generate minimum required strengthening values for the design/build manufacturer's calculations, a structural analysis was performed to determine the original capacities of the walls as well as the required strength and estimated loss of capacity due to earthquake damage. The manufacturer then submitted calculations, and an FRCM layout for each wall was submitted for structural review during construction by the manufacturer. Since this was one of the first applications of FRCM in California, a mockup was constructed to test installation procedures and identify any potential issues that could affect installation in the historic building. Key elements for successful installation were proper saturation of the walls to reach the surface saturated-dry (SSD) condition, which took significant quantities of water because the walls were 150 years old, plus proper installation sequencing of the fiber grid due to the shallow lift thickness of the FRCM matrix.

Conclusion

FRCM systems are currently being introduced in the structural repair and rehabilitation industry as a new and effective strengthening technology. Due to their reduced thickness, excellent durability, superior performance in high temperatures, and ease of installation, FRCM systems are a good alternative to traditional strengthening and repair methods. Compared to shotcrete, they add little weight to the structure and can provide an excellent solution for strengthening on concrete and masonry substrates, particularly in seismic retrofit applications. ■

References

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Acknowledgement

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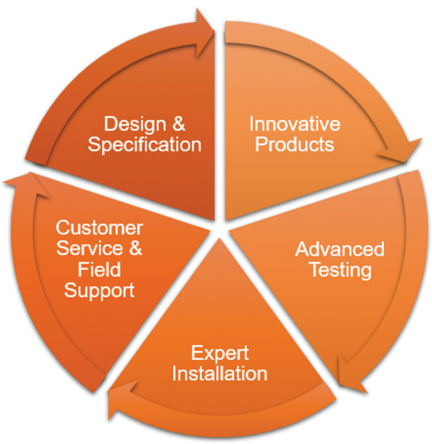

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