Guide to Design and Construction of Externally Bonded Fabric-Reinforced Cementitious Matrix and Steel-Reinforced Grout Systems for Repair and Strengthening of Concrete Structures

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Fabric-reinforced cementitious matrix (FRCM) and steel-reinforced grout (SRG) systems for rehabilitation and strengthening concrete structures are an alternative to traditional techniques such as fiber-reinforced polymers (FRPs), steel plate bonding, section enlargement, and external post-tensioning. An FRCM/SRG is a composite material consisting of one or more layers of inorganic matrix reinforced with dry fibers in the form of open mesh or fabric. The inorganic matrixes are typically cement-based, lime-based, or geopolymer. When adhered to concrete structural members, they form an FRCM/SRG system that acts as supplemental, externally bonded
reinforcement. This guide addresses the history and use of FRCM and SRG systems rehabilitation and strengthening; their unique material properties; and recommendations on their design, construction, and inspection. Guidelines are based on experimental research, analytical work, and field applications.

Keywords: bridges; buildings; cracking; cyclic loading; deflection; development length; earthquake-resistant; fabric-reinforced cementitious matrix fatigue systems; fiber-reinforced polymer systems; flexure; lap splices; inorganic; meshes; mortar matrix; shear; stress; structural analysis; structural design; substrate repair; rehabilitation; surface preparation.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Fabric-reinforced cementitious matrix (FRCM) and steel-reinforced grout (SRG) composites have recently emerged as a viable technology for rehabilitation and strengthening concrete structures. The strengthening and rehabilitation of existing concrete structures has traditionally been accomplished using new and conventional materials and construction techniques, including externally bonded fiber-reinforced polymer (FRP) systems, steel plates, reinforced concrete (RC) overlays, and post-tensioning.

The primary reasons for considering FRCM/SRG as a suitable strengthening material stems system from the inorganic matrix that shows properties of:

a) Inherent heat resistance

b) Compatibility with the substrate (that is, allows vapor permeability and application on a wet surface)

c) Long-term durability

FRCM and SRG are systems where all constituents are developed and tested as a unique combination and should not be created by randomly selecting and mixing products available in the marketplace.
AC434 establishes guidelines for the manufacturers for necessary tests and calculations required to receive a product research report from ICC-ES. Once received, the evaluated system can be accepted by code officials under Section 104.11.1 of the International Building Code (IBC 2018). Section 104.11.1 allows research reports to be used as a source of information to show building code compliance of alternative materials.

1.2—Scope

This guide covers fabric-reinforced cementitious matrix (FRCM) and steel-reinforced grout (SRG) composite systems used to strengthen or rehabilitate existing concrete structures, providing background information and field applications; composite material properties; axial, flexural, and shear capacities of the FRCM/SRG-strengthened structures; and structural design procedures.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

\begin{align*}
A_c &= \text{net cross-sectional area of compression member, in.}^2 (\text{mm}^2) \\
A_e &= \text{area of effectively confined concrete, in.}^2 (\text{mm}^2) \\
A_f &= \text{area of mesh reinforcement by unit width, in.}^2/\text{in.} (\text{mm}^2/\text{mm}) \\
A_g &= \text{gross cross-sectional area of compression member, in.}^2 (\text{mm}^2) \\
A_s &= \text{area of longitudinal steel reinforcement, in.}^2 (\text{mm}^2) \\
b &= \text{short side dimension of compression member with rectangular cross section, in. (mm)} \\
b_w &= \text{web width, in. (mm)} \\
D &= \text{diameter of compression member, in. (mm)}
\end{align*}
\( d \) = distance from extreme compression fiber to centroid of tension reinforcement, in. (mm)

\( d_f \) = effective depth of the FRCM/SRG shear reinforcement, in. (mm)

\( E_2 \) = slope of linear portion of stress-strain model for FRCM/SRG-confined concrete, psi (MPa)

\( E_c \) = modulus of elasticity of concrete, psi (MPa)

\( E_f \) = tensile modulus of elasticity of cracked FRCM/SRG specimen, psi (MPa)

\( E_f^* \) = tensile modulus of elasticity of uncracked FRCM/SRG specimen, psi (MPa)

\( f_c \) = compressive stress in concrete, psi (MPa)

\( f_c' \) = specified compressive strength of concrete, psi (MPa)

\( f_{cc}' \) = maximum compressive strength of confined concrete, psi (MPa)

\( f_e \) = effective tensile stress level in FRCM/SRG attained at failure, psi (MPa)

\( f_t \) = transition stress corresponding to transition point, psi (MPa)

\( f_{tu} \) = ultimate tensile strength of FRCM/SRG, psi (MPa)

\( f_{sv} \) = design tensile strength of FRCM/SRG shear reinforcement, psi (MPa)

\( f_s \) = tensile stress in FRCM/SRG reinforcement under service load, psi (MPa)

\( f_i \) = maximum confining pressure due to FRCM/SRG jacket, psi (MPa)

\( f_{ss} \) = tensile stress in the steel reinforcement under service load, psi (MPa)

\( f_y \) = steel tensile yield strength, psi (MPa)

\( h \) = long side dimension of compression member with rectangular cross section, in. (mm)

\( i \) = grid spacing of fabric (in)

\( \ell_{df} \) = critical length to develop bond capacity of FRCM/SRG, in. (mm)
$M_{cr} = \text{cracking moment of unstrengthened member, in.-lb (N-mm)}$

$M_f = \text{contribution of FRCM/SRG to nominal flexural strength, in.-lb (N-mm)}$

$M_n = \text{nominal flexural strength, in.-lb (N-mm)}$

$M_s = \text{contribution of steel reinforcement to nominal flexural strength, in.-lb (N-mm)}$

$n = \text{number of layers of mesh reinforcement}$

$P_n = \text{nominal axial strength, lb (N)}$

$r = \text{radius of edges of a rectangular cross section confined with FRCM/SRG, in. (mm)}$

$V_c = \text{contribution of concrete to nominal shear strength, lb (N)}$

$V_f = \text{contribution of FRCM/SRG to nominal shear strength, lb (N)}$

$V_n = \text{nominal shear strength, lb (N)}$

$V_s = \text{contribution of steel reinforcement to nominal shear strength, lb (N)}$

$t = \text{equivalent thickness of fabric, in. (mm)}$

$\varepsilon_c = \text{compressive strain level in concrete, in./in. (mm/mm)}$

$\varepsilon_c' = \text{compressive strain of unconfined concrete corresponding to } f_{c'}, \text{ in./in. (mm/mm)}$; may be taken as 0.002

$\varepsilon_{ccu} = \text{ultimate compressive strain of confined concrete corresponding to } 0.85f_{c'} \text{ in a lightly confined member (member confined to restore its concrete design compressive strength), or ultimate compressive strain of confined concrete corresponding to failure in a heavily confined member}$

$\varepsilon_{fd} = \text{design tensile strain of FRCM/SRG, in./in. (mm/mm)}$

$\varepsilon_{fe} = \text{effective tensile strain level in FRCM/SRG composite material attained at failure, in./in. (mm/mm)}$

$\varepsilon_{ft} = \text{transition strain corresponding to the transition point, in./in. (mm/mm)}$

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2.2—Definitions

Please refer to the latest version of ACI Concrete Terminology for a comprehensive list of definitions. Definitions provided herein complement that resource.

coating—an organic compound applied to fabric after weaving to protect fibers, increasing the long-term durability and stability of the fabric, and allowing for ease of handling and installation.

inorganic matrix—inorganic hydraulic and nonhydraulic binder (mortar) that holds in place the structural reinforcement meshes in FRCM and SRG composite materials. If the mortar is polymer-
modified, the maximum content of organic compounds (dry polymers) in the matrix is limited to 5 percent by weight of cement.

**coating**—an organic compound applied to fabric after weaving to protect fibers, increasing the long-term durability and stability of the fabric, and allowing for ease of handling and installation.

**engineered cementitious composite**—easily molded mortar-based composite reinforced with specially selected short random fibers, usually polymer fibers.

**fabric**—manufactured planar textile structure made of fibers, yarns, or both, that is assembled by various means such as weaving, knitting, tufting, felting, braiding, or bonding of webs to give the structure sufficient strength and other properties required for its intended use.

**fabric-reinforced cementitious matrix composite**—material consisting of a sequence of one or more layers of inorganic matrix reinforced with dry fibers in the form of open single or multiple fabric that, when adhered to concrete structural members, forms a FRCM system.

**greige fabric**—unfinished fabric just off the loom or knitting machine.

**steel reinforced grout material**—composite material consisting of a sequence of one or more layers of inorganic matrix reinforced with high-resistant steel wires in the form of open single or multiple textiles that, when adhered to concrete structural members, forms a SRG system.

**fabric-reinforced cementitious matrix composite configuration**—combination of all applicable parameters that affect the performance of FRCM, such as layers, thicknesses, components, and bonding agents.

**mesh**—fabric (two-dimensional structure) or textile (two- or three-dimensional-structure) with open structure; in an open structure, the yarns or strands do not come together, leaving interstices in the fabric or textile.
passive composite system--composite system that is not pre- or post-tensioned during installation.

sizing--organic compound applied to fibers during the fiber manufacturing process to provide enhanced fiber characteristics such as abrasion resistance.

strand--ordered assemblage of filaments of predetermined quantity based on the number of filaments per strand that have a high ratio of length to diameter, are normally used as a unit, and are bundled together to resist splitting or filamentation.

steel reinforced grout composite--material consisting of a sequence of one or more layers of inorganic matrix reinforced with high-strength steel wires in the form of open single or multiple textiles that, when adhered to concrete structural members, forms an SRG system.

steel reinforced grout composite configuration--combination of all applicable parameters that affect the performance of SRG, such as layers, thicknesses, components, and bonding agents.

greige fabric—unfinished fabric just off the loom or knitting machine.

mesh--fabric (two-dimensional structure) or textile (two- or three-dimensional structure) with open structure; in an open structure, the yarns or strands do not come together, leaving interstices in the fabric or textile.

passive composite system--composite system that is not pre- or post-tensioned during installation.

sizing--organic compound applied to fibers during the fiber manufacturing process to provide enhanced fiber characteristics such as abrasion resistance.

strand--ordered assemblage of filaments of predetermined quantity based on the number of filaments per strand that have a high ratio of length to diameter, are normally used as a unit, and are bundled together to resist splitting or filamentation.
structural reinforcement mesh--open mesh of strands made of steel wires or dry fibers, like alkali-resistant glass, aramid, basalt, carbon, and poly(paraphenylene benzobisoxazole, consisting of primary-direction and secondary-direction strands connected perpendicularly; polymeric coatings are typically applied to dry fibers to increase long-term durability of the mesh and ease of handling and installation; the typical strand spacing of primary-direction and secondary-direction strands is less than 0.75 in. (19 mm).

CHAPTER 3—BACKGROUND

3.1—FRCM and SRG systems features

Fabric-reinforced cementitious matrix (FRCM) and steel-reinforced grout (SRG) are systems based on inorganic (cementitious, lime-based, or geopolymeric) matrixes. Unlike polymeric binders, inorganic matrixes cannot fully impregnate individual fibers. Therefore, the fiber sheets typically used in fiber-reinforced polymer (FRP) that are installed by manual layup are replaced in FRCM and SRG with a structural reinforcing mesh (fabric). The strands of the FRCM fabric are typically made of fibers that are individually coated but are not bonded together by a polymeric resin. If a polymer is used to either cover or bond the strands, such polymer does not fully penetrate and impregnate the fibers as it would in FRP. For these reasons, the term dry fiber is used to characterize an FRCM fabric. The strands of the SRG are usually made of ultra-high-strength, galvanized steel wires that are twisted together to form the cords.

FRPs FRP systems for reinforcement of concrete, in both new construction and repair, are addressed in ACI 440R and ACI 440.2R. One example of an FRP material system for concrete reinforcement, in the form of a closely-spaced grid, is an epoxy-impregnated carbon fiber grid successfully used in precast and prestressed concrete products (Grimes 2009).
FRCM and SRG systems have several advantageous features (RILEM Technical Committee 2012006; Peled 2007c; Fallis 2009; Nanni 2012):

a) Compatibility with chemical, physical, and mechanical properties of the concrete substrate

b) Ease of installation as traditional plastering or trowel trades can be used

c) Porous matrix structure that allows air and moisture transport both into and out of the substrate

d) Good performance at elevated temperatures in addition to partial fire resistance

e) Ease of reversibility (that is, the ability to undo the repair without harming the original structure)

3.2—Background

Fabric-reinforced cementitious matrix (FRCM) and steel-reinforced grout (SRG) composite systems evolved from the conventional ferrocement where the metallic reinforcement is replaced by fabrics of dry fibers in case of FRCM (Fig. 3.2a) or ultra-high-strength resistant metal strands in case of SRG (Naaman 2012). Recent advances in textile engineering have added significant knowledge to this area where reinforcement options have been extended to two-dimensional fabrics and three-dimensional textiles made from carbon, alkali-resistant (AR) glass, polyparaphenylene benzobisoxazole (PBO), aramid, basalt, steel, vegetal (Mercedes et al. 2018), or hybrid systems using a variety of configurations. Figure 3.2b to 3.2g present fabrics with open constructions or meshes.

Textile reinforced concrete (TRC) has been used in Europe for new construction such as cladding applications or industrially-manufactured products. When this class of composites has been used in Europe for new construction, such as cladding applications or industrially-
manufactured products, the term textile-reinforced concrete (TRC) was selected (Aldea 2007, 2008; Dubey 2008). In particular, the emphasis on textile has been to signify continuous dry fibers (that is, not resin-impregnated) arranged in the direction of the tensile stresses rather than randomly distributed short fibers. Development work has been conducted since the late 1990s on topics including advanced processing, bonding, interface characteristics, and strengthening of concrete (Donini et al. 2016; Brückner et al. 2006; Hartig et al. 2008; Zastrau et al. 2008; Banholzer 2004; Banholzer et al. 2006; Peled et al. 1994, 1997, 1998a, 1999; Peled and Bentur 1998).

In addition to TRC, FRCM and SRG have also been identified in the technical literature as textile-reinforced mortar (TRM) (Triantafillou et al. 2006; Triantafillou and Papanicolaou 2006), mineral-based composites (MBC) (Blanksvärd et al. 2009), and fiber-reinforced cement (Wu and Sun 2005).

The following sections report on published technical literature covering topics from material systems to structural performance of strengthened members.

Fig. 3.2a--Different fabric assembly: (a) woven; (b) knitted; and (c) bonded.

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Fig. 3.2b—Commercially available basalt fabrics.

Fig. 3.2c—Commercially available carbon fabrics.

Fig. 3.2e—Commercially available glass fabrics.
3.2.1 **FRCM mechanical properties**—The mechanical properties of FRCM materials have been addressed in a series of publications by various researchers. Detailed analysis of the tensile mechanical response of these composites revealed that microcracking and crack distribution are two main internal parameters that result in pseudo-ductility. Three distinct measures of damage under tensile loading include quantitative crack spacing, stiffness degradation, and microstructural evaluation (Peled and Mobasher 2007; Mobasher et al. 2004). Using an automated method to determine crack density, crack spacing, and damage accumulation, statistical measures of the evolution of a distributed cracking system as a function of applied strain were correlated with tensile response and stiffness degradation (Mobasher et al. 2004). Similarly, microstructural evaluation refers to a broad range of tools that were used to better understand FRCM modes of failure. These included microscopic evaluation; thin sectioning microscopy; microcrack freezing.
by means of vacuum impregnation of tested samples using fluorescent epoxy; and thin sectioning to evaluate the interaction of yarns with matrix in crack opening, bifurcation, crack bridging, fiber debonding, and fiber fracture.

Figure 3.2.1a shows the tensile stress-strain behavior of specimens with various fabrics compared with the performance of glass fiber-reinforced concrete (GFRC) and engineered cementitious composite (ECC). Figure 3.2.1b shows the formation of distributed crack spacing throughout an alkali-resistant (AR) glass FRCM specimen (Peled and Mobasher 2006). Different fabric configurations have varying characteristic responses that correlate to crack spacing and composite stiffness (Mobasher et al. 2006).

Contamine et al. (2011) developed a direct tensile test for design purpose that is reliable, efficient, and relatively easy to implement. Results were based on a large series of experiments using a laminating technique and field measurements known as photogrammetry measurements. Protocol limitations were identified, including the poorly reproducible nature of the initial zone and the impact of implementation defects. As FRCM presents significant complexities (for example, warping and reinforcement asymmetry), behavior prior to the onset of the first through-crack is not exploitable. However, the states that follow are representative of the FRCM composite’s overall behavior. Although the number and the spacing of cracks is the same on the two sides in the case of warping specimens, this is not the case for specimens with asymmetrical reinforcement. Therefore, it is important to be cautious when considering the spacing and the crack opening as intrinsic properties of the FRCM composite.

Arboleda et al. (2012) performed experiments with the objective of investigating the mechanical properties of two FRCM systems, where carbon fibers and poly(paraphenylene benzobisoxazole) (PBO) fibers were used. They determined the values of the tensile modulus of elasticity of the
cracked and uncracked coupons, transition point of the bilinear behavior, and ultimate point (Table 3.2.1). The strain properties show the most variation because displacement measurement did not cover the entire coupon length (Fig. 3.2.1c). The main failure mode was by slippage of fibers—an indicator of the importance of bond strength in the performance of these materials.

In addition to tensile characterization under quasi-static conditions, research work has been undertaken in tension under high-speed impact and flexure (Peled et al. 1994, 1999; Zhu et al. 2010a,b, 2011; Haim and Peled 2011; Butnariu et al. 2006; Peled 2007b).

The mechanical characteristics of the FRCM and SRG composites depend on the test method. In North America, the use of clevis grips per AC434 has been adopted whereas in Europe, single-lap shear bond tests combined with clamped tests on the fabric only are more common. De Santis et al. (2018) conducted a comparative study testing FRCM and SRG composites in accordance with either test method. For the composites investigated in the study, the ultimate strength values provided by the two methods were comparable and coincided for the carbon FRCM, which failed by fabric slippage also in the bond test. However, the different boundary conditions applied in the tensile tests generally led to a lower tensile modulus of elasticity and to a higher ultimate strain from the clevis-grip tests in comparison to the clamping-grip tests.
Fig. 3.2.1a--Tensile stress-strain behavior of FRCM with AR-glass, E-glass, and polyethylene meshes compared with GFRC and ECC.

Fig. 3.2.1b--Distributed cracking in AR-glass-FRCM (width = 1 in. [25 mm]).
3.2.1.1 Fabric geometry and fiber type—Existing literature indicates that the mechanical properties of FRCM and SRG are influenced by: a) textile/yarn/fiber geometry, including three-dimensional structures (Akbari Hadad 2018; Peled et al. 1998a, 2008a, 2011b; Peled and Bentur 2000, 2003; Peled 2007a); and b) fiber type, including hybrid combinations (Peled et al. 2009, 2011a).

3.2.1.2 Modification of cement matrix—Penetration of cement paste between the openings of the fabric is a controlling factor in improving the mechanical properties of FRCM. Penetration is dependent on fiber, strand size, fabric opening, and viscosity of the matrix (Peled et al. 2006). Research has focused on optimizing mixture viscosity during the manufacturing process and optimal mechanical performance.
3.2.1.3 Shrinkage and time-dependent behavior--Researchers have studied the effects of fibers on plastic shrinkage cracking behavior in FRCM (Mechtcherine 2012; Mechtcherine and Lieboldt 2011). A general observation is that fiber fineness is effective in reducing the width of plastic shrinkage cracks (Qi and Weiss 2003; Banthia and Gupta 2006). The effectiveness of fabrics in improving the shrinkage resistance of concrete materials has also been studied (Poursaeed et al. 2010, 2011). Fine microfibers with a high specific fiber surface area are particularly effective in reducing plastic shrinkage cracking. Test methods to address creep behavior of fiber reinforcements for FRCM have been developed (Seidel et al. 2009).

3.2.1.4 Fatigue and cyclic behavior--Performance of RC beams strengthened with FRCM in flexure was experimentally investigated by Pino et al. (2017) for PBO FRCM, Akbari Hadad et al. (2018) for carbon FRCM, Akbari Hadad (2018) for glass FRCM varying the maximum applied cyclic load. The studies concluded that FRCM showed an excellent fatigue behavior and the failure of the strengthened RC beams was associated with the fatigue rupture of the steel reinforcing bars. D’Antino et al. (2015) studied fatigue and post-fatigue behavior of PBO FRCM-concrete joints, and concluded that at higher stress amplitudes, the fiber rupture caused the fatigue failure. It was also observed that the combination of high amplitude and high mean value of the load range implies greater damage measured in terms of global slip, energy dissipation, and interfacial stiffness degradation.

3.2.1.5 Glass fiber durability--Alkali-resistant (AR) glass fibers have been widely and successfully used with cementitious matrixes (PCI MNL128). Their change in properties with time has been studied for more than 35 years. A design methodology based on durability has been established that considers the long-term properties of glass fibers (PCI MNL128). There have been no demonstrated product failures due to durability issues in AR glass fibers. Design procedures can be based on the empirical relationships between accelerated aging regimens using a range of temperatures between 41 and 176°F (5 and 80°C) along with real weathering acceleration factors.
(Aindow et al. 1984; Litherland 1986; Proctor et al. 1982). Tables that include the relationship between time in accelerated aging at varying temperatures to the exposure to real weather have been proposed (Proctor et al. 1982).

Matrix modifications to improve long-term durability that are aimed at reducing portlandite produced during hydration include the addition of certain ingredients, additives, or both. They include slag cement, silica fume (Kumar and Roy 1986), metakaolin (Marikunte et al. 1997), fly ash (Leonard and Bentur 1984), finely ground E-glass fiber (Jones et al. 2008), or the use of other hydraulic cement matrixes—in particular, calcium aluminate or sulpho-aluminate cements (Litherland and Proctor 1986). The use of fly ash in the matrix modifies rheology and improves the bond between the fabric and cement paste (Peled and Mobasher 2007), in addition to improving the durability of glass and natural fibers (Mobasher et al. 2004).

ACI 544.5R presents details of various degradation mechanisms and options to improve long-term durability of AR glass fiber systems. Additionally, work has been successfully undertaken to improve durability of glass fibers by filling the spaces between yarns with polymers and nano-silica particles (Cohen and Peled 2010, 2012; Bentur et al. 2008).

3.2.2 Concrete strengthening—FRCM systems have been developed to strengthen existing concrete structures. The following sections present an overview of research used to verify bond behavior and flexural, shear, and axial strengthening of existing structures.

3.2.2.1 Bond behavior--Bond development within a woven mesh composite system contributes to crack-bridging mechanisms (Peled et al. 2006). The woven strands stretch and straighten to continue carrying the load across the matrix crack. This process is repeated as FRCM is loaded beyond the multiple-cracking region. Ultimate strength of the composite is determined by the strength of the fabric or the interface fiber-matrix as delamination and fiber debonding occurs.
The bond between a PBO FRCM-strengthening material and the concrete was experimentally analyzed by means of double shear tests (D’Ambrisi et al. 2013) to evaluate an effective anchorage length of 9.8 to 11.8 in. (250 to 300 mm) and a maximum debonding fiber strain of 0.00825. A calibration of a local bond-slip relation based on experimental results published a year later (D’Ambrisi et al. 2013) is reported in D’Ambrisi et al. (2012).

Ombres (2015) studied the bond between the FRCM and concrete substrate, varying the number of fabric layers, the width, and the testing environment temperature. He concluded that the loss of bond between the concrete and the FRCM system occurred at the fibers/matrix interface, with large fibers/matrix slippage occurring before the specimen’s failure. Increasing the number of reinforcing layers, the failure was due to the delamination between the reinforcing system and the concrete substrate.

Sneed et al. (2015) compared the bond behavior of PBO FRCM composite in single- and double-lap shear tests and concluded that the idealized load response developed from single-lap shear tests is found to characterize the response of the composite in double-lap shear tests, although with a few key differences. With the double-lap shear test, load redistribution among the composite strips influences the post-peak response if debonding does not occur equally in both strips. Values of the ultimate (peak) stress determined using double-lap shear tests are generally consistent, but slightly lower than those determined by single-lap shear tests when the bonded length is longer than the effective bond length.

D’Antino et al. (2015) studied the effect of substrate preparation in the bond behavior of FRCM-concrete joints. In their study, different specimens’ widths and lengths with different substrate preparations and different concrete strengths were used. Different failure modes were observed, namely debonding of the fibers at the matrix-fiber interface, detachment of the composite at the
concrete--composite interface, and fiber failure (rupture) outside the bonded length. Detachment of the entire composite or portion of it from the concrete substrate was observed for four specimens that were not subjected to surface preparation except for cleaning. The failure was attributed to poor bond at the concrete--composite interface combined with the presence of matrix shrinkage cracks. However, 14 specimens with an untreated concrete surface failed due to fiber debonding at the matrix-fiber interface. The load responses obtained were compared with those previously obtained by the authors for other FRCM-concrete joints with the same geometrical characteristics and a treated (sandblasted) concrete surface, showing that the surface preparation has a limited role in the behavior of the FRCM-concrete joint, provided that the matrix shrinkage is controlled.

Grande and Milani (2018), Focacci et al. (2017), and Carloni et al. (2017) studied the interface models to develop cohesive material law, which is an important step in advancing numerical models for analysis and design of FRCM systems and FRCM-strengthened structures.

3.2.2.2 Flexural strengthening—Triantafillou (2007) reports on a feasibility study to investigate the effectiveness of carbon FRCM as flexural strengthening materials of RC beams subjected to four-point bending. One control beam was tested without strengthening and the second one strengthened with four-layer FRCM. The FRCM-strengthened beam displayed a failure mechanism governed by inter-laminar shear and showed a good pseudo-ductility.

In another study, Papanicolaou et al. (2009) carried out experimental and analytical investigations on the use of carbon and glass FRCM to strengthen 6.6 x 6.6 ft (2 x 2 m) two-way slabs subjected to concentrated forces. The load-carrying capacity of the FRCM-strengthened slabs using one carbon, two carbon, and three glass fabric layers increased by more than 25, 50, and 20 percent, respectively, over the control specimen with experimental results in good agreement with analytical predictions.
Gencoglu and Mobasher (2007) strengthened plain concrete flexural members with glass FRCM. Results indicated an increase in load-carrying and deformation capacities, and also pseudo-ductility by using multiple layers of AR glass fabric. A design procedure based on composite laminate theory was proposed (Mobasher 2012) to address the contribution of FRCM, where an algorithm produces a moment-curvature relationship for the section, which in turn can be used to calculate the load-deflection response of a structural member (Soranakom and Mobasher 2010b). Flexural performance of concrete members strengthened with FRCM under impact rather than from quasi-static loads has also been reported (Katz et al. 2011).

Experimental results of RC beams strengthened in flexure with various types of FRCM materials are discussed in D’Ambrisi and Focacci (2011). Carbon and PBO fabrics and two types of cementitious matrixes were tested. The failure of FRCM-strengthened beams was caused by loss of strengthening action as a result of fiber debonding; three different debonding modes were identified. In most cases, the fiber debonding involved the fiber/matrix interface instead of the concrete substrate. PBO FRCM performed better than carbon FRCM. The fiber strain at beam failure was estimated at 0.8 to 0.9 percent in carbon FRCM and 1.3 to 1.5 percent for PBO FRCM. The performance of FRCM materials is strongly dependent on the matrix design and constituents as they affect the fibers/matrix bond.

Akbari Hadad et al. (2018) and Pino et al. (2017) studied the flexural behavior of RC beams strengthened with FRCM composites, in which they found the relation between the FRCM/steel reinforcing bar reinforcement ratio and the flexural enhancement of the beams in terms of capacity. In their studies, they found that the application of FRCM mitigates crack openings and delays crack propagation, and the application of FRCM to RC beams provides an increase in stiffness, yield point, and strength compared to control specimens. However, there is a threshold for which
additional FRCM reinforcement does not provide increase in strength, and this threshold is dependent on the bond capacity at the FRCM-concrete interface and the fabric-matrix.

Sneed et al. (2016) studied the flexural capacity of the SRG-strengthened RC beams. RC beams strengthened in flexure with steel-FRCM composite failed due to loss of composite action from debonding of the composite. Debonding occurred at the fiber-internal matrix layer, similar to the single-lap direct-shear tests. Failure of the strengthened beams without U-wraps was associated with a sudden, rapid progression of interfacial cracking resulting in peel-off of the external matrix layer and fibers. For the strengthened beam with U-wraps, the evidence suggests that a mix of debonding phenomena (a combination of Mode II [shear] and Mode I [peeling] loading conditions) occurred at different locations along the bonded length that contributed to the failure mechanism. The strengthening system increased the yield load by 15 to 21 percent relative to the unstrengthened beam. The debonding load was larger than the yield load, and the ratio of the load at which debonding occurred to the load at yielding $F_{deb}/F_y$ ranged from 1.11 to 1.19 for each strengthened beam. The ratio of the midspan displacement at debonding to that at yielding $D_{deb}/D_y$ ranged from 1.71 to 2.07. The debonding load and corresponding midspan displacement for the strengthened beam with U-wraps anchorages were similar to those of the strengthened beams without U-wraps, which indicates that the U-wraps did not improve the effectiveness of the strengthening system, opposite to the FRP application.

3.2.2.3 Shear strengthening--Triantafillou and Papanicolaou (2006) investigated the use of FRCM to increase the shear resistance of RC members with rectangular cross sections under monotonic or cyclic loading. They concluded that FRCM jacketing provides substantial gain in shear resistance. This gain increases as the number of mesh layers do and, depending on the number of layers, could transform the shear-type failure into flexural failure.
Al-Salloum et al. (2012) investigated the use of basalt FRCM as a means of increasing the shear resistance of RC beams using two mortar types—cementitious and polymer-modified cementitious—as binder. The studied parameters also included the number of reinforcement layers and their orientation. The experimental program comprised of testing two control beams that were intentionally designed to be deficient in shear, in addition to testing eight strengthened beams. It was concluded that FRCM provides substantial gain in shear resistance and this gain is higher as the number of reinforcement layers increases. With a higher number of layers, 45-degree orientation and polymer-modified cementitious mortar provides the highest shear strength enhancement.

Azam and Soudki (2014) experimentally studied different FRCM systems for strengthening shear-critical RC beams in two configurations (side-bonded and U-wrapped) and found that the increase in load-carrying capacity of the FRCM-strengthened beams ranged between 19 and 105 percent.

Ombres (2015) studied the continuous and discontinuous U-wrap FRCM strengthening of RC beams. The use of the PBO-FRCM strengthening system allows the shear capacity of reinforced concrete beams to improve significantly if an adequate strengthening configuration is adopted. For beams strengthened in shear with discontinuous U-wrapped strips, an inadequate ratio width/spacing did not permit a correct activation of the strips, reducing their contribution to the shear capacity.

Tzoura and Triantafillou (2016) studied shear strengthening of reinforced concrete T-beams under cyclic loading with FRCM and FRP. For beams without anchors, it was concluded that the effectiveness of FRCM increases nonproportionally with the number of layers and that, for the same total volume fraction of fibers in the jacket, one layer of textile is more effective than two.
For beams with anchored FRCM jackets, it is concluded that the effectiveness of the strengthening system is quite high, as is the effectiveness of an anchored FRP system. Gonzalez-Libreros et al. (2017) studied the shear strengthening of RC beams with FRP, SRP, FRCM, and SRG composites. Results show that the increase in the shear strength of strengthened beams increases with increasing axial stiffness of the composite, $A/E_f$. For the SRP- and SRG-strengthened beams that had similar values of $A/E_f$, the increase in shear strength was similar, that is, it did not vary depending on the type of matrix. All FRCM strengthened beams without anchors failed in shear. Internal-external shear reinforcement interaction was observed for all strengthening beams. However, this interaction appears to be less pronounced for beams with FRCM and SRG composites. The anchors used in this study modified the failure mode, concrete crack pattern, and midspan displacement of beams strengthened with FRCM composites. However, the use of anchors did not significantly increase the shear strength.

3.2.2.4 Axial strengthening—Confinement with FRCM systems has been investigated for damaged and undamaged RC members (Peled 2007c; Ombres 2014). Triantafillou et al. (2006) used cylindrical and prismatic plain concrete specimens. The investigation with cylindrical specimens studied the effects and strength of two inorganic mortars and a number of reinforcement layers (two and three). Jacketing of all cylinders was accomplished with the use of a single fabric in a spiral configuration until the desired number of layers was achieved. Testing on rectangular prisms aimed at investigating the number of reinforcement layers (two and four) and effectiveness of bonded versus unbonded confinement. Considering all results, it was concluded that:

a) Fabric-reinforced cementitious matrix-confining jackets provide substantial gain in compressive strength and deformation capacity. In the case of ultimate capacity, for example, the
increase over the unconfined specimen varies between 25 and 75 percent based on mortar type, number of reinforcement layers, and specimen cross section type.

b) This gain increases as the number of fabric layers increases and is dependent on the tensile strength of the mortar, which determines whether failure of the jacket occurs due to fiber fracture or debonding.

c) Failure of FRCM jackets is due to the slowly progressing fracture of individual fiber strands.

De Caso y Basalo et al. (2009, 2012) reported on a feasibility study to develop a reversible and potentially fire-resistant FRCM system for concrete confinement applications. A candidate system was selected from different fiber and cementitious matrix combinations on the basis of: a) constructability; b) confined concrete cylinders enhancement of strength and deformability; c) quality of the concrete FRCM interface; and d) level of fiber impregnation monitored with scanning electron microscope images. The selected FRCM system was further assessed using different reinforcement ratios and by introducing a bond breaker between concrete and jacket to facilitate reversibility. Substantial increases in strength and deformability with respect to unconfined cylinders were attained. For example, in the case of bonded jackets, the increase in ultimate capacity over the unconfined specimen varied between 21 and 121 percent when the number of reinforcement layers varied from one to four. The predominant failure mode was fiber-matrix separation, which emphasized the need of improving fiber impregnation.

Di Ludovico et al. (2010) appraised the performance of basalt FRCM as a strengthening material for the confinement of RC members. Effectiveness of the technique was assessed by comparing different confinement schemes on concrete cylinders. Based on experimental results, the basalt FRCM technique showed an increase of peak stress between 27 and 45 percent over the unconfined member when the number of reinforcement layers varied from one to two.
Abegaz et al. (2012) tested a total of 27 approximately one-quarter-scale RC columns wrapped with FRCM to investigate and quantify the enhancement in strength and ductility for different cross-sectional shapes. Rectangular, square, and circular specimens with equal cross-sectional area and slenderness ratio were considered to properly isolate the effect of shape on the confinement effectiveness. In addition to cross-sectional shape, columns with one and four layers of FRCM wrapping were tested to investigate the effect of the number of plies. Results indicated that FRCM wrapping can significantly enhance the load-bearing capacity (up to 71 percent) and ductility (exceeding 200 percent) of RC columns subjected to a monotonic axial compressive load, with the highest improvement obtained for circular cross sections.

Ombres and Verre (2015) experimentally studied the effect of eccentricity in structural behavior of FRCM confined RC columns. In their study, eight RC columns with end corbels were confined with PBO FRCM jackets and were tested varying the FRCM reinforcement ratio and eccentricity-to-section height ratio ($e/h$) and performed a nonlinear second-order analysis to predict the structural response of confined columns. The confinement by FRCM allows to increase the strength of eccentrically loaded reinforced concrete columns; with respect to the unconfined specimen, the increase of the load carrying capacity of confined specimens was ranging between 20 and 39 percent; the strength gain was inversely proportional to the eccentricity values. By increasing the $e/h$ ratio, a decrease of the strength gain was recorded for tested columns. Failure modes of tested specimens are dependent on the confinement ratio whereas the eccentricity values are not influential.

Thermou et al. (2015) and Thermou and Hajirasouliha (2018) conducted an experimental study and developed design-oriented models on concrete columns confined by SRG jackets. The SRG confinement is considered successful when rupture of the fabric occurs before mortar reaches its
ultimate shear strength. For one-layered SRG jackets, using 36 cm overlap length generally led to
the rupture of steel fabric and therefore is considered to be adequate. While the overlap length of
24 cm was sufficient for two-layered SRG jackets with low- to medium-density fabrics (1 to
2 cords/cm), in the case of 4.72 cords/cm density textiles, it resulted in a mixed mode of failure.
SRG jackets with very high-density fabrics (9.06 cords/cm) failed due to debonding (unfavorable
failure mode) and were shown to be impractical due to the difficulties in the wrapping process and
penetration of mortar through the small spacing between the cords. Similar to the observations
made for FRP and TRM jacketing systems, it was shown that in general the effectiveness of SRG
jacket increases as the unconfined concrete strength decreases.

3.2.2.5 Torsion strengthening—Alabdulhady et al. (2017) experimentally studied the torsional
behavior of RC beams strengthened with PBO-FRCM. This study demonstrated that externally
bonded PBO-FRCM composites can be used to strengthen RC beams in torsion. Failure of the
strengthened beams was associated with debonding of the composite, which was characterized by
significant slippage between the fibers and matrix. Increases in the cracking torque, torsional
strength, and corresponding values of twist were achieved by beams strengthened with a four-
sided wrapping configuration relative to the control (unstrengthened) beam. On the other hand, the
three-sided wrapping configuration was found to be largely ineffective in improving the torsional
performance. The contribution of the strengthening system to the torsional strength was reasonably
predicted (±20 percent) by the strains in the composite fibers. Provisions used to estimate the
torsional strength of RC beams with externally-bonded FRP composites were found to be
applicable for beams strengthened with FRCM composites.

3.2.2.6 Seismic retrofitting—Bournas et al. (2007) investigated the effectiveness of FRCM jackets
as a means of confining RC columns. Tests were carried out on short prisms under concentric
compression and on nearly full-scale, nonseismically detailed RC columns subjected to cyclic
uniaxial flexure under constant axial load. Compression tests on prisms indicated that FRCM
jackets provide substantial gain in compressive strength and deformation capacity by delaying
buckling of the longitudinal bars; this gain increases with the volumetric ratio of the jacket. Tests
on nearly full-scale columns show that FRCM jacketing is effective as a means of increasing the
cyclic deformation capacity and energy dissipation of RC columns with poor steel detailing by
delaying bar buckling. Further experimental and analytical investigations on bar buckling at the
plastic hinge of old-type RC columns confined with FRCM jackets are reported in Bournas and
Triantafillou (2011).

Bournas et al. (2009, 2011) investigated the effectiveness of FRCM as a means of confining old-
type RC columns with limited capacity due to bond failure at lap splice regions and made
comparisons with equal stiffness and strength FRP jackets. Tests on nearly full-scale columns
subjected to cyclic uniaxial flexure under constant axial load indicated that FRCM jacketing is
effective as a means of increasing the cyclic deformation capacity by preventing splitting bond
failures in columns with lap-spliced bars. Compared with their FRP counterparts, the FRCM
jackets used in these studies were found to be equally effective in terms of increasing strength and
deformation capacity of the retrofitted columns. As a result of the experimental investigation of
RC members confined with FRCM, simple equations were proposed for calculating the bond
strength of lap splices.

3.2.2.7 Beam-column connections—The performance and behavior of RC exterior beam-column
joints rehabilitated using FRCM was studied (Mobasher 2012). The strengthening was applied to
seismically deficient beam-column joints subjected to cyclic loads that simulate seismic excitation.
Six half-scale exterior beam-column joints were prepared. One specimen was designed in
accordance with ACI 318 and the others insufficiently reinforced to study the shear, anchorage, and ductility aspects of the beam-column connection. Two beam-column joints used an AR glass FRCM as the basis for the retrofit. By shifting failure location and failure mode of the exterior beam-column hinges that form during reverse cyclic loads, FRCM strengthening showed better results than the ACI 318-detailed specimen in terms of ductility; total absorbed, dissipated, and recovery energy; ultimate displacement; and load-carrying capacity.

Al-Salloum et al. (2011) studied efficiency and effectiveness of FRCM on upgrading the shear strength and ductility of seismically-deficient exterior beam-column joints compared with that of carbon fiber-reinforced polymer (CFRP) and GFRP systems. Joints were constructed with deficient design and encompassing the majority of existing beam-column connections. Two specimens were used as a baseline and the third was strengthened with FRCM. All subassemblies were subjected to quasi-static cyclic lateral load histories to provide the equivalent of severe earthquake damage. The results demonstrated that FRCM can effectively improve the shear strength and deformation capacity of seismically deficient beam-column joints. In particular, the peak load increased 10 percent and the ultimate displacement (measured after a 20 percent drop in peak load) increased 28 percent.

3.2.3 Elevated temperature performance—Performance of FRCM/SRG exposed to elevated temperatures in tension and bending was studied (Donini et al. 2017; Kulas et al. 2011; Antons et al. 2012; Colombo et al. 2011).

An important consideration in applying any strengthening system in an existing building is its performance during fire. Fire severity, flame spread, smoke generation, and toxicity cannot be ignored as they impact the tenability conditions in a building during the early stages of a fire. FRCM/SRG systems are inherently noncombustible and can be used unprotected.
Research aimed at comparing the performance of members strengthened with an FRCM/SRG system against FRP systems was performed (Bisby et al. 2009, 2011) to investigate the idea that FRCM/SRG can provide retention of mechanical and bond properties at elevated temperatures. Steady-state flexural tests were performed on commercially available FRCM/SRG-strengthened RC beams and unreinforced concrete prisms at temperatures up to 392°F (200°C). The test data showed good performance of the FRCM system at elevated temperatures (Fig. 3.2.4). Combined with FRCM/SRG-inherent noncombustibility, nontoxic, and nonflaming characteristics, FRCM-strengthening systems are an attractive option for fire-safe structural strengthening, and also in warm climates or industrial environments. Additional testing is needed to clearly define upper service temperature limits for FRCM/SRG.

![Graph of Load-Deflection Response](image)

**Fig. 3.2.4—Load-deflection response for FRCM-strengthened concrete prisms tested at: (a) 68°F (20°C); (b) 122°F (50°C); and (c) 176°F (80°C).**

### 3.3—Commercially available FRCM/SRG systems

A number of commercially available fabric-reinforced cementitious matrix (FRCM) and steel-reinforced grout (SRG) systems for strengthening of concrete structural members are available.
Appendix A shows a representative sample of constituent properties of available systems as provided by the manufacturers.

CHAPTER 4—FIELD APPLICATION EXAMPLES

The following examples of commercial projects provide evidence of the potential uses for fabric-reinforced cementitious matrix (FRCM) technology for repairing and strengthening concrete structures.

4.1—Concrete repair applications

4.1.1 Strengthening roof openings for high-temperature ducts—FRCM was used to strengthen a roof slab to allow an opening to be cut for the passage of air ducts. These ducts were to be operated at temperatures considered too high for conventional fiber-reinforced polymer (FRP) repair systems. As per design requirements, strengthening was completed before slab cutting (Fig. 4.1.1). For ease of access and installation, the application was performed on the top side of the roof slab. First, the insulation and roof deck membrane were removed, followed by preparation of the concrete surface by means of grinding. After the first layer of mortar matrix was applied, fabric was installed by pressing it into the mortar layer, which was followed immediately by installing the top mortar layer. Once the FRCM had reached the required strength, openings were cut in the slab and new insulation and roof membrane were placed.

4.1.2 Unreinforced concrete vault strengthening—FRCM was used to strengthen a railroad bridge along the Roma-Formia line in Italy (Berardi et al. 2011). The superstructure consists of six semicircular vaults made of unreinforced concrete with approximately the same span, resting on...
masonry abutments made of blocks of tuff (Fig. 4.1.2a(a)). The deck is 34.4 ft (10.5 m) wide with a vault thickness that varies between 27.5 in. (0.7 m) at the crown to 39.4 in. (1.0 m) at the skewback. The project was preceded by a field investigation for characterization of the geometry and evaluation of the material mechanical properties. FRCM was adhered to the soffit of each vault to prevent formation of hinges at the exterior surface. This repair method that can be implemented without disrupting traffic modifies the vault ultimate behavior without affecting behavior of the structure under service loads. Safety of the structure was assessed by the limit state analysis considering all possible mechanisms of collapse with formation of hinges.

Final design called for the soffit of each vault to be strengthened by application of a two-ply mesh FRCM. To begin, the concrete surface was thoroughly cleaned, and portions of deteriorated concrete removed and reconstructed. A first layer of cementitious matrix, approximately 0.12 to 0.20 in. (3 to 5 mm) thick, was applied on the concrete surface, followed by application of the first fabric (Fig. 4.1.2a(b)). A second, thinner layer of cementitious matrix and the second fabric were added. Figure 4.1.2b shows the fabric rolls freely hanging from the vault as the scaffolding is moved to the next location. Strengthening concludes with application of a final top layer of the same matrix.

4.1.3 Strengthening of reinforced concrete tunnel lining—The reinforced concrete (RC) lining of a vehicular tunnel along the Egnatia Odos Motorway in Greece was strengthened with FRCM to correct a structural deficiency (Nanni 2012). The original lining was 25.6 in. (650 mm) thick with clear cover of 2 in. (50 mm) and was reinforced with top and bottom steel bar mats. According to a structural analysis, the ultimate flexural capacity in the transverse direction of the tunnel lining was increased 14 percent (top portion) and 4 percent (side portions) by adding a single fabric. Additionally, a flexural strength increment of 100 percent (which would exceed the usable limit

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imposed by this guide) was attained in the longitudinal direction in the top portion of the tunnel lining using two fabrics. The concrete surface was scarified using hydrojetting (Fig. 4.1.3(a)) followed by FRCM installation and finishing (Fig. 4.1.3(b)).

4.1.4 Trestle bridge base confinement—FRCM was chosen to provide confinement to the concrete support base for the trestle of a railway bridge in New York (Nanni 2012) because a breathable strengthening material system with vapor permeability was required. The base had cracked, and the concrete deteriorated over time (Fig. 4.1.4a). Although cracking and deterioration did not necessarily affect performance of the support base, long-term durability of the concrete base was a concern that had to be addressed. The first step was to remove and replace the deteriorated concrete by chipping it out and replacing it with an engineered fast-set concrete repair material. The concrete surface was prepared by grinding to provide a good bonding surface. The FRCM matrix was applied and the fabric pressed into the substrate (Fig. 4.1.4b). Finally, the crew installed the top mortar layer and a curing compound.

4.1.5 Equipment base confinement in high ambient temperature—FRCM was chosen to confine the concrete support base of a piece of equipment in an industrial plant in the Midwestern United States U.S. because the ambient temperature of the concrete was approximately 180°F (82°C), which is considered too high for conventional FRP repair systems. The concrete substrate was first prepared by means of grinding to provide a good bonding surface. Because the concrete temperature during the installation was at approximately 140°F (60°C), its surface was constantly wetted to have it in a saturated surface-dry condition at the application of FRCM. A crew then applied the first matrix layer to the surface and immediately after, because of high temperature, a second crew installed the mesh by pressing it into the initial layer of mortar (Fig. 4.1.5). A third
crew followed with the top mortar layer. Upon completion, a polymer coating and wet burlap were installed to provide proper curing.

4.1.6 **Strengthening of reinforced concrete bridge pier**—The RC bridge piers of a structure located in Novosibirsk, Russia, were strengthened with FRCM (Nanni 2012). The piers of this bridge were reconstructed in 1958 by increasing their height to 32.4 ft (9.87 m) and their width at the top to 34.8 ft (10.6 m). Significant temperature and shrinkage stresses following reconstruction caused the formation of cracks along the construction joints and new corbels. Although the cracks were epoxy-injected in 1991, they reappeared 6 years later with widths ranging from 0.08 to 0.20 in. (2 to 5 mm). Given the lack of success with the previous repair techniques, the owner elected to repair and strengthen the structure with FRCM. The project, which was completed in 2007, was made up of the following:

   a) Sandblasting the concrete surface
   b) Rounding corners to a radius of 1.2 in. (30 mm)
   c) Repairing cracks and resurfacing with single-component polymer-modified cementitious mortar
   d) Strengthening with FRCM
   e) Surface sealing with a two-component, polymer-modified, cementitious waterproofing and protective slurry

Given the cold weather conditions of this region, curing tents warmed from within by construction-grade heaters kept a constant air temperature in the enclosure at approximately 59 to 64°F (15 to 18°C). The heaters remained until 7 days after project completion.

4.1.7 **Strengthening of reinforced concrete beams in flexure with carbon FRCM**—Flexural strengthening of RC beams was undertaken using an FRCM system consisting of carbon fabric...
and cement-based mortar (Fig. 4.1.7). The compressive strength of the mortar was 7252 psi (50 MPa). The strengthened structure is an old courthouse building located in the direct vicinity of a harbor in Turkey. Insufficient concrete cover and poor concrete quality facilitated the diffusion of chlorides present in the environment such that they could reach the reinforcing steel. Furthermore, lack of maintenance and vacancy for years caused serious corrosion of the reinforcement in beams and slabs. After removing deteriorated concrete and rust from the reinforcement, slabs and beams were strengthened with FRCM. A layer of mortar with 0.2 in. (5 mm) thickness was applied first. Following that, a carbon fabric having density of 1367 lb/in.\(^2\) (400gr/m\(^2\)) was fixed to the surface using stainless steel nails. Then, the final layer of mortar with 0.4 in. (10 mm) thickness was applied.

Fig. 4.1.7—Flexural strengthening of RC beams with carbon FRCM.

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4.1.8 Strengthening of reinforced concrete slab in flexure with carbon FRCM—For a hospital building located in Ankara, Turkey, it was requested to increase the load carrying capacity of an RC floor due to the increase in equipment load. The RC floor area of 9.84 x 13.12 ft (3 x 4 m) was strengthened using an FRCM system consisting of carbon fabric and inorganic matrix (Fig. 4.1.8). The FRCM constituents and the application method were as described in 4.1.7.

![Flexural strengthening of hospital RC floor with carbon FRCM.](image)

4.1.9 Strengthening of reinforced concrete beams in flexure with steel-reinforced grout—The Ansaldo ex-foundry in Genova, Italy, was subjected to retrofit and reinforcement interventions in
2015 due to change in destination of use to become a commercial mall. Steel-reinforced grouts (SRGs), made of inorganic cementitious mortar and ultra-high-strength steel fiber were fabric (characteristic tensile strength greater than 435 ksi [3000 MPa]) was installed to strengthen in flexure the RC beams (Fig. 4.1.9).

CHAPTER 5—FRCM AND SRG CONSTITUENT MATERIALS AND SYSTEM

QUALIFICATIONS

5.1—Constituent materials

The two principal components of fabric-reinforced cementitious matrix (FRCM) and steel-reinforced grout (SRG) are the inorganic matrix and the structural reinforcement fabric. The former is typically a mortar based on portland cement, lime, or geopolymers and a low dosage of

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dry polymers at less than 5 percent by weight of binder. The organic polymer compounds are sometimes used to ensure proper workability, setting time, and mechanical properties. The mechanical effectiveness of FRCM and SRG is strongly influenced by:

a) Capacity of the inorganic matrix to impregnate the dry fiber strands (Peled and Bentur 1998; Banholzer 2004; Wiberg 2003; Peled et al. 2008a)


c) Bond between the inorganic matrix and the concrete substrate (Ortlepp et al. 2004, 2006; Mobasher et al. 2007)

In case of FRCM, there are a variety of fabrics available in the marketplace that could be potentially used. In these meshes, the typical spacing of primary-direction (PD) and secondary-direction (SD) strands is less than 1 in. (25.4 mm) 0.75 in. (19 mm), and the total coverage area of the fabric is less than two-thirds of total area (that is, there is at least 33.3 percent of open area among strands). With reference to fiber types in particular, extensive descriptions of various physical and mechanical properties exist in the literature (ACI 440R; ACI 440.2R; ACI 440.7R-10; ACI 544.1R; RILEM Technical Committee 201 2006). Although a significant amount of research was carried out on the use of greige (uncoated) alkali-resistant (AR) glass fibers, the results, although interesting, appear to be of limited practical application. This is because AR glass meshes for the applications discussed in this guide are typically coated to improve their long-term durability in an inorganic matrix and for ease of handling and installation.

While many interesting and promising field applications have been undertaken, and FRCM and SRG technologies have been proven reliable, experimental and theoretical research continues to fully characterize FRCM and SRG and quantify its mechanical effectiveness based on parameters.

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such as type and arrangement of fibers, type of inorganic matrix, and conditions of the substrate (D’Antino et al. 2015; D’Ambris and Focacci 2011). Several analytical approaches are available that allow for measurement of the contribution of different reinforcement fabric and matrix systems using mechanics-based approaches (Mobasher 2012; Soranakom and Mobasher 2010a,b).

Appendix A presents the constituent material properties of some commercially available FRCM and SRG systems as provided by the respective manufacturers. While these parameters should be disclosed by manufacturers, they cannot be directly used to infer the values of the parameters to be used in design, nor to assess the durability of an FRCM/SRG system. Based on the provisions of AC434, 5.2 to 5.4 of this guide describe the test protocols required to qualify an FRCM system and how to obtain the design values used in Chapters 10 and 11.

5.2—FRCM and SRG system qualifications

Each fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM/SRG) system should be qualified for use in a project based on the independent laboratory test data of the FRCM/SRG constituent materials and coupons made with them, structural test data for the type of application being considered, and durability data representative of the anticipated environment. Test data provided by the FRCM/SRG system manufacturer demonstrating that the proposed system meets all mechanical and physical design requirements including tensile strength, durability, and bond to substrate should be considered, but not used as the sole basis for qualification. The specified material-qualification programs should require laboratory testing to measure repeatability and reliability of critical properties. Untested FRCM/SRG systems should not be considered for application.
5.2.1 **Qualification test plan according to AC434**—A qualification test plan should be undertaken following the requirements of AC434 with the intent of verifying the design properties to be used in FRM and SRG systems. This testing would provide data on material properties, force, and deformation limit states, including failure modes of FRM/SRG to support a rational analysis and design procedure. Specimens should be constructed under conditions specified by AC434 and be prepared to verify the range of FRM/SRG configurations, including layers, thickness, components, and bonding agents recommended by the manufacturer. Tests should simulate the anticipated range of loading conditions, load levels, deflections, and ductility.

5.3—**Physical and mechanical properties of FRM/SRG**

5.3.1 **Composite tensile strength**—Tensile testing to determine the tensile strength, elongation, and modulus of elasticity is conducted on coupons cut from fabric-reinforced cementitious matrix/steel-reinforced grout (FRM/SRG) panels laid up using a procedure similar to that in the actual in-service application and according to manufacturer’s instructions. The test procedure should comply with the Annex A of AC434 acceptance criteria. Quantities considered to characterize the tensile behavior of each FRM system are:

- a) Tensile modulus of elasticity of the uncracked specimen, \( E_f^* \)
- b) Tensile modulus of elasticity of the cracked specimen, \( E_f \)
- c) Ultimate tensile strain \( \varepsilon_{fu} \)
- d) Tensile strain corresponding to the transition point, \( \varepsilon_{ft} \)
- e) Ultimate tensile strength \( f_{fu} \)
- f) Tensile stress corresponding to the transition point, \( f_{ft} \)
- g) Lap tensile strength
The idealized tensile stress-strain curve of an FRCM coupon specimen is initially linear until cracking of the cementitious matrix occurs, deviates from linearity, and becomes linear again until the tensile failure of the fibers happens, as illustrated in Fig. 5.3.1a. The plot can be reduced to a simple bilinear curve with a bend-over point (transition point as defined in AC434) corresponding to the intersection point obtained by continuing the initial and secondary linear segments of the response curve. The initial linear segment of the curve corresponds to the FRCM uncracked linear elastic behavior and it is characterized by the uncracked tensile modulus of elasticity \( E_f^* \). The second linear segment, which corresponds to the FRCM cracked linear elastic behavior, is characterized by the cracked tensile modulus of elasticity \( E_f \).

FRCM/SRG tensile properties should be determined according to the test procedure specified in Annex A of AC434. Figure 5.3.1b shows five experimental curves obtained with tests conducted according to Annex A of AC434 using the clevis-type grips prescribed in its provisions (Fig. 3.2.1c). In particular, Fig. 5.3.1b shows the tensile modulus of elasticity and the ultimate tensile strain as computed based on AC434. That is, on the segment of the response curve corresponding to cracked behavior after the transition point, two points are selected on the experimental curve at a stress level equal to 0.90\( f_{fu} \) and 0.60\( f_{fu} \). The slope of the line that connects these two points represents the tensile modulus of elasticity at that region

\[
E_f = \frac{\Delta f}{\Delta \varepsilon} = \frac{(0.90f_{fu} - 0.60f_{fu})}{(\varepsilon_{f@0.90f_{fu}} - \varepsilon_{f@0.60f_{fu}})}
\]

Ultimate tensile strain \( \varepsilon_{fu} \) is the y-intercept of the line used to compute \( E_f \) (that is, \( y_{intercept} = 0.60f_{fu} \), \( E_f \varepsilon_{f@0.60f_{fu}} \)) and the following equation
Fig. 5.3.1a—Idealized tensile stress versus strain curve of an FRCM coupon specimen.
5.3.2 Bond and inter-laminar shear strength—The bond strength of FRCM to the concrete substrates and the composite inter-laminar shear strength between the fabric and the cementitious matrix should be evaluated for each FRCM system according to the procedures indicated in ASTM C1583/C1583M and ASTM D2344/D2344M, respectively. AC434 offers interpretation and limits for three possible modes of failure:

a) Cohesive when failure occurs in the substrate material

b) Adhesive when failure occurs at the interface FRCM and substrate material

c) Adhesive when failure is at the interface between the reinforcement mesh and matrix within the FRCM

Fig. 5.3.1b—Experimental tensile stress versus strain curve of FRCM coupons as per Annex A of AC434.
5.3.3 Properties of matrix—For each FRCM system, normal compressive strength of the cementitious matrix should be evaluated at 7 and 28 days according to ASTM C387/C387M for cement- or polymer-modified cement-based mortars, or ASTM C141/C141M for hydraulic lime-based mortars. The mortar compressive strength shall be representative of the mortar strength used in structural tests. The minimum compressive strength for cement-based mortars and hydraulic lime-based mortars shall at 28 days be 1450 psi and 750 psi, respectively.

5.3.3.1 Drying shrinkage and void content—For each FRCM system, drying shrinkage and void content of the cementitious matrix should be determined. Drying shrinkage tests should be conducted in accordance with the general procedures outlined in ASTM C157/C157M and void content tests conducted in accordance with ASTM C173/C173M. Air content and unit weight are to be measured.

5.4—Durability

5.4.1 Aging—For each fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM/SRG) system, the tensile properties, bond, and composite inter-laminar shear strengths should be evaluated on FRCM specimens after being subjected to each of the conditioning regimens (AC434):

a) Ambient

b) Aging in water (100 percent humidity, 100°F [37.7°C]) for 1000 and 3000 hours

c) Aging in saltwater (immersion, 73°F [22°C]) for 1000 and 3000 hours

d) Aging in alkaline environment (immersion, pH ≥ 9.5, 73°F [22°C]) for 1000 and 3000 hours
5.4.2 Freezing and thawing—For each FRCM system, the tensile properties and composite inter-laminar shear strength should be evaluated on specimens after being subjected to freezing-and-thawing cycles, with each cycle consisting of a minimum of 4 hours at 0°F (-18°C), followed by 12 hours in a humidity chamber (100 percent humidity, 100°F [37.7°C]).

5.4.3 Fuel resistance—For each FRCM system, the tensile properties should be determined on FRCM specimens after being exposed to diesel fuel reagent for a minimum of 4 hours.

5.4.4 Aged properties of SRG fabric—Steel fabrics are susceptible to degradation due to corrosion. Therefore, the AC434 mandates exposure to salt spray for 1000 and 3000 hours according to ASTM D1141 and ASTM G85. Both straight and prebent steel fabrics should be exposed to the salt spray and tested in tension.

CHAPTER 6—SHIPPING, STORAGE, AND HANDLING

6.1—Shipping

The user of fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM/SRG) constituent materials is advised to observe federal and state packaging and shipping regulations. Packaging, labeling, and shipping for construction materials are controlled by the Code of Federal Regulations.

6.2—Storage

6.2.1 Storage conditions—To preserve the properties of and maintain safety in fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM/SRG) system constituents, materials should be stored in accordance with the manufacturer’s recommendations. In particular, for the fabric
reinforcement before encapsulation in the matrix, consider exposure to ultraviolet light (UV), extreme temperatures, moisture, and other environmental conditions that can be deleterious to synthetic fibers such as aramid and polyparaphenylene benzobisoxazole (PBO) (Chin et al. 1997). Certain constituent materials have safety-related requirements and should be stored as recommended by the manufacturer and Occupational Safety and Health Administration (OSHA).

6.2.2 Shelf life—The manufacturer sets a recommended shelf life within which the properties of materials should continue to meet or exceed stated performance criteria. Any component material that has exceeded its shelf life, deteriorated, or been contaminated should not be used. FRCM/SRG materials deemed unusable should be disposed of as specified by the manufacturer and in a manner acceptable to state and federal environmental control regulations.

6.3—Handling

6.3.1 Material Safety Data Sheets—For all fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM/SRG) constituent materials and components, an safety data sheets (SDSs) should be obtained from the manufacturer and be accessible at the job site.

6.3.2 Information sources—Detailed information on the handling and potential hazards of FRCM/SRG constituent materials can be found in information sources, such as ACI and International Concrete Repair Institute (ICRI) reports, manufacturer literature and guides, and OSHA guidelines.

6.3.3 Personnel safe handling and clothing—Gloves and safety glasses or goggles are suitable for handling FRCM/SRG materials.

6.3.4 Workplace safe handling—Each FRCM/SRG system constituent material may have handling and storage requirements to prevent damage. Consult with the material system
manufacturer for guidance. Consult the system manufacturer’s literature for proper mixing procedures and MSDSs SDSs for specific handling hazards.

6.3.5 Clean-up and disposal—All waste materials should be contained and disposed of as prescribed by the prevailing environmental authority.

CHAPTER 7—INSTALLATION

7.1—Contractor qualifications

The fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM/SRG) system installation contractor should demonstrate competency for surface preparation and application of the FRCM/SRG system to be installed. Contractor competency can be demonstrated by providing evidence of training and documentation of related work previously completed by the contractor; for example, surface preparation and installation of the FRCM/SRG system on portions or mockups of the structure. The FRCM/SRG system manufacturer or its authorized agent should train the contractor’s application personnel in the installation procedures of its system.

7.2—Environmental considerations

Temperature at the time of installation can affect performance of the FRCM/SRG systems: temperatures in the range of 95 to 120°F (35 to 50°C) may reduce the workability of the mortar, while temperatures in the range of 39 to 43°F (4 to 6°C) may slow down setting considerably. Conditions observed and documented before and during installation include surface temperature of the substrate, air temperature, relative humidity, and wind speed.

When the surface temperature of the substrate falls below a minimum level as specified by the FRCM/SRG system manufacturer, improper installation can occur, compromising the integrity of...
the FRCM/SRG system. Auxiliary heat sources can be used to raise the ambient and surface
temperature during installation. Heat sources should not contaminate the substrate surface or the
uncured FRCM/SRG system.

When the surface temperature of the substrate is higher than an ambient level, as specified by
the FRCM/SRG system manufacturer, improper installation can occur, compromising the integrity
of the FRCM/SRG system. At higher temperatures within the limits provided by the manufacturer,
it is important that the surface be maintained at a saturated surface-dry condition until immediately
prior to the FRCM/SRG Installation.

When FRCM/SRG is applied in a wet environment, it is important that the surface be dried to a
saturated surface-dry condition immediately prior to the FRCM/SRG installation.

FRCM/SRG systems can typically be applied to substrate surfaces subjected to moisture vapor
transmission. The transmission of moisture vapor from a substrate surface does not typically
compromise the bond between the FRCM/SRG system and substrate.

7.3—Equipment

As different fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM/SRG) systems
are used in the field, equipment requirements are specific to the selected system. In general, the
advantage of FRCM/SRG strengthening is associated with light weight, ease, and speed of
application; therefore, special equipment requirements are limited. Equipment may include
grinding and grooving tools, sandblasting equipment, and shotcrete installation equipment All
equipment should be maintained, clean, and in good operating condition.
The contractor should have personnel trained in equipment operation. Personal protective gear, such as gloves, eye guards, and coveralls, should be worn as required by manufacturer’s specifications.

Equipment and material supplies in sufficient quantities should be available to allow continuity in installation and quality control tasks. Safe and convenient access to those surfaces being strengthened will help ensure proper FRCM/SRG application.

7.4—Substrate repair and surface preparation

The behavior of members strengthened or retrofitted with fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM/SRG) systems is highly dependent on substrate and proper preparation and profiling of the substrate surface. An improperly prepared surface can result in debonding or delamination of the FRCM/SRG system before achieving the design load transfer. General guidelines presented herein should be applicable to all bonded FRCM/SRG systems. Specific guidelines for a particular FRCM/SRG system should be obtained from its manufacturer.

7.4.1 Substrate repair—Problems associated with the condition of the original member and its substrate that can compromise the integrity of the FRCM/SRG system should be addressed before surface preparation begins. The FRCM/SRG system manufacturer should be consulted to verify the compatibility of materials used for repairing the substrate with the composite system.

7.4.2 Surface preparation—Surface preparation requirements depend on the FRCM/SRG system used. Specific guidelines regarding procedures for surface preparation for each composite system should be obtained from the system manufacturer.

Surface preparation might involve:

a) Sandblasting, roughening, grinding, or hydrojetting to abrade the surface
b) Application of primers and putty or mortar fillers as per manufacturer’s recommendations

Particular care should be taken to ensure that the surface is clean from dust and laitance, and to avoid unintentional damage to the substrate by using excessive force.

7.5—Mixing of mortar matrix

Mixing of the mortar matrix should be done in accordance with the fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM/SRG) system manufacturer’s recommended procedure. The manufacturer should provide recommended batch sizes and mixture ratios, methods, and times.

Mixing equipment can include small mortar mixers, specialty units, or by hand stirring, if allowed by the manufacturer. Batching should be in sufficiently small quantities to ensure that the mortar can be used within its plastic state. Batches that exceed their plastic life should not be used because the increased viscosity will adversely affect the ability of the mortar to penetrate the reinforcement mesh.

7.6—Application of FRCM/SRG systems

7.6.1 Mortar matrix—If required, matrix material could also be used to smooth out surface discontinuities smaller than approximately 1/16 in. (2 mm) before the application of the layer necessary for embedding the fabric. The mortar matrix is considered an inorganic glue and not a repair material. Some mortar matrixes may also be considered a concrete repair material. Special putty fillers or mortars can be used to fill voids and repair the substrate, as per manufacturer’s recommendations, with typical thicknesses up to approximately 0.5 in. (12 mm).
7.6.2 **FRCM and SRG systems**—Fabric-reinforced cementitious matrix (FRCM) and steel-reinforced grout (SRG) systems are typically installed by hand or shotcrete application method per the manufacturer’s recommendations. The procedure consists of applying the matrix and the fabric directly to the member being strengthened. The matrix is first applied uniformly to all prepared surfaces where the system is placed. Fabric is gently pressed into the matrix in a manner recommended by the FRCM/SRG system manufacturer. Successive layers of matrix and fabric are placed before the complete cure of the previous layer of matrix.

7.6.3 **FRCM protective coatings**—Coatings should be compatible with the FRCM system and applied in accordance with the manufacturer’s recommendations. Coatings should be periodically inspected, and maintenance provided to ensure their effectiveness. Inspections should be performed periodically in conjunction with other regular inspections of the structure or at a frequency that is based on the exposure conditions and facility use.

7.7—**Alignment of FRCM/SRG reinforcement**

The fabric-reinforced cementitious matrix (FRCM) fabric orientation and stacking sequence should be specified by the licensed design professional (LDP). Fiber orientation for both the primary direction (PD) and secondary direction (SD) may vary depending on the purpose of strengthening, such as for flexure or shear, and is of critical importance when unbalanced (that is, PD different from SD) fabrics are used.

Small variations in angle as little as ±5 degrees from the intended direction of fiber alignment can cause a substantial reduction in strengthening performance. Deviations in mesh orientation should only be made if approved by the LDP.
Fabrics should be handled in a manner to maintain the fiber straightness and orientation. Kinks, folds, or other forms of severe waviness in the fabric layer should be reported to the LDP.

7.8—Multiple fabrics and lap splices

Multiple fabrics can be used, provided all of which are fully impregnated with the matrix system, the matrix shear strength is sufficient to transfer the shearing load between fabric layers, and the bond strength between substrate and fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM/SRG) system is sufficient to transfer design forces. Lap splices should be staggered and without overlap so that at any cross section through the FRCM, only one fabric is spliced. Lap splice details, including lap length, should be based on the results of tests performed in accordance with the latest version of AC434. Multiple fabrics and lap splices may not always be possible, depending on the characteristics of the specific FRCM/SRG system.

7.9—Curing of mortar matrix

The matrix should be cured according to the system manufacturer’s recommendation. Field modification of the matrix chemistry should not be permitted without consulting the system manufacturer.

When required as a result of hot and windy conditions, curing compounds may be applied on the fresh fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM/SRG) immediately following installation to prevent evaporation of water necessary for hydration of the mortar.
7.10—Temporary protection

Adverse temperatures and direct contact by rain, dust, dirt, or vandalism can damage a fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM/SRG) system during installation and cause improper curing of the matrix. Temporary protection such as tents and plastic screens could be required during installation and until the matrix has cured. If temporary shoring is required, the FRCM/SRG system should be fully cured before removing the shoring and allowing the structural member to carry the design loads. In the event of suspected damage to the FRCM/SRG system during installation, the licensed design professional (LDP) should be notified and the FRCM/SRG system manufacturer consulted.

CHAPTER 8—INSPECTION, EVALUATION, AND ACCEPTANCE

8.1—Inspection

Fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM/SRG) systems and all associated work should be inspected as required by the applicable local codes. In the absence of such requirements, inspection should be conducted by or under the supervision of a licensed design professional (LDP) or qualified inspector. Inspectors should be knowledgeable of and trained in the installation of FRCM/SRG systems. The qualified inspector should require compliance with design drawings and project specifications. During installation of the FRCM/SRG system, the scope of the inspection should include:

a) Date and time of installation
b) Ambient temperature, relative humidity, and general weather observations
c) Surface temperature of substrate
d) Surface preparation methods and resulting profile
e) Qualitative description of surface cleanliness
f) Type of auxiliary heat source, if applicable, the start/stop times for the heaters
g) Reinforcement batch number(s) and approximate location in structure
h) Batch numbers, mixture ratios, mixing times, and qualitative descriptions of the appearance of all mixed matrix and additional materials such as primers, putties, and coatings mixed for the day
i) Conformance with installation procedures
j) Compression test results of mortar cubes of the matrix material, if required
k) Pull-off test results according to ASTM C1583/C1583M completed or supervised by an LDP or owner’s independent testing agency, if required
l) FRCM/SRG properties from tests of field sample panels or witness panels, if required
m) Location and size of any defects
n) General progress of work

The inspector should provide the LDP or owner’s representative with inspection records and witness test panels when required. The installation contractor should retain sample mortar cubes or cylinders and maintain a record of the placement of each batch.

8.2—Evaluation and acceptance

Fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM/SRG) systems should be evaluated based on conformance with the design drawings and specifications and the manufacturer’s installation recommendations. Nonconformance of the FRCM/SRG system should be reported to the licensed design professional (LDP) for further evaluation. The FRCM/SRG system material properties, installation within specified placement tolerances, presence of defects,
cure of matrix, and adhesion to substrate should be evaluated. The evaluation should also consider
mesh orientation and lap splice lengths of the installed FRCM/SRG system.

Witness test panel and pull-off tests can be used to evaluate the installed FRCM/SRG system.
In-place load testing can also be used where applicable to confirm the installed behavior of the
FRCM/SRG-strengthened member.

8.2.1 Materials—Before starting the project, the FRCM/SRG system manufacturer should
submit certification of specified material properties and identification of all materials to be used.
Additional material testing can be conducted if deemed necessary based on the project’s
complexity. Evaluation of delivered FRCM/SRG materials can include tests for tensile and
compressive strength of constituents. These tests are usually performed on material samples sent
to a laboratory, according to the quality-control test plan. Materials that do not meet minimum
requirements as specified by the LDP should be rejected.

Witness panels can be used to evaluate the tensile strength and modulus, and lap splice strength
of the FRCM/SRG system installed and cured on-site using installation procedures similar to those
used to install and cure the FRCM/SRG system. During installation, flat panels of the specified
dimensions and thickness can be fabricated on-site according to a predetermined sampling plan.
After curing on-site, the panels can then be sent to a laboratory for testing. Witness panels can be
retained or submitted to an approved laboratory for testing of tensile strength. Strength and elastic
modulus of the FRCM/SRG system is determined in accordance with the requirements of AC434.
Properties to be evaluated by testing should be specified by the LDP, which may waive or alter the
testing frequency.

8.2.2 Fabric orientation—Fabric orientation should be evaluated by inspection using a level or
a straightedge. Mesh misalignment of more than ±5 degrees from that specified on the design
drawings (approximately 1 in./ft [80 mm/m]) should be reported to the LDP for evaluation, who
should calculate the capacity of the system considering this misalignment to determine if the
design criteria are still satisfied. If the design criteria cannot be satisfied, remedial actions such as
the use of a reduction factor to calculate effective strength may be warranted.

8.2.3 Defects—The cured FRCM/SRG system should be evaluated for defects between multiple
layers or between the FRCM/SRG system and substrate surface. In addition to coring,
nondestructive test methods such as acoustic sounding (for example, hammer sounding, impact-
echo, impulse response, ultrasonic, and infrared thermography) can be used to detect
delaminations. Delaminations should be evaluated and repaired in accordance with the LDP’s
direction. Upon completion of repairs, the FRCM/SRG should be reinspected to verify the repair
was properly installed.

8.2.4 Cure of matrix—The relative cure of FRCM/SRG systems can be evaluated by laboratory
testing of matrix samples. The FRCM/SRG system manufacturer should be consulted to determine
specific matrix-cure verification requirements.

8.2.5 Adhesion strength—Tension adhesion testing of cored samples should be conducted using
ASTM C1583/C1583M. Sampling frequency should be specified. The conditions of acceptance
are given in AC434.

8.2.6 Cured thickness—Small core samples may be taken to visually determine the cured
FRCM/SRG thickness or number of fabrics at locations approved by the LDP. Cored samples
required for adhesion testing also can be used to determine the FRCM/SRG thickness or number
of fabrics. The sampling frequency should be specified by the LDP. Taking samples from high-
stress or splice areas should be avoided. For aesthetic reasons, the cored hole can be filled and
smoothed with a repair mortar or the FRCM/SRG system matrix.
CHAPTER 9—MAINTENANCE AND REPAIR

9.1—General

As with any repair system (per ACI 562), the owner or owner’s representative should periodically inspect and assess the performance of the strengthening system. Inspections should be performed periodically in conjunction with other regular inspections of the structure or at a frequency that is determined based on the exposure conditions and facility use. The causes of any damage or deficiencies detected during routine inspections should be identified and addressed before performing any repairs or maintenance.

9.2—Inspection and assessment

9.2.1 General inspection—A visual inspection should be performed to observe any debonding, cracking, deflections, changes in color, and other anomalies. In addition, ultrasonic, acoustic sounding (hammer tap), or thermography tests may reveal signs of progressive debonding and delamination.

9.2.2 Assessment—Test data and observations are used to assess any damage and the structural integrity of the strengthening system. The assessment should include repair recommendations and suggestions for reducing the incidence of future damage.

9.3—Repair of strengthening system

The repair method for an fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM/SRG) strengthening system depends on causes of the damage, the type of material, the form of degradation, and the level and extent of damage. Before repairing the FRCM/SRG system,
causes of the damage should be identified. Consult the system manufacturer for repair methods and materials.

9.4—Repair of surface coating
If the surface protective coating requires replacement, the fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM/SRG) should be inspected for structural damage or deterioration. Consult the system manufacturer for surface coating repair.

CHAPTER 10—GENERAL DESIGN CONSIDERATIONS FOR REINFORCED CONCRETE STRENGTHENED WITH FRCM/SRG

10.1—Design philosophy
These design recommendations are based on limit-state design principles and are consistent with the provisions of AC434. When evaluating the serviceability of a member, linear elastic material properties may be assumed so that modular ratios and transformed sections can be used to calculate service stresses and deformations. In assessing the nominal strength of a member, the possible failure modes and subsequent strains and stresses in each material should be assessed.
Design procedures should be in accordance with ACI 318 and ACI 562, as applicable. Specific guidance on FRCM/SRG system design is presented in Chapter 11. Load and strength reduction factors for FRCM/SRG design should be obtained from ACI 318 and ACI 562, as appropriate.
10.2—Strengthening limits

Careful consideration should be given to determine reasonable strengthening limits. These limits are imposed to guard against collapse of the structure should bond or other failure of the fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM/SRG) system occur due to damage, vandalism, or other causes. The required strength of a structure without repair should be as specified in ACI 562.

For flexural strengthening applications, primary direction (PD) fiber strands should be oriented parallel to the major axes of the member and should be installed so that the strands are no more than ±5 degrees from the design orientation. Similarly, for shear strengthening applications, PD fiber strands are typically oriented perpendicular to the axis of the member and should not be misaligned more than ±5 degrees. For a combined contribution to shear strength of parallel and perpendicular fiber strands; however, it is allowable to orient PD fiber strands in a parallel direction to the member axis, provided that continuity of the fabric is maintained.

Appendix B provides a summary for relevant design limits for all types of strengthening methods.

10.3—Selection of FRCM/or-SRG system

Given the anticipated service conditions, the licensed design professional (LDP) should select a fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM-or/SRG) system based on the known behavior of that system as available in an ICC-ES Evaluation Report. Such reports can be obtained from the FRCM/SRG system manufacturer.
10.4—Design properties

Fabric-reinforced cementitious matrix and steel-reinforced grout (FRCM and SRG) properties to be used for design as described herein are obtained from tests performed in accordance to AC434 and recommended in Chapter 5. As per AC434, the values of strength and strain used in the design equations herein are defined as the average value minus one standard deviation, and the elastic modulus is the average value.

CHAPTER 12—FABRIC-REINFORCED CEMENTITIOUS MATRIX/STEEL-REINFORCED GROUT REINFORCEMENT DETAILS

This chapter offers guidance for detailing externally bonded fabric-reinforced cementitious matrix and steel-reinforced grout (FRCM and SRG) systems. Detailing typically depends on the geometry of the structure, the soundness and quality of the substrate, and the levels of load that are to be sustained by the FRCM/SRG system. Bond-related failures may be avoided by following these general guidelines for detailing:

a) Do not turn inside corners such as at the intersection of beams and joists with the underside of slabs. If this is unavoidable, proper anchorage is to be provided.

b) The cross section corners should be rounded to a radius \( r \) not less than 3/4 in. (20 mm), before placing FRCM material.

c) Provide adequate development length (minimum of 6 in. [152 mm]).

d) Provide sufficient overlap when splicing fabrics as determined according to test methods specified in AC434.
12.1—Bond and delamination

12.1.1 FRCM/SRG bond strength—The bond strength of a fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM/SRG) system is determined according to test methods specified in AC434. Mechanical anchorages can be effective in increasing stress transfer, although their efficacy results from their ability to resist the tensile normal stresses rather than in enhancing the interfacial shear capacity. The performance of any anchorage system should be substantiated through testing and approved by the licensed design professional (LDP).

12.1.2 Development length—The bond capacity of FRCM/SRG is developed over a critical length $\ell_{df}$. To develop the effective FRCM/SRG stress at a section, the available anchorage length of FRCM should exceed the minimum development length of 6 in. (152 mm) for any type of substrate material. Longer values of $\ell_{df}$ may be necessary for multi-layer FRCM/SRG application.

The LDP should also consider the concrete cover delamination that can also result from the normal stresses developed at the ends of externally bonded FRCM/SRG. With this type of delamination, the existing internal reinforcing steel essentially acts as a bond breaker in a horizontal plane, and the concrete cover pulls away from the rest of the element. The following general guidelines for the location of cutoff points for FRCM/SRG can be used to avoid concrete cover delamination failure mode:

a) For simply supported beams, FRCM/SRG reinforcement should be terminated at least a distance equal to $\ell_{df}$ past the point along the span corresponding to the cracking moment $M_{cr}$.

b) For continuous beams, FRCM/SRG reinforcement should be terminated at $d/2$ or $\ell_{df}$,
whichever is larger, beyond the inflection point (point of zero moment resulting from factored loads).

12.1.3 Detailing of laps and splices—Splices of FRCM/SRG reinforcement should be provided only as permitted on drawings, specifications, or as authorized by the LDP and as recommended by the system manufacturer.

The fabric should be continuous and oriented in the direction of the largest tensile forces. Fabric continuity can be maintained with a lap splice. For FRCM/SRG systems, a lap splice should be made by overlapping the two fabrics along their length. The required overlap, or lap-splice length, depends on the tensile strength and thickness of the FRCM/SRG material system and on the bond strength between adjacent layers of FRCM/SRG reinforcement. Sufficient overlap should be provided to promote the failure of the FRCM/SRG reinforcement before debonding of the overlapped FRCM/SRG reinforcement. The required overlap for an FRCM/SRG system should be provided by the material manufacturer and substantiated through testing that is independent of the manufacturer.

Jacket-type FRCM and SRG systems used for column members should provide appropriate development area at splices, joints, and termination points to ensure failure through the FRCM/SRG jacket thickness rather than failure of the spliced sections.

Unless otherwise specified, lap splices are not required in the transverse direction of the fabric. FRCM/SRG reinforcement consisting of multiple meshes oriented in more than one direction or multidirectional meshes require lap splices in more than one direction to maintain the continuity of the fabric and the overall strength of the FRCM/SRG reinforcement.

To determine the relative tensile strength at the mesh overlap area, lap tensile strength testing is required as per AC434. This test method is particularly useful if the joint configuration closely
simulates the actual joint in material field application. It is understood that in application of multilayer FRCM/SRG composite materials, the laps should be staggered from the laps in the nearby layer. Laps in one layer should start with a minimum distance equivalent to the development length of fiber strands in the matrix established by the manufacturer, or larger.

CHAPTER 13—STRENGTHENING OF REINFORCED CONCRETE MEMBERS WITH FABRIC-REINFORCED CEMENTITIOUS MATRIX AND STEEL-REINFORCED GROUT

13.1—FRCM/SRG flexural strengthening

The fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM/SRG) composite material bonded to surfaces of reinforced concrete (RC) members may be used to enhance the design flexural strength of sections by acting as external tension reinforcement. In such cases, section analysis is based on the following assumptions:

a) Plane sections remain plane after loading
b) The bond between the FRCM/SRG and substrate remains effective
c) The maximum usable compressive strain in concrete is 0.003
d) FRCM/SRG has a bilinear elastic behavior to failure

This section does not apply to FRCM/SRG systems used to enhance the flexural strength of members in the expected plastic hinge regions of ductile moment frames resisting seismic loads.

The flexural strength of an RC section depends on the controlling failure mode. Failure modes for an FRCM/SRG-strengthened section include:

a) Crushing of the concrete in compression before yielding of the reinforcing steel
b) Yielding of the steel in tension followed by concrete crushing
c) Shear/tension delamination of the concrete cover or cover delamination
d) Debonding of the FRCM/SRG from the concrete substrate (FRCM/SRG debonding)
e) Debonding of fabric from the cementitious matrix (mesh debonding)
f) Tensile rupture of FRCM/SRG material

Effective tensile strain level in the FRCM/SRG reinforcement attained at failure, $\varepsilon_{fe}$, should be limited to the design tensile strain of the FRCM/SRG composite material, $\varepsilon_{fd}$, defined in Eq. (13.1a)

$$\varepsilon_{fe} = \varepsilon_{fd} = \varepsilon_{fu} \leq 0.012 \quad (13.1a)$$

The effective tensile stress level in the FRCM/SRG reinforcement attained at failure, $f_{fe}$, in the FRCM/SRG reinforcement is calculated in accordance with Eq. (13.1b)

$$f_{fe} = E_f \varepsilon_{fe} \text{ where } \varepsilon_{fe} \leq \varepsilon_{fd} \quad (113.1b)$$

The design flexural strength is calculated in accordance with Eq. (13.1c)

$$\phi_m M_n = \phi_m(M_s + M_f) \quad (13.1c)$$

where $M_n$ is the nominal flexural strength, and $M_s$ and $M_f$ are the contribution of steel reinforcement and FRCM/SRG composite material to the nominal flexural strength, respectively. The strength reduction factor $\phi_m$ is given by Eq. (13.1d), as defined in ACI 318 and ACI 562

$$\phi_m = \begin{cases} 0.90 \text{ for } \varepsilon_t \geq 0.005 \\ 0.65 + \frac{0.25(\varepsilon_t - \varepsilon_{sy})}{0.005 - \varepsilon_{sy}} \text{ for } \varepsilon_{sy} < \varepsilon_t < 0.005 \\ 0.65 \text{ for } \varepsilon_t < \varepsilon_{sy} \end{cases} \quad (13.1d)$$

where $\varepsilon_t$ is the net tensile strain in extreme tension steel reinforcement at nominal strength, and $\varepsilon_{sy}$ is the steel tensile yield strain.

### 13.1.1 Design limitations

For strengthening and rehabilitation achieved with unprotected external reinforcing systems that are susceptible to damage by fire, vandalism, or collision, the required strength of the structure without rehabilitation should equal or exceed the effects of the load combinations specified by ACI 562 under.

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13.1.2 Serviceability—The tensile stress in the steel reinforcement under service load, $f_{ss}$, should be limited to 80 percent of the steel yield strength, $f_y$, as indicated in Eq. (13.1.2a).

$$f_{ss} \leq 0.80f_y \quad (13.1.2a)$$

The tensile stress in the steel reinforcement under cyclic fatigue load, $f_{sf}$, should be limited to 65 percent of the steel yield strength, $f_y$, as indicated in Eq. (13.1.2b).

$$f_{sf} \leq 0.65f_y \quad (13.1.2b)$$

13.1.3 Creep-rupture and fatigue stress limits—The tensile stress levels in the FRCM/SRG reinforcement under service load, $f_\sigma$, should be limited to the values shown in Table 13.1.3.

**Table 13.1.3—Creep rupture and fatigue stress limits for reinforcement based on fiber type**

<table>
<thead>
<tr>
<th>Fiber type</th>
<th>AR glass</th>
<th>Aramid</th>
<th>Basalt</th>
<th>Carbon</th>
<th>PBO</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Creep Rupture and Fatigue</td>
<td>$0.30f_u$</td>
<td>$0.40f_u$</td>
<td>$0.30f_u$</td>
<td>$0.55f_u$</td>
<td>$0.40f_u$</td>
<td>$0.55f_u$</td>
</tr>
</tbody>
</table>

13.2—Shear strengthening

This section presents guidance on the calculation of added shear strength resulting from the addition of fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM/SRG) shear reinforcement to reinforced concrete (RC) beams or columns. The additional shear strength that can be provided by the FRCM/SRG system is based on many factors, including geometry of the beam or column, wrapping scheme, and existing concrete strength.

13.2.1 FRCM/SRG contribution to shear strength—The FRCM/SRG composite material bonded to surfaces of an RC member can be used to enhance the design shear strength by acting as external shear reinforcement. Shear strengthening using external FRCM/SRG can be provided at locations of expected plastic hinges or stress reversal and for enhancing post-yield flexural behavior of
members in moment frames resisting seismic loads only by completely wrapping the section. Only continuous FRCM/SRG U-wraps (beams) or continuous complete wraps (beams and columns) should be considered.

The design tensile strain in the FRCM and SRG shear reinforcement, $\varepsilon_{fv}$, is calculated by Eq. (13.2.1a)

$$\varepsilon_{fv} = \varepsilon_{fu} \leq 0.004 \quad (13.2.1a)$$

The design tensile strength of the FRCM and SRG shear reinforcement, $f_{fv}$, is calculated in accordance with Eq. (13.2.1b)

$$f_{fv} = E_f \varepsilon_{fv} \quad (13.2.1b)$$

where $E_f$ is the tensile modulus of elasticity of the cracked FRCM/SRG composite material.

The design shear strength is calculated in accordance with Eq. (13.2.1c).

$$\phi V_n = \phi (V_c + V_s + V_f) \quad (13.2.1c)$$

where $V_n$ is the nominal shear strength, and $V_c$, $V_s$, and $V_f$ are the contribution of concrete, existing steel reinforcement, and the composite material to the nominal shear strength, respectively. The strength reduction factor $\phi$ should be equal to 0.75 as per ACI 318 and ACI 562. $V_c$ and $V_s$ are calculated according to ACI 318. The shear contribution of FRCM/SRG shear reinforcement, $V_f$, is given by Eq. (13.2.1d)

$$V_f = nA_{ff}d_f \quad (13.2.1d)$$

where $n$ is the number of fabric layers; $A_{ff}$ is the area of fabric by unit width effective in shear; and $d_f$ is the effective depth of the FRCM/SRG shear reinforcement (Fig. 13.2.1). Where PD and SD fiber strands are used to reinforce the same portion of a member, $V_f$ is computed as the sum of the values computed for the two shear reinforcement directions. At least 50 percent of the
reinforcement shall be provided by the fiber strands perpendicular to the member axis. The total shear strength provided by FRCM/SRG and steel reinforcement should be limited to the following

\[ V_s + V_f \leq 8 \sqrt{f_c} \cdot b_w d \]  \hspace{1cm} (13.2.1e)

\[ V_s + V_f \leq 0.66 \sqrt{f_c} \cdot b_w d \] \hspace{1cm} (SI units) \hspace{1cm} (13.2.1f)

where \( b_w \) is the web width. For rectangular sections with shear enhancement provided by transverse FRCM/SRG composite material, section corners should be rounded to a radius not less than 3/4 in. (20 mm) before placement of the FRCM/SRG material.

**Fig. 13.2.1—df values for rectangular and T-sections.**

**13.2.1.1 Design limitations**—For strengthening and rehabilitation achieved with unprotected external reinforcing systems that are susceptible to damage by fire, vandalism, or collision, the required strength of the structure without rehabilitation should equal or exceed the effects of the load combinations specified by ACI 562.

**13.3—Strengthening for axial force**

Confinement of RC columns by means of fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM/SRG) jackets can be used to enhance existing column strength and ductility. The
increase in capacity is an immediate outcome typically expressed in terms of improved peak load resistance. Overall ductility enhancement requires more complex calculations to determine the ability of a member to sustain rotation and drift without a substantial loss in strength. Therefore, this section applies only to flexural ductility enhancement resulting from increasing the effective ultimate compression strain.

13.3.1 Axial load capacity enhancement—The FRCM/SRG composite material may be applied to external surfaces of circular and rectangular RC compression members to enhance the axial load capacity (Bournas et al. 2007; Abegaz et al. 2012; De Caso y Basalo et al. 2012).

The stress-strain for FRCM/SRG-confined concrete is illustrated in Fig. 13.3.1 and is determined using the following expressions

\[
 f_c = \begin{cases} 
 E_c \varepsilon_c - \frac{(E_c - E_2)^2}{4f_c'} (\varepsilon_c')^2 & 0 \leq \varepsilon_c \leq \varepsilon_c' \quad (13.3.1a) \\
 f_c' + E_2 \varepsilon_c & \varepsilon_c' > \varepsilon_c 
\end{cases} 
\]

\[
 \varepsilon_c' = \frac{2f_c'}{E_c - E_2} \quad \varepsilon_c' \leq \varepsilon_c \leq \varepsilon_{ccu} \quad (13.3.1b) 
\]

\[
 E_2 = \frac{f_c' - f_c'}{\varepsilon_{ccu}} \quad (13.3.1c) 
\]

where \( E_c \) is the modulus of elasticity of concrete; \( E_2 \) is the slope of linear portion of stress-strain model for FRCM/SRG-confined concrete; \( f_c \) is the compressive stress in concrete; \( f_c' \) is the specified compressive strength of concrete; \( f_{cc}' \) is the maximum compressive strength of confined concrete; \( \varepsilon_c \) is the compressive strain level in the concrete; \( \varepsilon_{ccu} \) is the ultimate axial compressive strain of confined concrete that corresponds to \( f_{cc}' \); and \( \varepsilon_c' \) is the transition strain in the stress-strain curve of FRCM/SRG-confined concrete.

The maximum confined concrete compressive strength, \( f_{cc}' \), and the maximum confinement pressure, \( f_t \), is calculated using Eq. (13.3.1d), (13.3.1e), and (13.3.1f).
\[ f_{cc'} = f_{c'} + 3.1 \kappa_a f_i \]  
(13.3.1d)

\[ f_i = \left(2n A_f E_f \varepsilon_{fe}\right)/D \] for circular cross section  
(13.3.1e)

\[ f_i = \left(2n A_f E_f \varepsilon_{fe}\right)/(b^2 + h^2)^{1/2} \] for rectangular cross section  
(13.3.1f)

where \( A_f \) is the fabric area by unit width; \( n \) is the number of fabric layers; \( D \) is the diameter of the compression member with circular cross section; and \( b \) and \( h \) are the short and the long side dimensions of the compression member with rectangular cross section, respectively. The efficiency factor \( \kappa_a \) is a function of the cross section shape and is calculated as given in 13.3.1.1 and 13.3.1.2 of this guide, respectively. The effective tensile strain level in the FRCM/SRG, \( \varepsilon_{fe} \), is given by

\[ \varepsilon_{fe} = \varepsilon_{fd} = \varepsilon_{fu} \leq 0.012 \]  
(13.3.1g)

The contribution of mortar matrix to compressive strength of the FRCM/SRG-confined compression member should be neglected.

The ultimate axial compressive strain of confined concrete, \( \varepsilon_{ccu} \), should not exceed 0.01 to prevent excessive cracking and the resulting loss of concrete integrity. \( \varepsilon_{ccu} \) is calculated using the following stress-strain relationship

\[ \varepsilon_{ccu} = \varepsilon_{c'} \left( 1.5 + 12 \kappa_b \frac{f_i}{f_{c'} E_{c'}} \left( \frac{\varepsilon_{fe}}{\varepsilon_{c'}} \right)^{0.45} \right) \leq 0.01 \]  
(13.3.1h)

where \( \varepsilon_{c'} \) is the compressive strain of unconfined concrete corresponding to \( f_{c'} \). The efficiency factor \( \kappa_b \) is calculated as given in 13.3.1.1 and 13.3.1.2, respectively.

Based on the limitation set by Eq. (13.3.1h), \( f_{cc'} \) should not exceed the value of the stress corresponding to \( \varepsilon_{ccu} \) equal to 0.01.
Fig. 13.3.1—Idealized stress-strain diagram for FRCM-confined concrete.

13.3.1.1 Circular sections—For circular cross sections, the shape factors $\kappa_a$ and $\kappa_b$ in Eq. (13.3.1d) and (13.3.1h), respectively, should be taken as 1.0.

13.3.1.2 Rectangular sections—Rectangular sections where the ratio of longer to shorter section side dimension is not greater than 2.0 may have axial compression capacity enhanced by the confining effect of FRCM/SRG material placed with fiber strands running essentially perpendicular to the member axis. For rectangular cross sections, the shape factors $\kappa_a$ in Eq. (13.3.1d) and $\kappa_b$ in Eq. (13.3.1h) is calculated using Eq. (13.3.1.2a) and (13.3.1.2b), respectively (Fig. 13.3.1.2).
\[ \kappa_a = \frac{A_c}{A_e} \left( \frac{b}{h} \right)^2 \]  
\[ \kappa_b = \frac{A_e}{A_c} \left( \frac{h}{b} \right)^2 \]

where

\[ \frac{A_c}{A_e} = 1 - \frac{3A_g}{1 - \rho_g} \left[ 1 - \left( \frac{b}{h} \right)^2 + \left( \frac{h}{b} \right)^2 \left( \frac{b-2r}{b} \right)^2 \right] \]

In Eq. (13.3.1.2c), \( A_c \) is the net cross-sectional area of the compression member; \( A_e \) is the area of the effectively confined concrete; \( A_g \) is the gross cross-sectional area of the compression member; and \( \rho_g \) is the ratio of the area of longitudinal steel reinforcement, \( A_s \), to the gross cross-sectional area of the compression member.

For rectangular sections with aspect ratio \( h/b > 2.0 \), the effectiveness of the confinement should be subject to special analysis confirmed by test results.

**Fig. 13.3.1.2—Equivalent circular cross section.**
13.3.1.3 Design limitations—The increase in axial strength provided by the FRCM/SRG reinforcement should not exceed 20 percent of the existing capacity of the column without strengthening. This increase cannot exceed the limit for strengthening established in ACI 562 as provided in Appendix B of this document.

When the intent of the design is to restore the existing compressive strength (for example, lightly confined member), $\varepsilon_{cuc}$ should be limited to the value corresponding to $0.85f_{cc}'$.

Unless confirmed by experimental evidence, the strengthening of existing columns should be limited to elements having a cross section with a maximum dimension of 36 in. (900 mm) for the long side (rectangular) or diameter (circular). This limit is based on half-scale tests (Bournas et al. 2007).

13.3.1.4 Flexural ductility enhancement—The FRCM/SRG composite material with PD strands oriented essentially perpendicular to the member axis may be used to enhance flexural ductility capacity of circular and rectangular sections where the ratio of longer to shorter section dimension does not exceed 2.0. The enhancement is provided by increasing the effective ultimate compression strain of the section as computed in Eq. (11.3.1h).

13.4—Design axial strength

The design axial strength $\phi_m P_n$ of a compression member should be computed according to the provisions of ACI 318 and ACI 562. For the calculation of $\phi_m P_n$, consideration should be given to the presence of steel tie or spiral reinforcement in the existing reinforced concrete (RC) member and the limit based on the axial strength at zero eccentricity. The expression for $\phi_m$ given in Eq. (13.1d) is for members without spiral reinforcement. For members with spiral reinforcement, $\phi_m$ becomes 0.75 when the tensile strain at failure is less or equal to $\varepsilon_y$. 
Members subject to compressive axial load should be designed for the maximum moment that can accompany the axial load.

13.5—Engineering requirements

Although federal, state, and local codes for the design of externally bonded fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM/SRG) systems do not exist, other applicable code requirements may influence the selection, design, and installation of the FRCM/SRG system. All design work should be performed under the guidance of a licensed design professional (LDP) familiar with the properties and applications of composite strengthening systems.

13.6—Drawings and specifications

The licensed design professional (LDP) should document calculations summarizing the assumptions and parameters used to design the fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM/SRG) strengthening system and should prepare design drawings and project specifications. The drawings and specifications should show, at a minimum, the following information specific to externally applied FRCM systems:

a) FRCM/SRG system to be used

b) Location of the FRCM/SRG system relative to the existing structure

c) Dimensions and orientation of each fabric

d) Number of fabric and the sequence of installation

e) Location of splices and lap length

f) General notes listing design loads and allowable strains in the FRCM/SRG reinforcement

g) Design properties of the FRCM/SRG and concrete substrate
h) Concrete surface preparation requirements, including corner preparation and maximum irregularity limitations

i) Installation procedures, including surface temperature and application time limits between successive layers

j) Curing procedures for FRCM/SRG system

k) Protective coatings and sealants, if required

l) Shipping, storage, handling, and shelf-life guidelines

m) Quality control and inspection procedures, including acceptance criteria

n) In-place load testing of strengthened structure, if necessary

13.7—Submittals

Specifications should require the FRCM/SRG system manufacturer, installation contractor, inspection agency (if required), and all those involved with the project to submit product information and evidence of their qualifications and experience to the LDP for review.

13.7.1 FRCM/SRG system manufacturer—Submittals required of the FRCM/SRG system manufacturer should include:

a) Product data sheets indicating the physical, mechanical, and chemical characteristics of all constituent materials

b) Mechanical properties of the FRCM/SRG system, including the method of reporting properties, test methods used, and the statistical basis used for determining the properties as per AC434

c) Installation instructions, maintenance instructions, and general recommendations regarding each material to be used. Installation procedures should include surface
preparation requirements

d) Manufacturer’s material safety data sheets (MSDSs) for all materials to be used
e) Quality control procedure for tracking FRCM/SRG materials and material certifications
f) Durability test data for the FRCM/SRG system as per AC434 and for the types of
environments expected, if necessary
g) Structural test reports pertinent to the proposed application
h) Reference projects

13.7.2 FRCM/SRG system installation contractor—Submittals required of the FRCM/SRG
system installation contractor should include:

a) Documentation from the FRCM/SRG system manufacturer of having been trained to
install the proposed strengthening system
b) Project references, including installations similar to the proposed installation
c) Evidence of competency in surface preparation techniques
d) Quality-control testing procedures including voids and delamination, FRCM/SRG bond
to concrete, and FRCM/SRG tensile properties
e) Daily log or inspection forms used by the contractor

13.7.3 FRCM/SRG system inspection agency—If an independent inspection agency is used,
submittals required of that agency should include:

a) The inspector should meet minimum qualifications required by local codes
b) A list of inspectors to be used on the project and their qualifications
c) Sample inspection forms
d) A list of previous projects inspected by the inspector
CHAPTER 14—REFERENCES

Committee documents are listed first by document number and year of publication followed by authored documents listed alphabetically.

American Concrete Institute

ACI 318-19 Building Code Requirements for Structural Concrete and Commentary
ACI 440R-07 Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures
ACI 440.2R-17 Guide for the Design and Construction ofExternally Bonded FRP Systems for Strengthening Concrete Structures
ACI 544.1R-96(2009) Report on Fiber Reinforced Concrete
ACI 544.5R-10 Report on the Physical Properties and Durability of Fiber-Reinforced Concrete
ACI 562-19 Code Requirements for Evaluation, Repair, and Rehabilitation of Concrete Buildings and Commentary

ASTM International

ASTM C141/C141M-14 Standard Specification for Hydrated Hydraulic Lime for Structural Purposes
ASTM C173/C173M-16 Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method
ASTM C387/C387M-17 Standard Specification for Packaged, Dry, Combined Materials for Concrete and High Strength Mortar

ASTM C1583/C1583M-13 Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method)


ASTM D2344/D2344M-16 Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates

ASTM G85-11 Standard Practice for Modified Salt Spray (Fog) Testing

ICC Evaluation Service, Inc.

AC434-2018 Acceptance Criteria for Masonry and Concrete Strengthening Using Fiber-reinforced Cementitious Matrix (FRCM) and Steel Reinforced Grout (SRG) Composite Systems

International Code Council

IBC 2018 International Building Code

Prestressed/Precast Concrete Institute

PCI MNL128-01 Recommended Practice for Glass Fiber-Reinforced Concrete Panels

Authored documents

International Symposium on Ferrocement and Thin Reinforced Cement Composites (FERRO 10), Havana, Cuba.


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12 Method to Calibrate the Interfacial Cohesive Material Law for FRCM-Concrete Joints,” Materials
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APPENDIX A—CONSTITUENT MATERIALS PROPERTIES OF COMMERCIALLY AVAILABLE FRCM SYSTEMS

<table>
<thead>
<tr>
<th>Textile material</th>
<th>System</th>
<th>γ [g/m²]</th>
<th>t [mm]</th>
<th>i [mm]</th>
<th>Notes</th>
<th>fₜ [N/mm²]</th>
<th>Eₜ [kN/mm²]</th>
<th>Type</th>
<th>fₘₜ [N/mm²]</th>
<th>Eₘₜ [kN/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aramid</td>
<td>A1</td>
<td>51</td>
<td>0.033</td>
<td>-</td>
<td>Dry, Uniaxial</td>
<td>3151</td>
<td>101</td>
<td>Lime</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>197</td>
<td>0.033</td>
<td>-</td>
<td>Dry, Quadraxial</td>
<td>3151</td>
<td>101</td>
<td>Lime</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>Basalt</td>
<td>B1</td>
<td>220</td>
<td>0.033</td>
<td>25×25</td>
<td>Coated</td>
<td>-</td>
<td>-</td>
<td>Cement</td>
<td>35</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>B2</td>
<td>220</td>
<td>0.033</td>
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<td>Coated</td>
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<td>-</td>
<td>Pozzolanic lime</td>
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<td>10</td>
</tr>
<tr>
<td></td>
<td>B3</td>
<td>350</td>
<td>0.058</td>
<td>25×25</td>
<td>Coated</td>
<td>3200(*)</td>
<td>90(*)</td>
<td>Pozzolanic lime</td>
<td>15</td>
<td>-</td>
</tr>
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<td></td>
<td>B4</td>
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<td>0.039</td>
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<td>Coated</td>
<td>1538</td>
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<td>Carbon</td>
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(*) Data referred to individual fiber