

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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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 is 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: cyclic loading; deflection; earthquake-resistant; fabric-reinforced cementitious matrix fatigue systems; fiber-reinforced polymer systems; lap splices; meshes; substrate repair; rehabilitation; surface preparation.

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APPENDIX A—CONSTITUENT MATERIALS PROPERTIES OF COMMERCIALY AVAILABLE FRCM SYSTEMS, p. 34**APPENDIX B—DESIGN LIMITATIONS, p. 36****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 system are 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**

A_c = net cross-sectional area of compression member, in.² (mm²)

A_e = area of effectively confined concrete, in.² (mm²)

A_f	= area of mesh reinforcement by unit width, in. ² /in. (mm ² /mm)	V_n	= nominal shear strength, lb (N)
A_g	= gross cross-sectional area of compression member, in. ² (mm ²)	V_s	= contribution of steel reinforcement to nominal shear strength, lb (N)
A_s	= area of longitudinal steel reinforcement, in. ² (mm ²)	t	= equivalent thickness of fabric, in. (mm)
b	= short side dimension of compression member with rectangular cross section, in. (mm)	ϵ_c	= compressive strain level in concrete, in./in. (mm/mm)
b_w	= web width, in. (mm)	ϵ_c'	= compressive strain of unconfined concrete corresponding to f_c' , in./in. (mm/mm); may be taken as 0.002
D	= diameter of compression member, in. (mm)	ϵ_{ccu}	= ultimate compressive strain of confined concrete corresponding to $0.85f_{cc}'$ 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
d	= distance from extreme compression fiber to centroid of tension reinforcement, in. (mm)	ϵ_{fd}	= design tensile strain of FRCM/SRG, in./in. (mm/mm)
d_f	= effective depth of the FRCM/SRG shear reinforcement, in. (mm)	ϵ_{fe}	= effective tensile strain level in FRCM/SRG composite material attained at failure, in./in. (mm/mm)
E_2	= slope of linear portion of stress-strain model for FRCM/SRG-confined concrete, psi (MPa)	ϵ_{ft}	= transition strain corresponding to the transition point, in./in. (mm/mm)
E_c	= modulus of elasticity of concrete, psi (MPa)	ϵ_{fu}	= ultimate tensile strain of FRCM/SRG, in./in. (mm/mm)
E_f	= tensile modulus of cracked FRCM/SRG specimen, psi (MPa)	ϵ_{fv}	= design tensile strain of FRCM/SRG shear reinforcement, in./in. (mm/mm)
E_f^*	= tensile modulus of elasticity of uncracked FRCM/SRG specimen, psi (MPa)	ϵ_{sy}	= steel tensile yield strain, in./in. (mm/mm)
f_c	= compressive stress in concrete, psi (MPa)	ϵ_t	= net tensile strain in extreme tension steel reinforcement at nominal strength, in./in. (mm/mm)
f_c'	= specified compressive strength of concrete, psi (MPa)	ϵ_t'	= transition strain in the stress-strain curve of FRCM/SRG-confined concrete, in./in. (mm/mm)
f_{cc}'	= maximum compressive strength of confined concrete, psi (MPa)	ϕ_m	= strength reduction factor for flexure
f_{fe}	= effective tensile stress level in FRCM/SRG attained at failure, psi (MPa)	ϕ_v	= strength reduction factor for shear
f_{fs}	= tensile stress in FRCM/SRG reinforcement under service load, psi (MPa)	κ_a	= efficiency factor for FRCM/SRG reinforcement in the determination of f_{cc}' (based on the geometry of cross section)
f_{ft}	= transition stress corresponding to transition point, psi (MPa)	κ_b	= efficiency factor for FRCM/SRG reinforcement in the determination of ϵ_{ccu} (based on the geometry of cross section)
f_{fu}	= ultimate tensile strength of FRCM/SRG, psi (MPa)	ρ_g	= ratio of the area of longitudinal steel reinforcement to the cross-sectional area of a compression member (A_s/bh)
f_{fv}	= design tensile strength of FRCM/SRG shear reinforcement, 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. (mm)		
ℓ_{df}	= critical length to develop bond capacity of FRCM/SRG, in. (mm)		
M_{cr}	= cracking moment of unstrengthened member, in.-lb (N-mm)		
M_f	= contribution of FRCM/SRG to nominal flexural strength, in.-lb (N-mm)		
M_n	= nominal flexural strength, in.-lb (N-mm)		
M_s	= contribution of steel reinforcement to nominal flexural strength, in.-lb (N-mm)		
n	= number of layers of mesh reinforcement		
P_n	= nominal axial strength, lb (N)		
r	= radius of edges of a rectangular cross section confined with FRCM/SRG, in. (mm)		
V_c	= contribution of concrete to nominal shear strength, lb (N)		
V_f	= contribution of FRCM/SRG to nominal shear strength, lb (N)		

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.

cure—providing adequate moisture, temperature, and time to allow the concrete/mortar to achieve the desired properties for its intended use.

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—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 an FRCM 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.

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

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.

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.

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—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.

structural reinforcement mesh—open mesh of strands made of or steel wires or dry fibers, such as alkali-resistant glass, aramid, basalt, carbon, and polyparaphenylene 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).

(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 high-strength, galvanized steel wires that are twisted together to form the cords.

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 201 2006](#); [Peled 2007c](#); [Fallis 2009](#); [Nanni 2012](#)):

- Compatibility with chemical, physical, and mechanical properties of the concrete substrate
- Ease of installation as traditional plastering or trowel trades can be used
- Porous matrix structure that allows air and moisture transport both into and out of the substrate
- Good performance at elevated temperatures in addition to partial fire resistance
- 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 high-strength metal strands in the 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.](#)

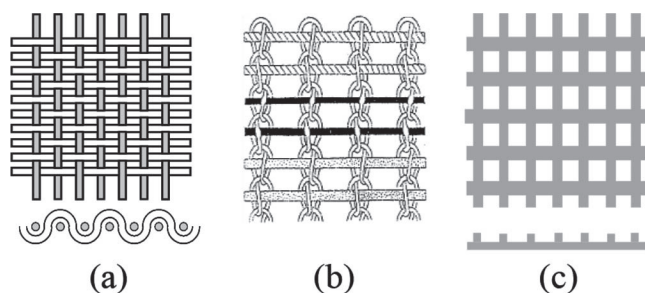


Fig. 3.2a—Different fabric assembly: (a) woven, (b) knitted, and (c) bonded.

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

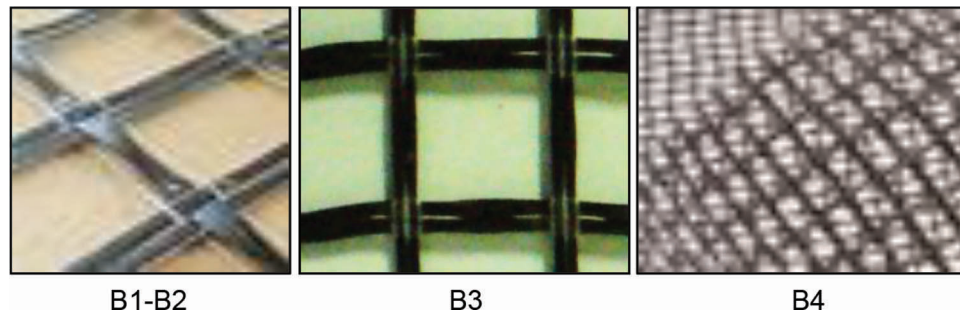


Fig. 3.2b—Commercially available basalt fabrics.

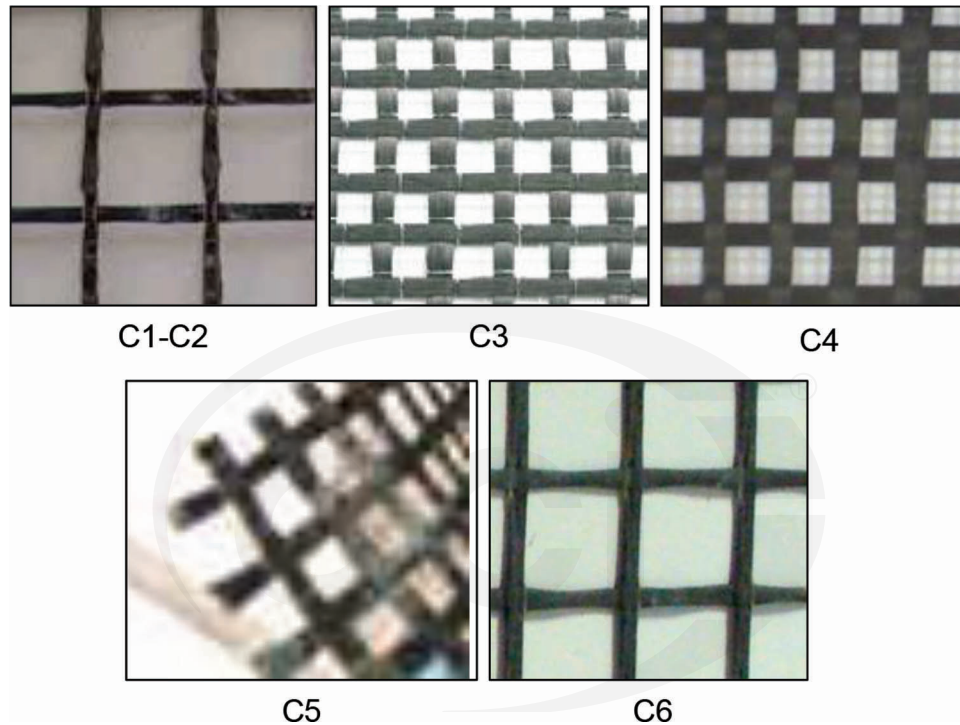


Fig. 3.2c—Commercially available carbon fabrics.

2018), or hybrid systems using a variety of configurations. Figures 3.2b to 3.2f present fabrics with open constructions or meshes.

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 et al. 2007; Aldea 2008; Dubey 2008). In particular, the emphasis on textile has been to signify continuous fibers 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 (Donnini 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 2007), 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.

3.2.1 FRCM mechanical properties—The mechanical properties of FRCM materials has 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 microscopy, including thin sectioning microscopy, microcrack freezing by means

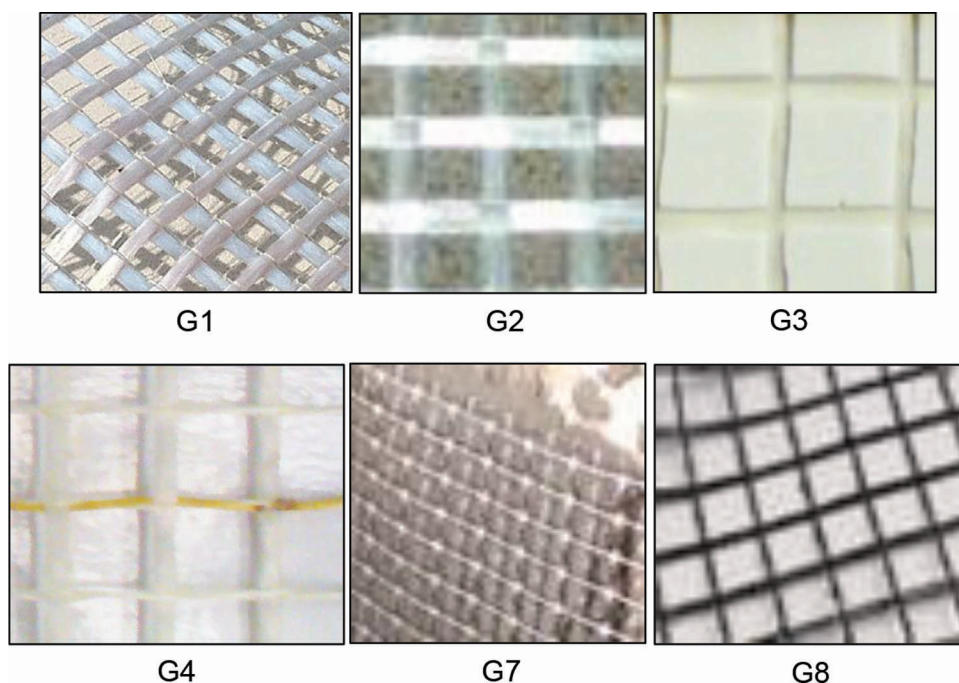


Fig. 3.2d—Commercially available glass fabrics.

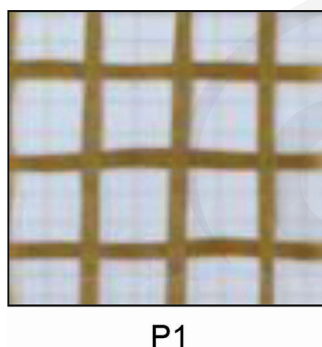


Fig. 3.2e—Commercially available PBO fabric.

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. 2007b).

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), test

performance prior to the onset of the first through-crack is not representative of the material's behavior. However, the cracked stress-strain behavior is 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 polyparaphenylene benzobisoxazole (PBO) fibers were used. They determined the values of the tensile modulus 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. 2010, 2011a,b; Haim and Peled 2011; Butnariu et al. 2006; Peled 2007b; Gencoglu and Mobasher 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

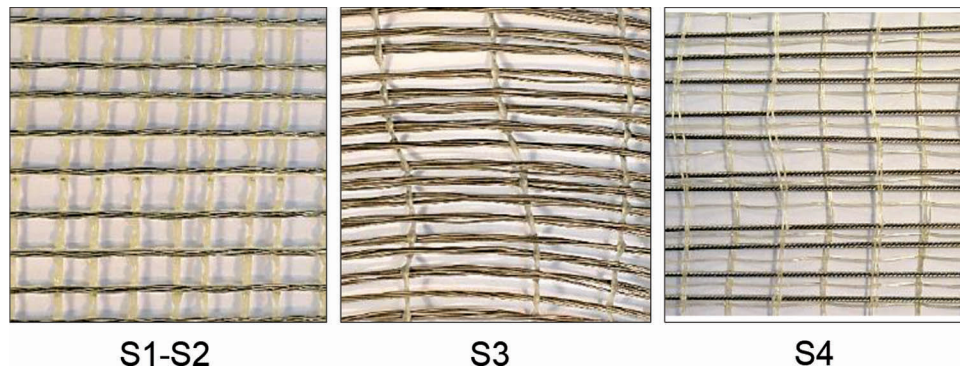


Fig. 3.2f—Commercially available steel fabrics.

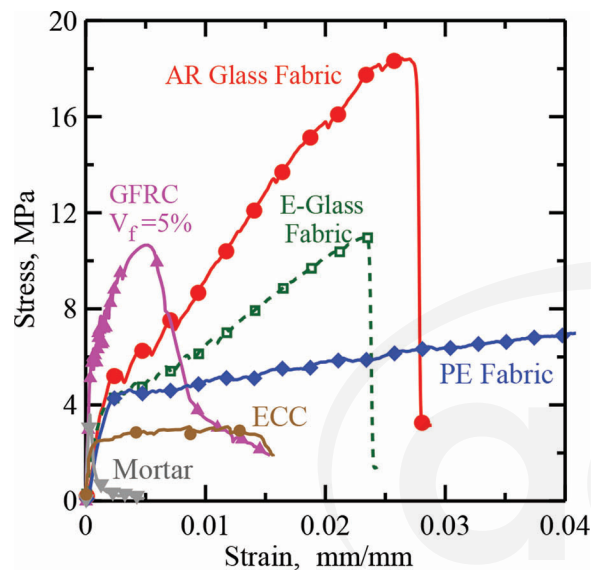


Fig. 3.2.1a—Tensile stress-strain behavior of FRCM with AR-glass, E-glass, and polyethylene meshes compared with GFRC and ECC.



Fig. 3.2.1b—Distributed cracking in AR-glass-FRCM (width = 1 in. [25 mm]).

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 and to a higher ultimate strain from the clevis-grip tests in comparison to the clamping-grip tests.

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,

Table 3.2.1—PBO- and carbon-FRCM tensile coupons tested according to AC434

FRCM property	Symbol	PBO-FRCM		Carbon-FRCM	
		Mean	STD	Mean	STD
Modulus of elasticity of the uncracked specimen, ksi (GPa)	E_f^*	261 (1805)	65 (452)	74 (512)	19 (130)
Modulus of elasticity of the cracked specimen, ksi (GPa)	E_f	18 (128)	2 (15)	12 (80)	3 (18)
Tensile stress corresponding to the transition point, ksi (MPa)	f_{ft}	54 (375)	12 (82)	66 (458)	7 (48)
Tensile strain corresponding to the transition point, %	ϵ_{ft}	0.0172	0.0044	0.1020	0.0449
Ultimate tensile strength, ksi (MPa)	f_{fu}	241 (1664)	11 (77)	150 (1031)	8 (54)
Ultimate tensile strain, %	ϵ_{fu}	1.7565	0.1338	1.0000	0.1405

Note: Coupon tested with 6 in. (150 mm) long tabs.

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 fibers with of smaller diameter and higher aspect ratio are effective in reducing the width of plastic shrinkage cracks (Qi et al. 2003; Banthia and Gupta 2006). The effectiveness of fabrics in improving the shrinkage resistance of concrete materials has also been studied (Pourasee 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. 2010).

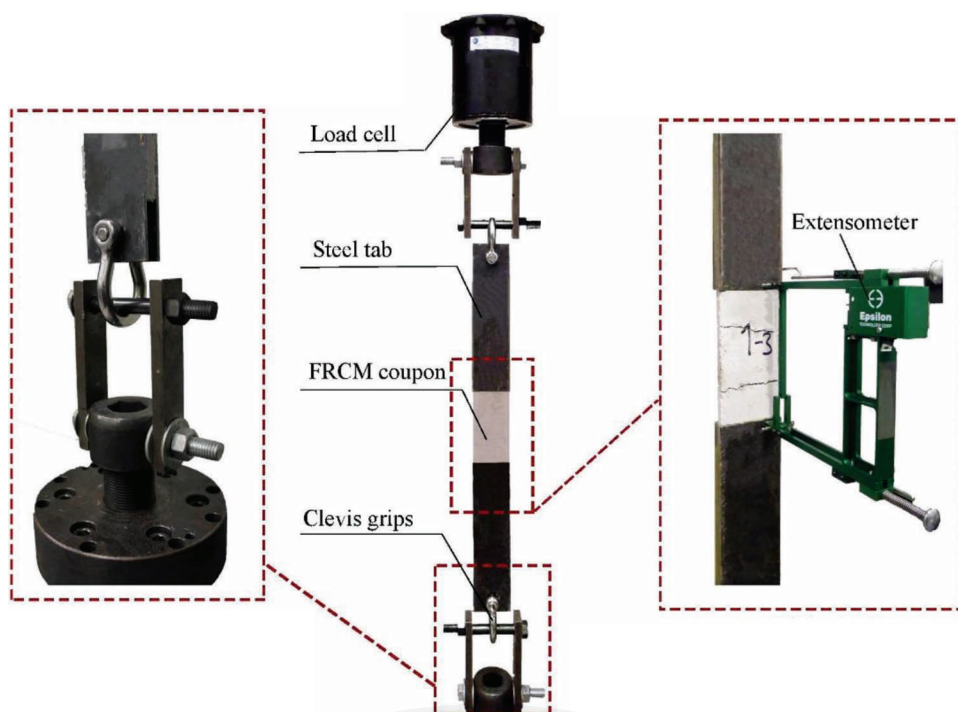


Fig. 3.2.1c—Tensile test with clevis-type grips.

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, and [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. \(2015a\)](#) 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 hydra-

tion 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 sulfoaluminate 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, improvement of durability of glass fibers by filling the spaces between yarns with polymers and nanosilica particles was successfully undertaken ([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](#)).

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 (2015a) 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. (2015b) 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. (2018) 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) reported 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 interlaminar 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 (2007a) strengthened plain concrete flexural members with glass FRCM. Results indicated an increase in load-carrying and deformation capacities as well as 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-matrix interface, similar to the single-lap 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 mixture 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 (2007)** 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 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 (2015b) 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 disproportionately 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 ($A_f E_f$). For the SRP- and SRG-strengthened beams that had similar values of $A_f E_f$, 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:

- 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.
- 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.
- 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) bond of the concrete FRCM interface; and d) level of fiber impregna-