

Guide to Design and Construction of Externally Bonded Fabric-Reinforced Cementitious Matrix (FRCM) and Steel-Reinforced Grout (SRG) Systems for Repair and Strengthening Masonry Structures

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Guide to Design and Construction of Externally Bonded Fabric-Reinforced Cementitious Matrix (FRCM) and Steel-Reinforced Grout (SRG) Systems for Repair and Strengthening Masonry Structures

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This guide addresses the use of externally bonded (EB) fabric-reinforced cementitious matrix (FRCM) and steel-reinforced grout (SRG) systems for repair and strengthening of masonry structures. FRCM and SRG are composite materials composed of a reinforcement in the form of open fabric bonded on the masonry surface through an inorganic matrix. In particular, the structural reinforcement for FRCM consists of an open grid fabric of continuous fibers made of carbon, alkali-resistant (AR) glass, polyparaphenylene benzobisoxazole (PBO), aramid, or basalt fibers, while SRG systems use steel cords of twisted wires arranged to form a unidirectional fabric. The matrixes are typically based on combinations of portland cement, silica fume, and fly ash as the binder (cement-based), or on natural hydraulic lime (lime-based), or even on geopolymer (geopolymer-based). FRCM and SRG systems represent an alternative to traditional strengthening techniques such as steel tie

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rods, section enlargement, or even fiber-reinforced polymer (FRP) systems. FRCM and SRG systems can be used for various structural purposes—for example, they are used to: 1) increase the load-bearing capacity of structural members; 2) improve the seismic capacity of buildings; 3) counteract specific incipient or already developed damage; 4) limit opening of cracks; and 5) strengthen local weaknesses. Based on experimental research, analytical work, and field applications, this guide provides the recommendations for the design and structural evaluation of FRCM and SRG systems according to both American and European existing regulations and guidelines.

Keywords: composites; confinement; earthquake-resistant; fabric-reinforced cementitious matrix; lap splices; mortar matrix; steel-reinforced grout; structural analysis; structural design.

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CHAPTER 1—INTRODUCTION

1.1—Introduction

Fabric-reinforced cementitious matrix (FRCM) and steel-reinforced grout (SRG) composites have recently emerged as a viable technology for repairing and strengthening masonry structures, as they offer important advantages in terms of tensile strength, weight, and thickness (Triantafyllou and Papanicolaou 2005; Barton et al. 2005; Prota et al. 2006; Papanicolaou et al. 2007a; Borri et al. 2009a; Nanni 2012; De Luca and Tumialan 2014; de Felice et al. 2014). The structural performance of FRCM/SRG, when externally bonded (EB) to masonry, relies on the capacity of the reinforcement to bear the tensile stress, while the compressive stress is carried by the masonry structural element. FRCM/SRG systems prove to be competitive for repair, retrofit, and rehabilitation of existing masonry structures

when compared to conventional techniques, such as steel tie rods, section enlargement, and reinforced concrete overlays. When compared to fiber-reinforced polymer (FRP) systems, the substitution of the polymeric matrix with an inorganic one overcomes some of the limitations of FRP in terms of compatibility with the masonry substrate, resistance at high temperature, vapor permeability, application on wet surfaces, and removability (possibility of being removed without significant damage in the original substrate). The advantages of FRCM/SRG composites, especially when lime-based mortars are used as matrixes, make them suitable for the rehabilitation of historic structures and architectural heritage (Valluzzi et al. 2014b).

In FRCM/SRG composites, the matrix has both roles to cover and protect the reinforcement that is embedded inside, and to ensure the stress transfer between the masonry substrate and the reinforcement. The matrix is generally made of fine-grained mortar with a combination of portland cement, silica fume, fly ash, ground-granulated blast furnace slag, and natural pozzolan as the binder (cement-based), or natural hydraulic lime (lime-based), or even of geopolymers (geopolymer-based). Organic components could be also added in the matrix to improve the bond and the workability; however, they may induce a decrease in vapor permeability and fire resistance.

The fabric consists of an open grid of yarns made of carbon, alkali-resistant (AR) glass, basalt, aramid or polyparaphenylene benzobisoxazole (PBO)-continuous fibers. Fabrics are usually arranged in two directions by means of weaving, knitting tufting, or braiding. The spacing of the yarns needs to allow the inorganic matrix to penetrate the fabric. When the reinforcement consists of steel cords of twisted wires arranged to form a unidirectional fabric, the technology is known as SRG (Casadei et al. 2005; Barton et al. 2005; Huang et al. 2005; Borri et al. 2011; De Santis and de Felice 2015a).

Based on the outcomes of the scientific research performed in the past 15 years, the structural members strengthened with FRCM and with SRG composites have analogous behavior. Therefore, the same approach can be used for the design of EB reinforcements with FRCM and SRG systems. On the other hand, some differences exist concerning durability and performance under elevated temperatures; the research on these issues is ongoing.

This guide is the outcome of the work carried out by the ACI 549-L Liaison Committee between ACI Committee 549, “Thin Reinforced Cementitious Products and Ferrocement,” and RILEM Committee TC 250-CSM (de Felice et al. 2018a), “Composites for Sustainable Strengthening of Masonry.” The joint committee provides guidance for the design of FRCM and SRG systems for repair and strengthening of masonry structures, according to both American and European approaches. The sections dealing with scientific background (Chapter 3); field application examples (Chapter 4); general design considerations (Chapter 6); and reinforcement details and drawing specification (Chapter 11) are common to the two approaches (American and European). To the contrary, a two-column format is used in the other

chapters dealing with material characteristics and systems qualification (Chapter 5), and with the design rules for out-of-plane strengthening of walls (Chapter 7), for the in-plane strengthening of walls (Chapter 8), for the confinement of columns (Chapter 9), and for the strengthening of vaults (Chapter 10), and with design examples (Chapter 12). The left column, identified by the ACI logo, is written according to the ASTM standards, the **International Code Council-Evaluation Services (ICC-ES) Acceptance Criteria AC434**, and **ACI 549.4R**. The right column, identified by the RILEM logo, is written according to the European Committee for Standardization (CEN) EN standards, RILEM TC 232-TDT (Brameshuber 2016), and RILEM TC 250-CSM (de Felice et al. 2018a) recommendations. Despite a number of names and acronyms (including TRM and FRM) used in the scientific literature when referring to externally bonded (EB) mortar-based reinforcements, as clarified in the historical development section of this guide (3.2), only FRCM and SRG are used in this guide.

1.2—Scope

Note that this guide is based on the most recent knowledge and interactions with other technical organizations, such as the working group of the Italian National Research Council (CNR), which was established for the development of guidelines for both the qualification of FRCM/SRG composites and the design of FRCM/SRG-strengthened structures. However, the scientific research on the structural behavior of FRCM/SRG-reinforced masonry structures and on design methods is still under development. Based on current knowledge, conservative values are proposed for the safety coefficients included in the design algorithms provided in this guide. The design algorithms may be subject to future update or revision, and less conservative values, or differentiated values for specific materials or applications, may be assigned to tuning coefficients, strength reduction factors, and partial coefficients based on validation with wider databases of experimental data.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

			
$A_e =$	area of the effectively confined masonry, in. ² (mm ²)	$A_e =$	area of the effectively confined masonry, mm ² (in. ²)
$A_f =$	area of the fabric effective in shear, in. ² (mm ²)	$A_f =$	area of the fabric effective in shear, mm ² (in. ²)
$A_m =$	cross-sectional area of the column, in. ² (mm ²)	$A_m =$	cross-sectional area of the column, mm ² (in. ²)
$A_s =$	area of the steel reinforcement, in. ² (mm ²)	$A_s =$	area of the steel reinforcement, mm ² (in. ²)



$b =$	width of the crowning beam cross section, in. (mm)	$b =$	width of the crowning beam cross section, mm (in.)
$b_c =$	short side dimension of compression member with rectangular cross section, in. (mm)	$b_c =$	short side dimension of compression member with rectangular cross section, mm (in.)
$c =$	cohesion of masonry, psi (MPa)	$c =$	cohesion of masonry, MPa (psi)
$c_u =$	neutral axis depth from the compressive edge of the cross section, in. (mm)	$c_u =$	neutral axis depth from the compressive edge of the cross section, mm (in.)
$c_u' =$	neutral axis depth determined under the preliminary assumption that both the masonry and the FRCM/SRG attain their ultimate strain, in. (mm)	$c_u' =$	neutral axis depth determined under the preliminary assumption that both the masonry and the FRCM/SRG attain their ultimate strain, mm (in.)
$D =$	diameter of the confined column, in. (mm)	$D =$	diameter of the confined column, mm (in.)
$E_{2c} =$	slope of linear portion of stress-strain model for FRCM-confined masonry, psi (MPa)		
$E_f =$	stiffness of cracked FRCM/SRG specimen, psi (MPa)	$E_f =$	design value of the elastic modulus of FRCM/SRG, MPa (psi)
		$E_1 =$	stiffness of uncracked FRCM/SRG specimen, MPa (psi)
		$E_2 =$	stiffness of cracked FRCM/SRG specimen, MPa (psi)
$E_f^* =$	stiffness of uncracked FRCM/SRG specimen, psi (MPa)		
$E_m =$	Young's modulus of masonry, psi (MPa)	$E_m =$	Young's modulus of masonry, MPa (psi)
		$E_{mat} =$	modulus of elasticity of mortar from compression test (Eurocode EN 998-2 and EN 13412), MPa (psi)
$E_s =$	Young's modulus of steel reinforcement, psi (MPa)	$E_s =$	Young's modulus of steel reinforcement, MPa (psi)
		$E_t =$	tensile modulus of elasticity of fabric, MPa (psi)

$F_f' =$	resultant loads for the FRCM/SRG in tension determined under the preliminary assumption that both the masonry and the FRCM/SRG attain their ultimate strain, lb (N)	$F_f' =$	resultant loads for the FRCM/SRG in tension determined under the preliminary assumption that both the masonry and the FRCM/SRG attain their ultimate strain, N (lb)
$F_m' =$	resultant loads for the masonry in compression determined under the preliminary assumption that both the masonry and the FRCM/SRG attain their ultimate strain, lb (N)	$F_m' =$	resultant loads for the masonry in compression determined under the preliminary assumption that both the masonry and the FRCM/SRG attain their ultimate strain, N (lb)
$F_s' =$	resultant loads for the internal reinforcement determined under the preliminary assumption that both the masonry and the FRCM/SRG attain their ultimate strain, lb (N)	$F_s' =$	resultant loads for the internal reinforcement determined under the preliminary assumption that both the masonry and the FRCM/SRG attain their ultimate strain, N (lb)
$F_{strip} =$	maximum tensile load in the FRCM/SRG strip, lb (N)	$F_{strip} =$	maximum tensile load in the FRCM/SRG strip, N (lb)
		$f_{c,mat} =$	characteristic compressive strength of the mortar matrix (Eurocode EN 998-2 and EN 12190), MPa (psi)
$f_{ccm} =$	maximum compressive strength of confined masonry, psi (MPa)	$f_{ccm} =$	maximum compressive strength of confined masonry, MPa (psi)
		$f_{fbk} =$	characteristic value of maximum axial stress in the textile attained in the bond test, MPa (psi)
$f_{fe} =$	effective tensile stress level in the FRCM/SRG reinforcement, psi (MPa)	$f_{fe} =$	effective tensile stress level in the FRCM/SRG reinforcement, MPa (psi)
$f_{fu} =$	ultimate tensile strength of FRCM/SRG, psi (MPa)	$f_{fu} =$	ultimate tensile strength of FRCM/SRG, MPa (psi)
$f_l =$	maximum confining pressure due to FRCM jacket, psi (MPa)	$f_l =$	maximum confining pressure due to FRCM jacket, MPa (psi)
$f_{l,eff} =$	effective confining pressure due to FRCM/SRG jacket, psi (MPa)	$f_{l,eff} =$	effective confining pressure due to FRCM/SRG jacket, MPa (psi)
$f_{mc} =$	compressive strength of mortar from compression test (ASTM C109/C109M), psi (MPa)		

f_{mu} =	compressive strength of masonry, psi (MPa)	f_{mu} =	compressive strength of masonry, MPa (psi)
		f_t =	tensile strength of fabric, MPa (psi)
		$f_{t,max}$ =	maximum stress of fabric in direct tensile test, MPa (psi)
		f_{td} =	design value of the tensile strength of masonry with respect to diagonal tension failure mode, MPa (psi)
		f_{tk} =	characteristic value of the tensile strength of the fabric, MPa (psi)
		f_{vd} =	shear strength of unreinforced masonry (URM) calculated in accordance with Eurocode 6 (EN 1996:1995-02), MPa (psi)
f_{yd} =	design yielding strength of steel reinforcement, psi (MPa)	f_{yd} =	design yielding strength of steel reinforcement, MPa (psi)
H =	height of the masonry wall, in. (mm)	H =	height of the masonry wall, mm (in.)
H_c =	effective height of the column, in. (mm)	H_c =	effective height of the column, mm (in.)
h =	height of the crowning beam cross section, in. (mm)	h =	height of the crowning beam cross section, mm (in.)
h_c =	long side dimension of compression member with rectangular cross section, in. (mm)	h_c =	long side dimension of compression member with rectangular cross section, mm (in.)
I =	moment of inertia of the crowning beam strengthened with FRCM/SRG, in. ⁴ (mm ⁴)	I =	moment of inertia of the crowning beam strengthened with FRCM/SRG, mm ⁴ (in. ⁴)
		i =	grid spacing of the fabric, mm (in.)
		k =	effectiveness factor, depending on the properties of the matrix
		k' =	factor depending on ρ_{mats} , $f_{c,mats}$ and f_{mu}
k_a =	shape factor in the determination of $f_{l,eff}$ (based on the geometry of cross section)	k_a =	shape factor in the determination of $f_{l,eff}$ (based on the geometry of cross section)
k_b =	efficiency factor for FRCM/SRG reinforcement in the determination of ε_{ccm} (based on the geometry of cross section)		

		k_{bc} =	coefficient that accounts for the boundary conditions of the wall
k_n =	fractile coefficient that depends on the number of tested specimens, defined in Annex D of Eurocode 0 (EN 1990:2002-02)		
k_v =	vertical efficiency factor for FRCM/SRG reinforcement in the determination of $f_{l,eff}$ (based on the geometry of cross section)	k_v =	vertical efficiency factor for FRCM/SRG reinforcement in the determination of $f_{l,eff}$ (based on the geometry of cross section)
L =	width of the masonry wall or vault, in. (mm)	L =	width of the masonry wall or vault, mm (in.)
		L_c =	length of the part of the wall in compression, mm (in.)
L_{df} =	development length over which the bond capacity of FRCM/SRG is developed, in. (mm)	L_{df} =	development length over which the bond capacity of FRCM/SRG is developed, mm (in.)
L_{eff} =	effective bond length of the FRCM/SRG system, in. (mm)	L_{eff} =	effective bond length of the FRCM/SRG system, mm (in.)
M_{Ed} =	existing bending moment, in.-lb (N-mm)	M_{Ed} =	existing bending moment, N-mm (in.-lb)
M_n =	nominal flexural strength, in.-lb (N-mm)	M_n =	nominal flexural strength, N-mm (in.-lb)
		M_n^{URM} =	nominal flexural strength of the wall without FRCM/SRG reinforcement, N-mm (in.-lb)
		M_{Rd} =	design flexural strength, N-mm (in.-lb)
		M_{Rd}^{URM} =	design value of the in-plane flexural strength of the unreinforced wall, N-mm (in.-lb)
N_{Ed} =	existing axial load, lb (N)	N_{Ed} =	existing axial load, N (lb)
N_{Edj} =	axial load at the section j of the arch, lb (N)	N_{Edj} =	axial load at the section j of the arch, N (lb)
N_n =	tensile strength of the crowning beam, lb (N)	N_n =	tensile strength of the crowning beam, N (lb)
		N_{Rd} =	design tensile strength of the crowning beam, N (lb)

		$N_{Rd,c}$ =	design axial strength of the column strengthened with FRCM/SRG, N (lb)
n =	number of wall sides strengthened with FRCM/SRG	n =	number of wall sides strengthened with FRCM/SRG
n_f =	number of plies of fabric in the FRCM/SRG reinforcement	n_f =	number of plies of fabric in the FRCM/SRG reinforcement
P_D =	dead load applied on the column, lb (N)		
P_L =	service load applied on the column, lb (N)		
P_i =	weight of the part of the vault placed between two hinges, including the arch self-weight, the backfill load, and that of the superstructure pertaining to the part itself, lb (N)	P_i =	weight of the part of the vault placed between two hinges, including the arch self-weight, the backfill load, and that of the superstructure pertaining to the part itself, lb (N)
R^2 =	correlation factor	R^2 =	correlation factor
r =	radius of gyration of the cross section of the column about the weak axis, in. (mm)		
r_c =	radius of edges of a rectangular cross section confined with FRCM, in. (mm)	r_c =	radius of edges of a rectangular cross section confined with FRCM, mm (in.)
s =	distance between two FRCM/SRG layers, in. (mm)	s =	distance between two FRCM/SRG layers, mm (in.)
s_f =	spacing between strips, in. (mm)	s_f =	spacing between strips, mm (in.)
s_{Ht} =	spacing between horizontal FRCM/SRG strips, in. (mm)	s_{Ht} =	spacing between horizontal FRCM/SRG strips, mm (in.)
s_{Vt} =	spacing between vertical FRCM/SRG strips, in. (mm)	s_{Vt} =	spacing between vertical FRCM/SRG strips, mm (in.)
t =	thickness of the masonry wall or vault, in. (mm)	t =	thickness of the masonry wall or vault, mm (in.)
t_f =	design thickness of the fabric in the direction of the load, in. (mm)	t_f =	design thickness of the fabric in the direction of the load, mm (in.)
t'_f =	design thickness of each ply of fabric in the load direction, in. (mm)	t'_f =	design thickness of each ply of fabric in the load, mm (in.)
t_{f*} =	equivalent thickness of the FRCM/SRG strips assumed to be uniformly distributed along the length L of the wall, in. (mm)	t_{f*} =	equivalent thickness of the FRCM/SRG strips assumed to be uniformly distributed along the length L of the wall, mm (in.)

t_{Ht} =	equivalent thickness of the FRCM/SRG reinforcement in the horizontal direction, in. (mm)	t_{Ht} =	equivalent thickness of the FRCM/SRG reinforcement in the horizontal direction, mm (in.)
t_{Vt} =	equivalent thickness of the FRCM/SRG reinforcement in the vertical direction, in. (mm)	t_{Vt} =	equivalent thickness of the FRCM/SRG reinforcement in the vertical direction, mm (in.)
t_{mat} =	total thickness of the matrix, in. (mm)	t_{mat} =	total thickness of the matrix, mm (in.)
V_{bjs1} =	bed-joint sliding strength of the URM wall at the initial uncracked stage determined in accordance with ASCE 41, lb (N)		
V_{bjs2} =	bed-joint sliding strength of the URM wall at the final cracked stage determined in accordance with ASCE 41, lb (N)		
V_{dt} =	diagonal tension strength of the URM wall determined in accordance with ASCE 41, lb (N)		
V_{Ed} =	existing shear stress, lb (N)	V_{Ed} =	existing shear stress, N (lb)
V_{Edi} =	external shear demand in the joint i corresponding to the given load multiplier, lb (N)	V_{Edi} =	external shear demand in the joint i corresponding to the given load multiplier, N (lb)
V_f =	contribution of FRCM/SRG to nominal shear strength, lb (N)	V_f =	contribution of FRCM/SRG to design shear strength, N (lb)
V_n^{URM} =	nominal lateral strength of URM wall determined in accordance with ASCE 41, lb (N)		
V_r =	rocking strength of the URM wall determined in accordance with ASCE 41, lb (N)		
		V_{Rd} =	design lateral strength of the wall strengthened with FRCM/SRG, N (lb)
V_{Rdi} =	shear capacity in correspondence of masonry cross sections strengthened with composite material for the given design load multiplier, lb (N);	V_{Rdi} =	shear capacity in correspondence of masonry cross sections strengthened with composite material for the given design load multiplier, N (lb);

$V_n^R =$	nominal lateral strength related to the shear-controlled failure modes of the FRCM/SRG-strengthened wall		
		$V_{Rd}^{OP} =$	design shear strength under out-of-plane loads of the wall strengthened with FRCM/SRG, N (lb)
		$V_{Rdt} =$	design lateral strength of the URM wall corresponding to diagonal tension, N (lb)
		$V_{Rd}^{URM} =$	design lateral strength of URM wall, N (lb)
		$V_{Rjs} =$	design lateral strength of the URM wall corresponding to joint sliding evaluated in accordance with Eurocode 6 (EN 1996:1995-02), N (lb)
		$V_{Rtc}^R =$	design lateral strength of the reinforced wall against toe-crushing, N (lb)
		$V_{Rtc} =$	design lateral strength of the URM wall corresponding to toe crushing, N (lb)
$V_{tc}^R =$	nominal lateral strength of the reinforced wall related to flexure-controlled mechanisms, lb (N)		
$V_{tc} =$	toe-crushing strength of the URM wall determined in accordance with ASCE 41, lb (N)		
$W_{MRj} =$	maximum resisting work, in.-lb (N-mm)	$W_{MRj} =$	maximum resisting work, N-mm (in.-lb)
$w_f =$	total width of the FRCM/SRG strips bonded to the wall along its width L , in. (mm)	$w_f =$	total width of the FRCM/SRG strips bonded to the wall along its width L , mm (in.)
$w_{f1} =$	width of the single strip of FRCM/SRG, in. (mm)	$w_{f1} =$	width of the single strip of FRCM/SRG, mm (in.)
$w_{fH} =$	width of the horizontal strips of the FRCM/SRG reinforcement, in. (mm)	$w_{fH} =$	width of the horizontal strips of the FRCM/SRG reinforcement, mm (in.)
$w_{fV} =$	width of the vertical strips of the FRCM/SRG reinforcement, in. (mm)	$w_{fV} =$	width of the vertical strips of the FRCM/SRG reinforcement, mm (in.)

$x_{ass} =$	position of the center of rotation in the arch collapse mechanism, in. (mm)	$x_{ass} =$	position of the center of rotation in the arch collapse mechanism, mm (in.)
$x_i =$	position of the hinge, in. (mm)	$x_i =$	position of the hinge, mm (in.)
$y_s =$	distance of the steel reinforcement from the compressed edge of the cross section of the wall, in. (mm)	$y_s =$	distance of the steel reinforcement from the compressed edge of the cross section of the wall, mm (in.)
$z =$	distance of the hinge from the end of the FRCM/SRG reinforcement, in. (mm)	$z =$	distance of the hinge from the end of the FRCM/SRG reinforcement, mm (in.)
		$\alpha_1 =$	coefficient calibrated by comparison between experimental results and average theoretical data, applied to ϵ_{fb} in the evaluation of ϵ_{fd}
		$\alpha_2 =$	coefficient calibrated by comparison between experimental results and average theoretical data, applied to ϵ_{tk} in the evaluation of ϵ_{fd}
$\alpha_V =$	ratio between V_{Edi} and V_{Rdi}	$\alpha_V =$	ratio between V_{Edi} and V_{Rdi}
$\beta =$	reduction factor applied to the neutral axis depth for the stress block diagram	$\beta =$	reduction factor applied to the neutral axis depth for the stress block diagram
		$\beta_s =$	slenderness factor
$\gamma =$	reduction factor applied to the compressive strength of masonry for the stress block diagram	$\gamma =$	reduction factor applied to the compressive strength of masonry for the stress block diagram
		$\gamma_k =$	safety factor
		$\gamma_M =$	partial safety factor on the design axial strain of the FRCM/SRG composite material
		$\gamma_m =$	compressive strength of masonry safety factor calculated in accordance with Eurocode 6 (EN 1996:1995-02)
		$\gamma_s =$	surface mass density of the fabric, g/m ² (lb/in. ²)
$\Delta F_{Exp} =$	experimental increase in the ultimate load of the vault, lb (N)	$\Delta F_{Exp} =$	experimental increase in the ultimate load of the vault, N (lb)
$\Delta F_{th} =$	theoretical increase in the ultimate load of the vault, lb (N)	$\Delta F_{th} =$	theoretical increase in the ultimate load of the vault, N (lb)

		$\Delta_f =$	standard deviation of the axial stress in the textile provided by the shear bond tests performed in accordance with RILEM TC 250-CSM Recommendation (de Felice et al. 2018a)
		$\Delta_t =$	standard deviation of the tensile strength of the fabric provided by the tensile tests on bare fabrics
$\Delta M^{Exp} =$	experimental increase in flexural strength, in.-lb (N-mm)	$\Delta M^{Exp} =$	experimental increase in flexural strength, N-mm (in.-lb)
$\Delta M^{th} =$	theoretical increase in flexural strength, in.-lb (N-mm)	$\Delta M^{th} =$	theoretical increase in flexural strength, N-mm (in.-lb)
$\Delta N_{exp} =$	experimental axial strength increase, lb (N)	$\Delta N_{exp} =$	experimental axial strength increase, N (lb)
$\Delta N_{th} =$	design value of the theoretical axial strength increase, lb (N)	$\Delta N_{th} =$	design value of the theoretical axial strength increase, N (lb)
$\Delta V^{Exp} =$	experimental shear strength contribution of FRCM/SRG, lb (N)	$\Delta V^{Exp} =$	experimental shear strength contribution of FRCM/SRG, lb (N)
$\Delta V^{th} =$	theoretical shear strength contribution of FRCM/SRG, lb (N)	$\Delta V^{th} =$	theoretical shear strength contribution of FRCM/SRG, lb (N)
$\Delta \epsilon =$	standard deviation of the tensile strain of the FRCM/SRG system		
$\Delta \theta_j =$	relative rotation between two parts of the arch at the hinge j , rad	$\Delta \theta_j =$	relative rotation between two parts of the arch at the hinge j , rad
$\epsilon_{ccm} =$	axial compressive strain corresponding to the compressive strength of the confined masonry column, in./in. (mm/mm)	$\epsilon_{ccm} =$	axial compressive strain corresponding to the compressive strength of the confined masonry column, mm/mm (in./in.)
		$\epsilon_{fb} =$	tensile strain corresponding to the characteristic value of the maximum axial stress in the textile attained in the bond test, mm/mm (in./in.)
$\epsilon_{fd} =$	design tensile strain of FRCM/SRG, in./in. (mm/mm)	$\epsilon_{fd} =$	design tensile strain of FRCM/SRG, mm/mm (in./in.)
$\epsilon_{fe} =$	effective tensile strain level in the FRCM/SRG composite material, in./in. (mm/mm)	$\epsilon_{fe} =$	effective tensile strain level in the FRCM/SRG composite material, mm/mm (in./in.)

$\epsilon_{fu} =$	ultimate tensile strain of FRCM/SRG, in./in. (mm/mm)	$\epsilon_{fu} =$	ultimate tensile strain of FRCM/SRG, mm/mm (in./in.)
$\epsilon_{f@0.90f_{fu}} =$	strain corresponding to the 90 percent of the ultimate tensile strength of FRCM/SRG in tensile test, mm/mm (in./in.)		
$\epsilon_{f@0.60f_{fu}} =$	strain corresponding to the 60 percent of the ultimate tensile strength of FRCM/SRG in tensile test, mm/mm (in./in.)		
$\epsilon_{lim} =$	limit strain introduced to prevent excessive damage in the structural member reinforced with FRCM/SRG, in./in. (mm/mm)		
$\epsilon_{mu} =$	ultimate compressive strain of masonry, in./in. (mm/mm)	$\epsilon_u =$	ultimate compressive strain of masonry, mm/mm (in./in.)
$\epsilon_s =$	tensile strain attained by the internal steel reinforcement, in./in. (mm/mm)	$\epsilon_s =$	tensile strain attained by the internal steel reinforcement, mm/mm (in./in.)
$\epsilon_s' =$	tensile strain attained by the internal steel reinforcement determined under the preliminary assumption that both the masonry and the FRCM/SRG attain their ultimate strain, in./in. (mm/mm)	$\epsilon_s' =$	tensile strain attained by the internal steel reinforcement determined under the preliminary assumption that both the masonry and the FRCM/SRG attain their ultimate strain, mm/mm (in./in.)
$\epsilon_{syd} =$	design yielding strain of steel reinforcement, in./in. (mm/mm)	$\epsilon_{syd} =$	design yielding strain of steel reinforcement, mm/mm (in./in.)
		$\epsilon_t =$	ultimate strain of fabric, mm/mm (in./in.)
		$\epsilon_{tk} =$	ultimate tensile strain corresponding to the characteristic value of the tensile strength of the fabric, mm/mm (in./in.)
		$\epsilon_{t,max} =$	strain corresponding to the maximum stress of fabric in direct tensile test, mm/mm (in./in.)
		$\epsilon_{t@0.1f_{t,max}} =$	strain corresponding to the 10% of the maximum stress of fabric in direct tensile test, mm/mm (in./in.)

		$\epsilon_{t@0.5f_{t,max}}$ =	strain corresponding to the 50% of the maximum stress of fabric in direct tensile test, mm/mm (in./in.)
ϵ'_t =	transition strain in the stress-strain curve of FRCM-confined masonry, in./in. (mm/mm)		
ϕM_n =	design flexural strength, in.-lb (N-mm)		
ϕ_m =	strength reduction factor for flexure		
ϕN_n =	design tensile strength of the crowning beam, lb (N)		
ϕP_n =	design axial strength of the column strengthened with FRCM/SRG, lb (N)		
ϕV_n =	design lateral strength of the wall strengthened with FRCM/SRG, lb (N)		
ϕ_v =	strength reduction factor for shear		
$\phi \lambda_c$ =	design value of the load multiplier		
η =	reduction factor applied to the contribution of FRCM/SRG to nominal shear strength, when the FRCM/SRG reinforcement is applied only to one side of the wall	η =	reduction factor applied to the contribution of FRCM/SRG to nominal shear strength, when the FRCM/SRG reinforcement is applied only to one side of the wall
η_F =	vertical component of the displacement of λF , in. (mm)	η_F =	vertical component of the displacement of λF , mm (in.)
η_i =	vertical component of the displacement of P_i , in. (mm)	η_i =	vertical component of the displacement of P_i , mm (in.)
λ =	load multiplier	λ =	load multiplier
λ_c =	collapse multiplier of the masonry vault strengthened with FRCM/SRG	λ_c =	collapse multiplier of the masonry vault strengthened with FRCM/SRG
$\lambda_{c,URM}$ =	collapse multiplier of the unreinforced masonry vault	$\lambda_{c,URM}$ =	collapse multiplier of the unreinforced masonry vault
λF =	live load, lb (N)	λF =	live load, lb (N)
		λ_{Rd} =	design value of the load multiplier
μ =	coefficient of friction of masonry	μ =	coefficient of friction
θ_i =	virtual rotation of the i -th part of the arch, rad	θ_i =	virtual rotation of the i -th part of the arch, rad

		ρ_{mat} =	factor depending on the total thickness of the matrix and the diameter of the confined column
σ_0 =	average vertical compression stresses over the cross section of the vault, psi (MPa)	σ_0 =	average vertical compression stresses over the cross section of the wall or vault, MPa (psi)
σ_s =	tensile stress attained by the internal steel reinforcement, psi (MPa)	σ_s =	tensile stress attained by the internal steel reinforcement, MPa (psi)
σ'_s =	tensile stress attained by the internal steel reinforcement determined under the preliminary assumption that both the masonry and the FRCM/SRG attain their ultimate strain, psi (MPa)	σ'_s =	tensile stress attained by the internal steel reinforcement determined under the preliminary assumption that both the masonry and the FRCM/SRG attain their ultimate strain, MPa (psi)
Ψ_f =	reduction factor applied to the effective confining pressure due to FRCM/SRG jacket		
$\langle E_p \rangle$ =	average value of the stiffness of cracked FRCM/SRG provided by the tensile tests on FRCM/SRG specimens, psi (MPa)		
		$\langle E_t \rangle$ =	average value of the tensile modulus of elasticity of the fabric, MPa (psi)
		$\langle f_{tb} \rangle$ =	average value of maximum axial stress in the textile provided by the shear bond tests performed in accordance with RILEM TC 250-CSM Recommendation (de Felice et al. 2018a), MPa (psi)
		$\langle f_t \rangle$ =	average value of the tensile strength of the fabric provided by the tensile tests on bare fabrics, MPa (psi)
$\langle \epsilon_{fu} \rangle$ =	average value of the ultimate tensile strain of FRCM/SRG by tensile tests performed in accordance with ICC-ES Acceptance Criteria AC434, in./in. (mm/mm)		

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.

cement-based matrix—inorganic hydraulic and nonhydraulic cementitious binder (mortar) that holds in place the structural reinforcement fabrics in fabric-reinforced cementitious matrix/steel-reinforced grout (FRCM/SRG). Mortar can be enriched with short fibers, polymeric additives, or both, to increase its strength, deformability capacity, and durability. If the mortar is polymer-modified, the maximum content of organic compounds (dry polymers) in the matrix is generally limited to 5 percent by weight of cement.

coating—an organic compound applied to fabric before or after weaving to increase bond performance between fabric and matrix and for ease of fabric handling and installation.

fabric—manufactured planar fabric structure made of steel cords, or fiber yarns, which 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 (FRCM)—composite material consisting of inorganic (for example, typically cement or lime-based) matrix (mortar) embedding the reinforcement fabric(s) that, when externally bonded (EB) to the substrate, forms the FRCM system; the total thickness of the matrix (for one reinforcement layer) is generally about 0.3 to 0.4 in. (8 to 10 mm) and not greater than 0.6 in. (15 mm); fabric yarns are made of dry fibers, such as alkali-resistant (AR) glass, aramid, basalt, carbon, and polyparaphenylene benzobisoxazole (PBO), consisting of a primary-direction (PD) and a secondary-direction (SD) yarns connected perpendicularly; multiaxial fabrics are available in the market in which the yarns are connected with a designed angle that may be different from 90 degrees; polymeric coatings or preimpregnation may be applied to fibers; the typical spacing of PD and SD yarns is less than 1.2 in. (30 mm).

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

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

lime-based matrix—inorganic hydraulic lime binder (mortar) that holds in place the structural reinforcement fabrics in fabric-reinforced cementitious matrix (FRCM/SRG). Mortar can be enriched with discontinuous fibers, polymeric additives, or both, to increase its strength, deformability capacity, and durability. 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 lime.

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.

steel cord—thin rope or string composed of two or more twisted steel wires; the diameter of the steel wire is typically in the order of 0.04 in. (0.1 mm).

steel-reinforced grout (SRG) composite material—composite material consisting of a sequence of one or more layers of inorganic (for example, typically, cement or lime-based) matrix reinforced with wires or cords of twisted wires arranged to form a unidirectional fabric that, when adhered to masonry structural members, forms an SRG system; in this system, the maximum total thickness of the matrix is generally about 0.3 to 0.4 in. (8 to 10 mm) and not greater than 0.6 in. (15 mm); the spacing between steel cords is usually not greater than 0.2 to 0.3 in. (6 to 8 mm).

yarn—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.

CHAPTER 3—SCIENTIFIC BACKGROUND

3.1—FRCM/SRG systems characteristics

Fabric-reinforced cementitious matrix (FRCM) and steel-reinforced grout (SRG) composites are systems based on inorganic (generally cement-based or lime-based) matrixes. Unlike polymeric binders, mortar matrixes cannot fully impregnate the space between individual fibers. Therefore, the fiber sheets that are typically used in FRP, which consist of unidirectional or bidirectional closed fabric sheets installed by manual layup, are replaced in FRCM by an open reinforcing grid or fabric and in SRG with high-strength steel cords. The yarns/cords of the FRCM fabric are typically made of fibers that can be completely dry, individually coated, or preimpregnated with a polymer. The degree of coating or preimpregnation may vary. The polymer may be applied to an individual yarn (to impregnate all its filaments), but not to more yarns—that is, the polymer does not fill the space between yarns. In other words, the yarns are not bonded together by the polymeric resin. If a polymer is used to either cover or bond the strands, such polymer generally does not fully penetrate and impregnate the fibers as it would in FRP. For these reasons, the term “dry fiber” is often used to characterize a FRCM/SRG fabric, even when they are either coated or preimpregnated.

Fiber-reinforced polymers as a reinforcement of masonry for new construction as well as strengthening the existing ones are addressed in other documents produced by ACI Committee 440 ([ACI 440R](#); [ACI 440.2R](#); [ACI 440.7R](#)).

With respect to FRP, FRCM/SRG systems have the following advantageous features ([RILEM TC 201-TRC; Peled 2007c; Fallis 2009](#)):

- (a) Compatibility with chemical, physical, and mechanical properties of the masonry substrate
- (b) Ease of installation as traditional plastering or trowel trades can be used
- (c) Matrix porosity that allows air and moisture transport both into and out of the substrate
- (d) Good performance at elevated temperatures

(e) Removability (that is, the ability to undo the repair without harming the original structure)

3.2—Historical development

The idea of embedding a high-strength fabric into a cement-based matrix is rather old. In the late 1840s, at the beginning of reinforced concrete, Josef-Louis Lambot used iron wires embedded into a cement mortar for the construction of boats and water tanks. Almost one century later, Pier Luigi Nervi effectively employed the ferrocement by applying cement plaster over one or more layers of a thin steel fabric, to build thin, hard shell structures. His patent was registered in 1943 and this technique was extensively used for numerous well-known engineering works.

More recently, a research effort targeting the development of inorganic-matrix composites in which the steel reinforcement is replaced by a textile reinforcement, named textile-reinforced concrete (TRC), initiated in the late 1990s at RWTH Aachen University (SFB 532) and at Technische Universität Dresden, Germany (SFB 528) (Hegger 2001; Curbach 2003; Peled and Mobasher 2005; Hegger 2006; Aldea 2007; Mobasher 2011; Peled et al. 2017). The TRC initially focused on new structural elements, such as very thin-walled, highly stressed concrete elements manufactured in an industrial way. Shortly after the start of the aforementioned projects, the use of these materials for structural repair and strengthening purposes was investigated (for example, Triantafillou and Papanicolaou [2005] and Triantafillou [2016]). The term employed for such purposes was TRM, which stands for textile-reinforced matrix, in an effort to better describe the microconcrete matrix and to include other cement-free matrixes—for example, lime-based ones. Under RILEM, several technical committees have been founded and concluded their works: RILEM TC 201-TRC, RILEM TC 232-TDT (Bramshuber 2016), RILEM TC 223-MSC, and RILEM 250-CSM (de Felice et al. 2018a). In the United States and Italy, the same technology was developed under the name “fabric-reinforced cementitious matrix” (FRCM) for rehabilitation and strengthening of concrete and masonry structures (Nanni 2012; de Felice et al. 2018b).

The use of different acronyms for essentially the same type of materials is the source of confusion for both academia and practitioners. In this guideline, to avoid multiple acronyms, the term FRCM has been used for systems comprising carbon, alkali-resistant (AR) glass, polyparaphenylene benzobisoxazole (PBO), aramid or basalt fabric, and the term SRG is used for systems made with steel reinforcement.

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

3.3—FRCM/SRG mechanical properties

The mechanical properties of FRCM/SRG have been addressed in a series of publications by various researchers. Test outcomes showed that the tensile stress-strain behavior is generally characterized by three response stages (Fig. 3.3a). In Stage I, the mortar is uncracked and provides the main contribution to both the stiffness and the load-bearing

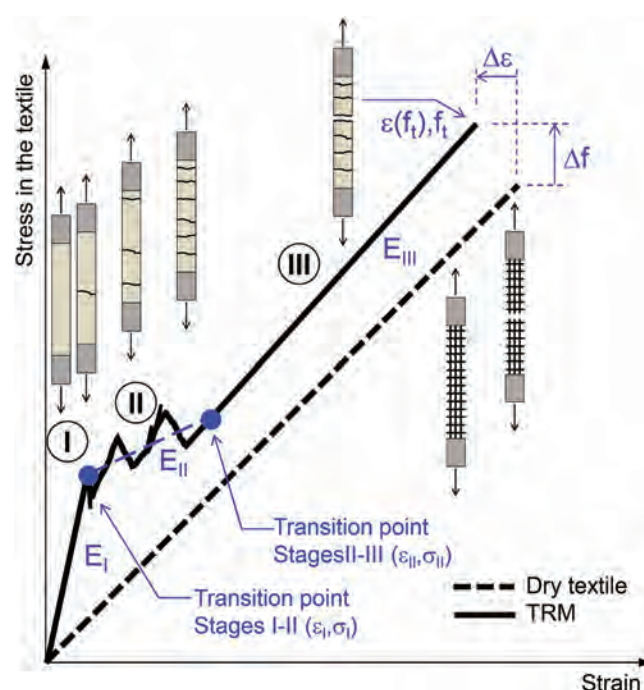


Fig. 3.3a—Response stages of FRCM/SRG under tensile loading for clamped specimens (De Santis and de Felice 2015b).

capacity of the composite. The occurrence of the first crack in the matrix identifies the beginning of Stage II. The larger the tensile strength of the matrix and the mortar-to-fabric bond/interlocking, the higher the stress level associated to the development of the first crack. During Stage II, the crack pattern progressively develops. After the crack pattern has completely developed, a stiffer response is observed and the increase of applied displacement produces a nearly linear stress growth. This conventionally marks the beginning of Stage III. In Stage III, no further cracks develop, and the increase of global displacement produces the widening of existing cracks. In clamped test configuration, in Stage III, the stiffness (slope of the response curve in this stage) and tensile strength (maximum load divided by the cross-sectional area of the fabric) are similar to those obtained in the tests on bare fabric specimens. Clearly, the enlargement of cracks in the matrix requires that debonding and sliding locally occur at the interface between fabric and matrix. Some studies highlighted that Stage II is hardly identifiable for some FRCM/SRG systems and that, in these cases, the tensile stress versus tensile strain behavior may be represented by a bilinear relationship. Particular care should be taken for lightly reinforced systems for which the load corresponding to the occurrence of the first crack in the matrix is higher than that producing the tensile rupture of the fabric (the systems that do not exhibit a strain-hardening behavior).

Direct tensile tests on FRCM/SRG coupons (prismatic composite specimens) are performed with either a clamping-grip setup (Fig. 3.3a) or with a clevis-grip setup (Fig. 3.3b) (refer to Chapter 5 for details). The experimental setup influences test results. In clamped configuration, when lateral pressure is applied in the loading production areas preventing

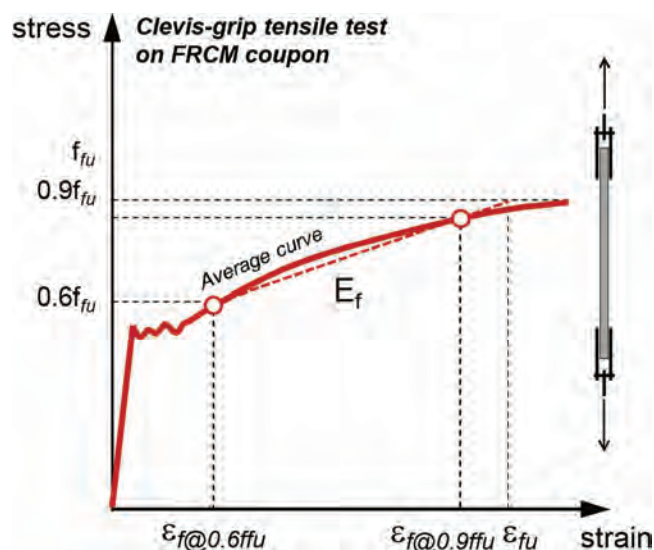


Fig. 3.3b—Response stages of FRCM and SRG under tensile loading for clevis-grip specimens (De Santis et al. 2018a).

the slippage of the fabric within the matrix, the stiffness and the load-bearing capacity of the composite system in Stage III rely on those of the textile, and tensile modulus of elasticity and tensile strength are therefore close to those of the fabric alone (Fig. 3.3a). In clevis-grip configuration, slippage at the fabric-matrix interface is not restricted because of absence of lateral pressure at the grips. Thus, the stiffness and load-bearing capacity of the composite system in Stage III depend mainly on the fabric-matrix bond performance (Fig. 3.3b). The load-bearing capacity of the cracked FRCM/SRG composite measured by clamping grip tensile tests may not be fully employed in structural applications in which the system is bonded onto the substrate on one side.

Three distinct measures of damage under tensile loading include quantitative crack spacing, stiffness degradation, and microstructural evaluation (Mobasher et al. 2004; Peled and Mobasher 2007). 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.

3.3.1 Tensile behavior—The tensile behavior of FRCM/SRG composites developed for applications to masonry structures has been studied by direct tensile tests on prismatic specimens by a number of authors (de Felice et al. 2014; Ascione et al. 2014, 2015; Yao et al. 2015; De Santis and de Felice 2015a,b; Carozzi et al. 2015, 2017; Arboleda et al. 2016; Ghiassi et al. 2016; Bellini et al. 2016; Caggegi et al. 2017; De Santis et al. 2017b; Leone et al. 2017; Lignola et al. 2017; Donnini and Corinaldesi 2017; Bilotta et al. 2017; D’Antino and Papanicolaou 2017). These studies highlight the importance of mechanical properties of the matrix and the fabric, as well the fabric-matrix interaction, which affect the overall stiffness and crack pattern (Fig. 3.3.1a). In specimens tested with clamped grips (refer to Fig. 3.3.1b and Chapter 5), mechanical properties of composites with weak mortars (which are widely used for repair and retrofit masonry structures) are governed by the Stage



Fig. 3.3.1a—Crack pattern of SRG specimens with: (a) geopolymer-based matrixes; and (b) lime-based matrixes (De Santis and de Felice 2015b).

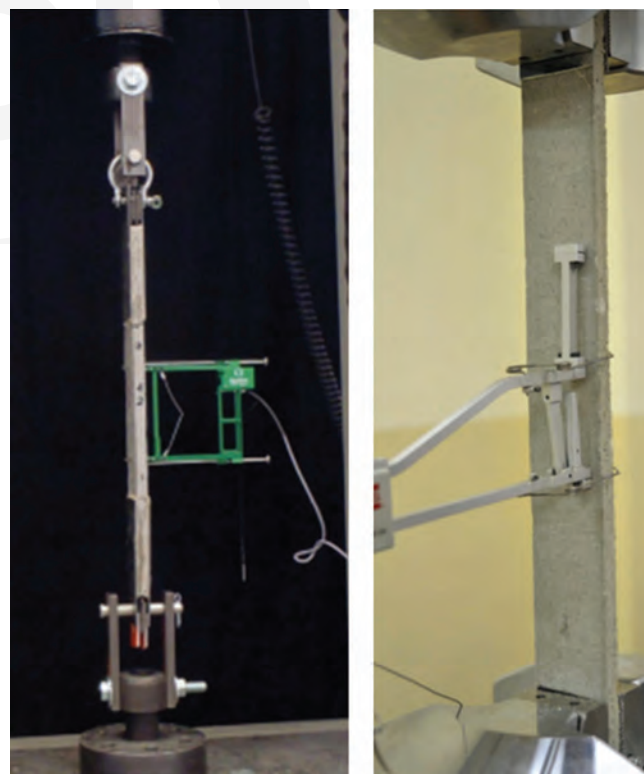


Fig. 3.3.1b—Experimental setups with clevis-type and gripping-type clamping methods (Arboleda et al. 2016).

III of the stress-strain curves. On the contrary, composites with high-strength matrixes (for example, cement-based or geopolymer-based), combined with glass fabrics, or with fabrics with large grid spacing (resulting in small amount of

fibers in the cross section) may display a response mainly governed by Stages I and II.

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).

Contamine et al. (2011) developed a direct tensile test for TRC composites that is efficient and relatively easy to implement. A large series of experiments were performed 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. Arboleda et al. (2012) performed experiments with the objective of investigating the mechanical properties of two FRCM/SRG systems, where carbon fibers and PBO fibers were used. They determined the tensile modulus of elasticity of the cracked and uncracked coupons, transition point of the bilinear curves, and ultimate stresses and strains. The strain properties show the larger variation because displacement measurement did not cover the entire coupon length. The main failure mode was slippage of fabric within the matrix—an indicator of the importance of bond strength in the performance of these materials.

Experimental studies led to the development of standard codes and recommendations dealing with test methods; ICC-ES Acceptance Criteria AC434, developed by International Code Council-Evaluation Services (ICC-ES), describes a method to perform direct tensile tests for the characterization of FRCM/SRG and SRG composites. A test recommendation to perform direct tensile tests has been also developed by the RILEM Technical Committee (TC) 232-TDT (Brameshuber 2016).

Statistical measures of crack evolution as a function of applied strain were correlated to the tensile stress and stiffness degradation by using an automated method that determines crack density, crack spacing, and damage accumulation (Mobasher et al. 2004). Similarly, microstructural evaluation refers to a broad range of tools that were used to better understand FRCM/SRG 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 3.3.1a shows the formation of distributed crack spacing throughout an SRG specimen (De Santis and de Felice 2015b). Different fabric and mortar configurations have different characteristic responses that correlate to crack spacing and composite stiffness (Mobasher et al. 2007b).

3.3.1.1 Fabric architecture and fiber type—Existing literature indicates that the mechanical properties of FRCM/SRG are greatly influenced by: a) fabric/yarn/fiber/cord geometry, including three-dimensional structures (Peled et al. 2008; 2011b; Peled and Bentur 1998, 2000, 2003; Peled 2007a);

and b) fiber type, including hybrid combinations (Peled et al. 2009, 2011a).

3.3.1.2 Matrix penetration—Penetration of mortar between the openings of the fabric is a controlling factor in improving the mechanical properties of FRCM/SRG. Mortar penetration depends on the fabric architecture and viscosity of the matrix (Peled et al. 2006).

3.3.1.3 Shrinkage and time-dependent behavior—Researchers have studied the effects of whiskers and discontinuous dispersed fibers on plastic shrinkage cracking behavior in FRCM/SRG (Mechtcherine 2012; Mechtcherine and Lieboldt 2011). A general observation is that the fineness of dispersed fibers added to the matrix is 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. Fine microfibers with a high specific fiber surface area are particularly effective in reducing plastic shrinkage cracking (Poursaei et al. 2010, 2011). Test methods to address creep behavior of fiber reinforcements for FRCM/SRG have been developed (Seidel et al. 2010).

3.3.1.4 Glass fabric durability—Alkali-resistant glass fabrics have been widely and successfully used with cementitious matrixes (MNL 128-01). 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 fabrics (MNL 128-01). There have not been demonstrated product failures due to durability issues in AR glass fabrics. 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; Micelli and Aiello 2017). Tables that include the relationship between accelerated aging and exposure to real environmental conditions have been proposed for different temperatures (Proctor et al. 1982; Dey and Mobasher 2018).

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 ground-granulated blast-furnace slag, silica fume (Kumar and Roy 1986), fly ash (Leonard and Bentur 1984), finely ground E-glass fabric (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 fabrics (Mobasher et al. 2004). ACI 544.5R presents details of various degradation mechanisms and options to improve long-term durability of AR glass fabric systems.

Recent work has aimed to improve durability of glass fabrics by filling the spaces between yarns with polymers and nanosilica particles (Cohen and Peled 2010, 2012; Bentur et al. 2008).



3.3.1.5 Carbon fabric durability—Numerous studies have been carried out on the durability of composites with carbon fabrics, for civil engineering and other applications. Most of them have investigated the deterioration of mechanical characteristics and bond performance of FRP laminates, and have shown that carbon fibers exhibit a high chemical resistance to moisture attack (Karbhari 2007), to high temperatures (El-Hacha et al. 2010), freezing-and-thawing cycles (Soudki and Green 1997), and in alkaline environment (Micelli and Aiello 2017).

3.3.1.6 Steel fabric durability—Some studies have been carried out on the durability of steel fabrics for applications to existing structures as externally bonded (EB) reinforcements, which are collected in a state-of-the-art review paper (De Santis et al. 2016b). In one study (Borri and Castori 2011), the durability of brass-coated steel textiles was investigated by leaving outdoors some specimens of brass-coated steel textiles, close to a thermoelectric station or to a cement factory for 57 weeks (two sets of four specimens each). The deterioration was 27 percent for the former ones and 33 percent for the latter ones. Other two sets of three specimens each were treated with either neutral or acid pH solutions and tested at 110°C (230°F). Artificial aging with acid pH solution induced a deterioration of 13 percent, while no strength reduction was found after treatment with neutral pH solution.

In another study (De Santis and de Felice 2015a), galvanized steel textiles were aged in substitute ocean water, prepared according to ASTM D1141-98. After 1000 hours of aging, the strength decreased by 5 percent, while the Young's modulus reduced by 8 percent, demonstrating the effectiveness of the zinc coating protection. Other specimens were flexed at 90 degrees (which is necessary for numerous applications on beams, columns, and nodes) and then tested under tension. Strength reduced by 15 percent and stiffness by 8 percent. Finally, other specimens were flexed

at 90 degrees and then aged in substitute ocean water for 1000 hours. The deterioration with respect to unaged specimens was 18 percent in strength and 9 percent in stiffness (roughly, the sum of the two contributions of salt attack and flexure taken separately), indicating that the protection layer was not strongly damaged by the mechanical flexure.

3.3.2 Bond behavior—The bond behavior on masonry substrates of FRCM/SRG composites has been investigated by many studies, and recently, a recommendation was proposed by RILEM TC 250-CSM (de Felice et al. 2018a). Most of the tests have been carried out in the laboratory with a push-pull setup using either a single-lap or a double-lap scheme (Grande et al. 2013; D'Ambrisi et al. 2013; de Felice et al. 2014; D'Antino et al. 2014; Ascione et al. 2015; Alecci et al. 2016a; Grande et al. 2015; Carozzi and Poggi 2015; Viskovic et al. 2014; De Santis et al. 2016a, 2017b; Bellini and Mazzotti 2016; Olivito et al. 2016; Ghiassi et al. 2016; Razavizadeh et al. 2014; Malena and de Felice 2014; Bilotta et al. 2017; Carozzi et al. 2017; Caggegi et al. 2017; Leone et al. 2017; Lignola et al. 2017; Donnini and Corinaldesi 2017). In some cases, a double-lap double prism setup was used (Malena and de Felice 2014; De Santis 2017; Askouni and Papanicolaou 2016, 2017). Many composite systems have been investigated, including aramid, glass, basalt, carbon, PBO, and steel fabrics combined with cement-based, lime-based, and geopolymer mortar matrixes. FRCM/SRG systems have been applied to brick units, tuff blocks, and masonry prisms. The effect of substrate curvature has been investigated in the literature (Malena and de Felice 2014; De Santis 2017) through laboratory and field tests. The effects of bond between fabric and cement matrix of different processing methods (casting, pultrusion, and vacuum conditions) were investigated in Peled et al. (2006). Test outcomes provided information on the influence of the substrate type, matrix mechanical properties, fabric architecture, and presence of coating/preimpregnation. The impor-

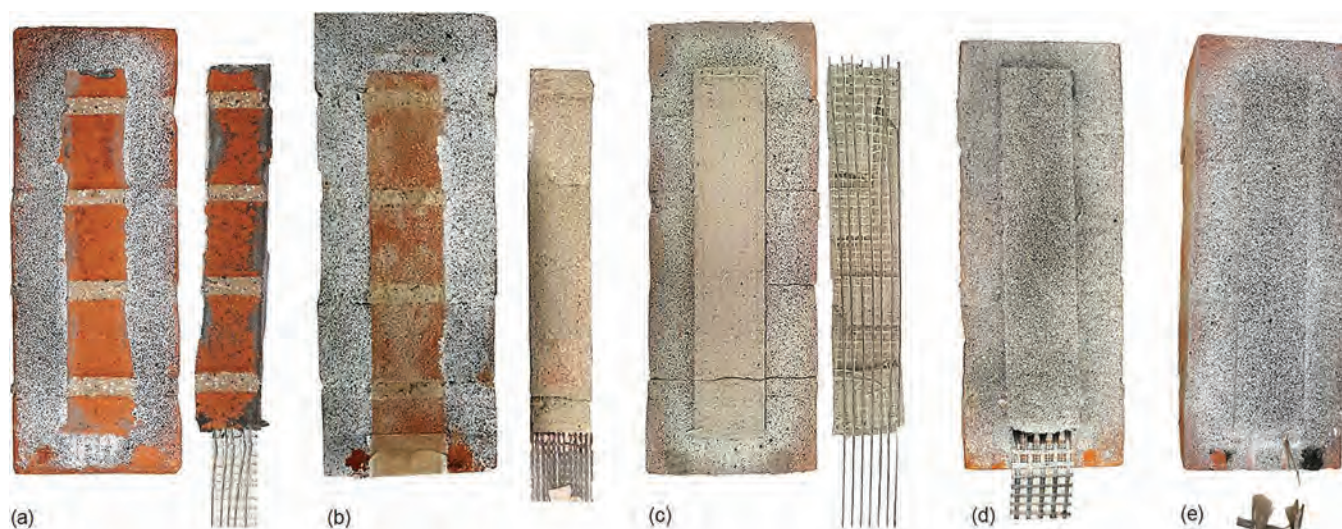


Fig. 3.3.2—FRCM/SRG-to-substrate failure modes (De Santis et al. 2017b).

tance of substrate surface preparation (artificial improvement of the roughness, consolidation, and application of adhesion promoters) and curing conditions of the mortar was highlighted. The effective bond length depends on substrate roughness, matrix tensile strength, and fabric-matrix bond behavior of the FRCM/SRG composite, but it is generally in the range of 8 to 10 in. (200 to 250 mm).

The possible failure modes (Fig. 3.3.2) include debonding with cohesive failure in the substrate, debonding at the composite-substrate interface, debonding at the fabric-matrix interface, slippage of the fabric within the mortar, and tensile rupture of the fabric. In the experimental investigations carried out thus far on the FRCM-to-substrate bond, cohesive debonding within the substrate (which typically takes place with FRP systems) occurred when a strong matrix is bonded to a relatively weak substrate. In some studies, the use of a stiff matrix may also have caused local stress concentrations and promoted this type of detachment that, once activated, instantly propagated to the entire bonded area. Detachment at the substrate-matrix interface took place on relatively smooth surfaces. It has been observed on clay brick substrates, whereas the uneven surface of masonry substrates generally inhibited this failure type. Nevertheless, it may still be caused by improper installation. Substrate preparation (removal of dust, wetting, improvement of surface roughness, and consolidation, if allowed when dealing with cultural heritage) and proper curing (in terms of humidity and temperature) of the mortar should therefore be ensured. Detachment at the fabric-matrix interface occurred with dense fabrics, in which mortar was not able to pass through the bundles of the fabric. Fabrics with sufficient grid spacing and matrixes with small grain size can control the fabric-matrix detachment. Relatively weak bond between fabric rovings and mortar may promote slippage failure. In this case, the stress-slip response generally shows a post-peak load decrease due to the progressive loss of friction of the fabric sliding within the mortar. Finally, FRCM/SRG systems comprising sparse fabrics of basalt or glass fabric failed by fabric rupture.

3.4—Strengthening of masonry

Extensive experimental results indicate that FRCM/SRG systems represent a viable solution for structural strengthening and seismic retrofit of masonry structures. Results in the literature are available for FRCM/SRG (comprising coated AR glass, bitumen-coated E-glass, basalt, greige carbon, PBO fabrics, and steel cords) composites to strengthen walls (under both in-plane and out-of-plane loads), columns (under centered and eccentric compression), and arched members (arches and vaults) made of concrete masonry units (CMUs), fired clay bricks, tuff blocks, and stone blocks.

3.4.1 Out-of-plane strengthening of walls—Numerous studies have investigated the out-of-plane behavior of masonry walls reinforced with fabric-reinforced mortars. Three- or four-point bending tests were carried out on medium-scale wall specimens, placed horizontally subjected to vertical monotonic and fatigue loads (Fig. 3.4.1a through

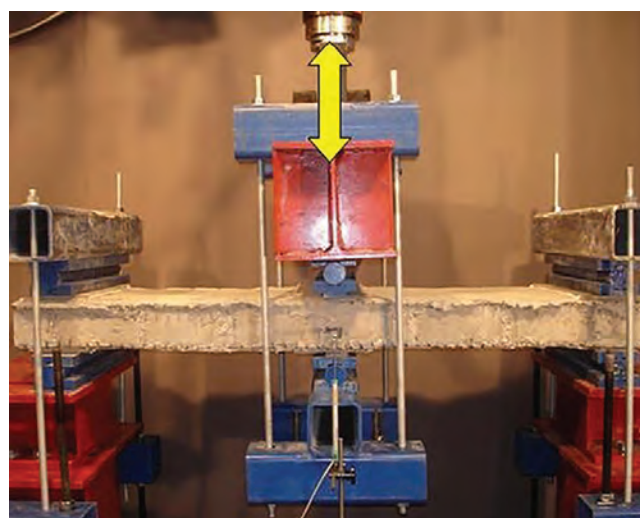


Fig. 3.4.1a—Experimental setup for three-point bending tests (Papanicolaou et al. 2011).

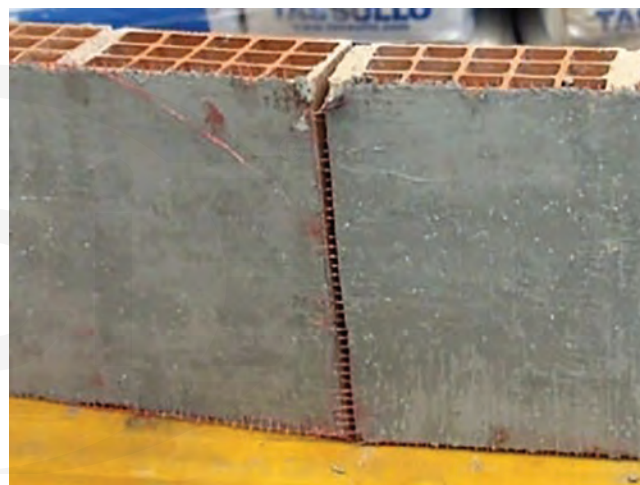


Fig. 3.4.1b—Failure by tensile rupture of the fabric (Valluzzi et al. 2014a).

3.4.1c). Among the tests performed with this setup, the reinforcement fabrics include carbon (Papanicolaou et al. 2008), steel, basalt, glass (Harajli et al. 2010; Papanicolaou et al. 2011; Valluzzi et al. 2014a), polypropylene, polyester (Papanicolaou et al. 2011), PBO, and PBO+glass (Carozzi et al. 2015). Fabrics were applied with either lime- or cement-based mortars (Harajli et al. 2010; Papanicolaou et al. 2008; 2011; Valluzzi et al. 2014a), which occasionally had short fibers (Papanicolaou et al. 2011) or polymeric additives (Carozzi et al. 2015).

Full-scale wall specimens reinforced with FRCM/SRG were tested by Babaeidarabad et al. (2014b,d), Bellini et al. (2016, 2017, 2018), and De Santis et al. (2016a). Two experimental investigations were carried out on full-scale walls made of clay bricks (Babaeidarabad et al. 2014b) or concrete masonry units (Babaeidarabad et al. 2014d), constrained on top (Fig. 3.4.1d and 3.4.1e). The specimens were reinforced with a bidirectional carbon FRCM/SRG and subjected to a uniform out-of-plane pressure applied with an air bag inducing vertical bending. A similar investigation is



Fig. 3.4.1c—Failure by slippage of the PBO fabric within the matrix, followed by the tensile rupture of the fabrics (Carozzi et al. 2015).



Fig. 3.4.1d—Crushing failure of the masonry panel reinforced with carbon FRCM/SRG (Babaeidarabad et al. 2014a).

described in Bellini et al. (2016, 2017, 2018) in which full-scale clay brick wall specimens (constrained at top) were subjected to a constant vertical (axial) load and a cyclic horizontal load (Fig. 3.4.1f). FRCM/SRG and SRG composites under investigation were four different bidirectional glass fabrics and a unidirectional steel fabric, all with a lime-based mortar. The strengthening schemes were full coverage of the specimen surface (in the case of glass fabrics) and vertical strips (in the case of the steel).

Moreover, two shake table tests were carried out on masonry walls reinforced with SRG subjected to out-of-



Fig. 3.4.1e—Failure by fabric slippage in the CMU wall panel (Babaeidarabad et al., 2014b).

plane seismic actions (Fig. 3.4.1g). One test was conducted on a full-scale tuff masonry U-shaped assembly, made out of a façade and two transverse walls (De Santis et al. 2016a). Another study was performed on two full-scale wall specimens, one made of two leaves of rubble stones and one of regular tuff blocks (De Santis et al. 2018b). The experimental studies concluded that FRCM/SRG composites with carbon and steel fabrics increased the unreinforced wall strength up to 15 times. Basalt, glass, and plaster, on the other hand, improved the wall displacement capacity up to 20 to 30 times. The out-of-plane (horizontal or vertical) bending performance of the wall specimens was improved by the EB FRCM/SRG composites. Complete overturning was effectively constrained by the combined use of connectors and composite strips. Dynamic tests on the shake table also showed that the reinforcement entailed a small modification of the dynamic properties of the wall and limited progressive damage accumulation (De Santis et al. 2016a). In most cases, failure occurred by FRCM/SRG tensile rupture (Fig. 3.4.1b), detachment from the substrate, and slippage of the fabric within the matrix (Fig. 3.4.1c). The use of composite reinforcement comprising multiple plies of fabric led to an increase in strength, but not directly proportional to the case of single ply. The multiply configurations resulted in a reduction of deflection, and in the occurrence of shear or crushing failure in the substrate (Papanicolaou et al. 2011; Babaeidarabad et al. 2014b,d).

Masonry crowning-beams reinforced with FRCM/SRG are built (generally on top) to improve the connection between adjacent orthogonal walls, to increase the flexural capacity of the wall, and to prevent overturning or bending failure under out-of-plane loads. They consist of top beams built on top of existing walls that include tensile resistant fabrics in the bed joints. The in-plane and out-of-plane (planes parallel and perpendicular to the masonry wall) behavior of masonry crowning-beams rein-

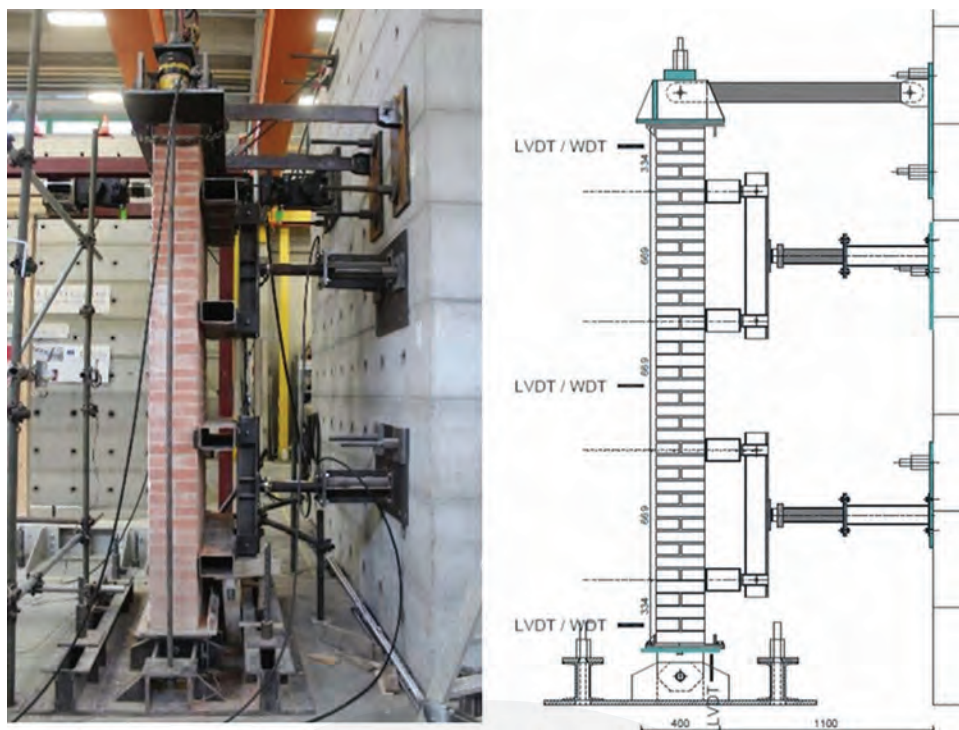


Fig. 3.4.1f—Experimental setup for tests on full-scale specimens under axial load and out-of-plane load (Bellini et al. 2016).



Fig. 3.4.1g—Shake table tests on masonry sub-assembly reinforced with SRG (De Santis et al. 2016a).

forced with FRCC/SRG composites have been studied (Borri et al. 2009b; Sisti et al. 2016). Three- or four-point bending tests with simply supported end conditions were carried out on full-scale bond beam specimens under monotonic and cyclic loadings (Fig. 3.4.1i). The fabrics used in these studies include glass, steel, and PBO+glass. Fabrics were applied with either cement-based mortars (Borri et al.

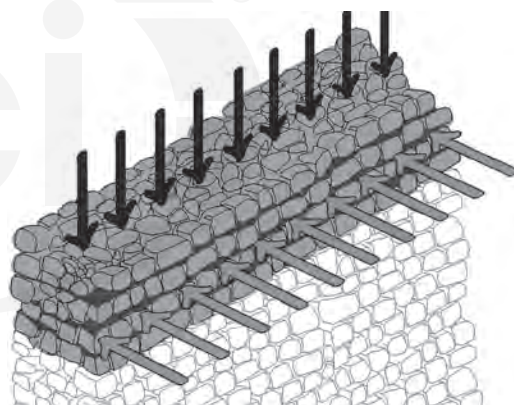


Fig. 3.4.1h—Direction of bending load: parallel and perpendicular to the reinforcement (Sisti et al. 2016).

2009b; Sisti et al. 2016) or lime-based mortars (Sisti et al. 2016).

Test outcomes indicated that the fabrics embedded in the bed joints provided a significant bending strength to the bond beams under in-plane and out-of-plane loads, particularly when the glass fabric was used. Specimens strengthened with PBO fabric exhibited large deflections and joint mortar cracking before the FRCC/SRG systems started to contribute to the flexural response. The experimental and analytical results (Fig. 3.4.1j) were compared for the evaluation of the ultimate flexural strength of the bond beam. For most of the tests, the analytical estimation of the bending capacity was in good agreement with the experimental data.

3.4.2 In-plane strengthening of walls—Marshall (2002), Mobasher et al. (2007a), and Aldea et al. (2007) studied in-plane shear performance of the full-scale masonry piers (lightly reinforced single-void masonry walls). The glass

FRCM system was compared with numerous commercially available FRP systems in different configurations. The studies were part of a broad experimental program that aimed to: a) assess the effectiveness of novel technologies in improving masonry seismic strength; and b) to improve wall performance by limiting deflection of the wall, as required by acceptance criteria for new or nonstandard materials for earthquake design. The FRCM system was applied on one



Fig. 3.4.1i—Experimental setup for four-point bending tests (Borri et al. 2009b).

side of the CMU wall (full coverage). The FRCM system added 38 to 57 percent to the shear strength and 29 to 44 percent to horizontal ultimate displacement capacity. In the FRCM-strengthened CMU walls, failures were due to shear between the front and rear faces of the blocks, with no delamination of the inorganic system from the CMU wall while holding the masonry pier together at failure.

The in-plane behavior of tuff, brick, autoclaved aerated concrete (AAC), and stone masonry walls reinforced with FRCM/SRG has been investigated in a number of studies (Faella et al. 2004; Prota et al. 2006; Papanicolaou et al. 2007; Faella et al. 2010; Papanicolaou et al. 2011; Lignola et al. 2012; Parisi et al. 2013; Babaeidarabad et al. 2014a,c; Kaluža et al. 2014; Babaeidarabad and Nanni 2015; Garofano et al. 2016; Mazzotti et al. 2016; Marcari et al. 2017; Ismail et al. 2017) in which diagonal compression tests were used. Diagonal compression (Calderini et al. 2010) and shear-compression tests are commonly used to evaluate the shear strength of masonry walls.

The FRCM system assessed by Prota et al. (2006) by means of diagonal compression tests on tuff panels was also validated on a two-story building subjected to dynamic tests on a shake table (Langone et al. 2006). In Pinho et al. (2014), the combination of glass FRCM with steel ties through the thickness of the wall was studied as a strengthening solution for rubble stone masonry. In the study of Balsamo et al. (2010), the strengthening system was specifically conceived to develop sustainable and reversible strengthening strate-

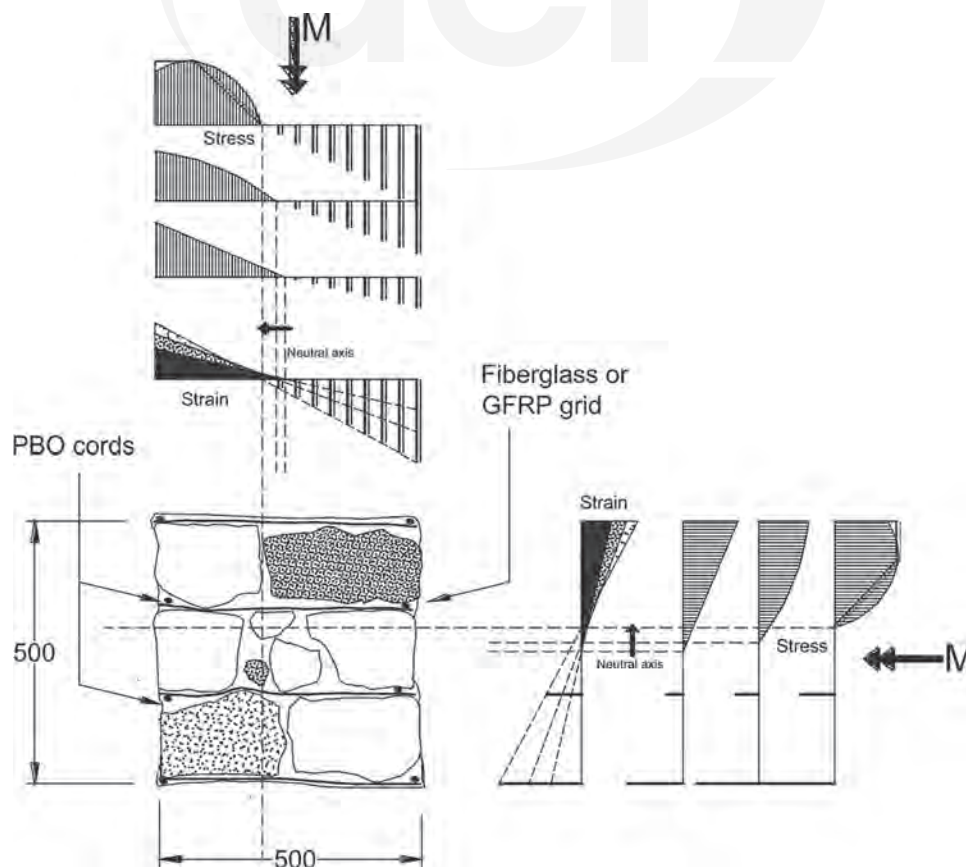


Fig. 3.4.1j—Example of constitutive behavior of masonry adopted in the analytical formulation (Sisti et al. 2016).

gies. A mortar with mechanical properties and porosity similar to mortars used in the existing historical buildings was formulated and combined with a basalt fabric. Experimental results showed that, for the test conditions of this study (including setup and substrate wall), a higher shear strength increase was achieved on specimens reinforced with AR-glass FRCM, and a better post-peak response was attained with the basalt FRCM. The study confirmed the effectiveness of FRCM composites in increasing the shear strength (by up to 3.4 times) and validated the use of a mortar specifically formulated for compatibility with existing masonry.

Augenti et al. (2011) applied a glass FRCM to a full-scale tuff masonry wall with an opening, which was tested under cyclic in-plane lateral loading up to near collapse. First, the monotonically increasing lateral displacement was induced on the unstrengthened masonry wall until the occurrence of diagonal shear cracks. The FRCM was then applied on both sides of the spandrel, and the specimen was tested under cyclic loading to assess the energy dissipation capacity of the strengthened spandrel. The failure mode of the FRCM-strengthened spandrel was changed from brittle diagonal shear cracking to ductile horizontal uniform cracking and the applied lateral load was increased by 17 percent.

From the experimental results, the increase in terms of shear strength of strengthened specimens ranged between 40 and 500 percent, the increase in terms of ductility ranged between 110 and 450 percent, and the increase in terms of stiffness ranged between 40 and 90 percent. The gain in strength, deformation capacity, and stiffness was more pronounced for weaker masonry substrates and depended on the amount of FRCM/SRG reinforcement. Glass and basalt FRCM systems were more efficient reinforcements than carbon ones due to the larger deformability (Prota et al. 2006). The stress distribution of the FRCM strengthened walls was improved, and a wider surface of the wall was engaged to carry the stresses (Fig. 3.4.2a and 3.4.2b). Studies observed that a diffused cracking phenomenon occurs in the FRCM/SRG-strengthened walls, instead of the typical concentrated cracks (Cascardi et al. 2016).

The effectiveness of the reinforcement is higher if it is installed to both sides of the wall rather than to only one side. The gain in terms of the strength was 1.9 and 3.1 times with respect to the unreinforced specimens and the gain in terms of the ductility was 1.1 and 2.3 in case of application to one side or both sides of the wall, respectively (Parisi et al. 2013; Babaeidarabad et al. 2014a; Marcari et al. 2017). Proper connection between the two sides of the wall on which the FRCM/SRG system is installed is also crucial (Papanicolaou et al. 2011), particularly when the failure mode is debonding of FRCM/SRG from the substrate (Faella et al. 2004; Triller et al. 2017).

The failure modes of the FRCM/SRG-strengthened masonry walls subject to the in-plane loads were slippage of the fabric within the matrix (for carbon or steel fabrics), tensile rupture of the fabrics (for basalt or glass fabrics), and crushing of the substrate. The last failure mode was observed when high FRCM/SRG reinforcement ratios were



Fig. 3.4.2a—Shear failure by diagonal cracking of a tuff masonry panel reinforced with a basalt FRCM/SRG (Parisi et al. 2013).



Fig. 3.4.2b—Crushing of the masonry panel reinforced with a carbon FRCM/SRG (Babaeidarabad et al. 2014a).

used, so the ultimate capacity was governed by the compressive strength of the masonry. In such a way, further increase of reinforcement would be ineffective (Babaeidarabad et al. 2014a,c).

Experimental tests on masonry panels reinforced with FRCM composites under cyclic in-plane loads (Triller et al. 2017) have shown that the increase in ultimate shear strength is associated with a significant increase of displacement capacity (improved by more than three times in this study) and amplitude of hysteretic cycles, whereas the elastic stiffness was basically unchanged, indicating that FRCM systems can be effectively used for the seismic retrofitting of existing masonry structures.

Based on the design approaches still adopted for the FRP strengthening of masonry shear walls (ACI 440.7R), several models have been proposed in the literature for the evaluation of the in-plane strength of masonry walls reinforced with FRCM/SRG systems. Typical FRP-strengthening schemes involve discrete unidirectional strips oriented as a grid or installed along the diagonals of the panel (when the flexural loads are negligible). The contribution of FRCM/SRG to the shear strength in the case of diagonal strips can be determined as the horizontal component of strips in tension (Prota et al. 2008).

The models, which are primarily based on the truss analogy, assume that the total in-plane shear strength of a strengthened panel is equal to the sum of the contributions of the masonry substrate and strengthening system (Babaeidabad et al. 2014a,c). The contribution of the masonry substrate is assumed equal to the in-plane shear strength of a URM panel, whereas the contribution of strengthening system depends on the failure mode (rupture or debonding) and on the anchorage length. The shear capacity can be evaluated by means of the equilibrium of a strut-and-tie model.

3.4.3 Confinement and flexural strengthening of columns—
A limited number of experimental investigations have been

carried out on masonry columns wrapped with FRCM/SRG systems comprising carbon (Ombres 2014); basalt (Fossetti and Minafò 2016; Monni et al. 2016), PBO (Carlioni et al. 2014), or steel (Sneed et al. 2017, 2018) fabrics (Fig. 3.4.3a and 3.4.3b). Specimens were subjected to either centered (Fossetti and Minafò 2016; Carlioni et al. 2014; Monni et al. 2016; Sneed et al. 2017, 2018) or eccentric (Ombres 2014) axial load. Test results showed that the load-carrying capacity could be even doubled with respect to unconfined columns, while both the vertical and lateral displacements were increased by up to 200 percent. The effectiveness of the confinement increases with the number of fabric layers, but not proportionally. FRCM/SRG systems modify the failure mode of the column, the development of several vertical cracks being replaced by the failure of the FRCM/SRG either at the overlap or by tensile rupture of the filaments followed by the crushing of the inner masonry.

The reported test data (Di Ludovico et al. 2008; Yilmaz et al. 2013; Ombres 2014; Carlioni et al. 2014; Incerti et al. 2015; Krevaiakas 2015; Guler and Ashour 2016; Fossetti and Minafò 2016; Mezrea et al. 2017; Witzany and Zigler 2016; Maddaloni et al. 2017; Sneed et al. 2017, 2018) show analogous behavior independently from the size of the samples. In terms of collapse mode, the FRCM/SRG failure often occurred due to a corner-effect in square/rectangular cross sections, which causes the rupture of the confining system. As for the FRCM/SRG-confining action, experimental evidence indicates that it is affected not only by the properties of the fabrics but also by those of the matrix: given the same reinforcement equivalent thickness, the use of a high-strength fabric combined with a weak mortar matrix may reduce the confining effectiveness because of the premature cracking of the mortar. Conversely, when a high-performance matrix is used in combination with a fabric with low Young's modulus, a significant confining effectiveness may be reached.

An analysis-oriented model has been proposed in Cascardi et al. (2017a) in order to evaluate the stress-strain relation-



Fig. 3.4.3a—Failure by tensile rupture of the basalt FRCM and crushing of the confined column (Fossetti et al. 2016).



Fig. 3.4.3b—Installation of a carbon FRCM for confining a masonry column (Ombres et al. 2014).

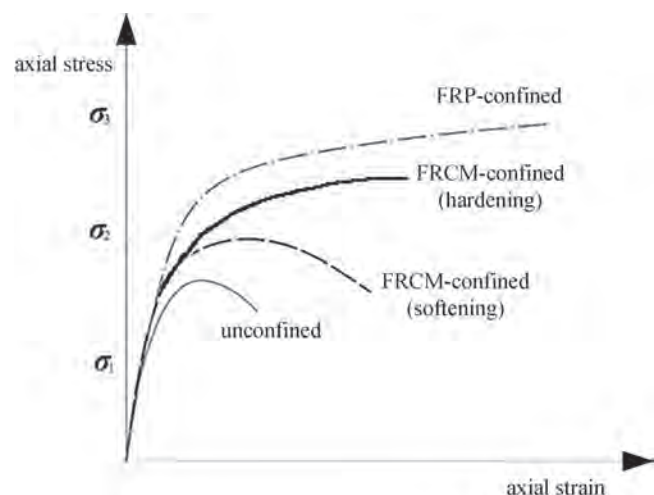


Fig. 3.4.3c—Qualitative axial stress-strain behavior of unconfined, FRCM/SRG-confined, and FRP-confined columns.

ship for a FRCM/SRG confined masonry column. Unlike the FRP (Cascardi et al. 2017c), the stress-strain curves of FRCM/SRG confined masonry columns do not always display hardening behavior but may also display a softening branch, as illustrated in Fig. 3.4.3c. For design purposes, the behavior of FRCM/SRG material can be assumed to be bilinear (Fig. 3.4.3d).

3.4.4 Strengthening of arches and vaults—Composite materials contribute to increase the load and displacement capacity (Triantafillou 1998), even in case of thin sections or complex configurations (Valluzzi et al. 2014b; Castori et al. 2016). A representative selection of comprehensive laboratory experimental research is summarized in the following and represented in Fig. 3.4.4a through 3.4.4c.

In the study of Girardello et al. (2013), six-barrel brick masonry vaults were tested in laboratory under cyclic vertical loads applied symmetrically at each quarter of the span. Specimens reinforced with SRG strips and basalt FRCM (covering the entire surface) were compared with the reference (unstrengthened) ones. In case of SRG, results showed a change in failure mode from the typical brittle rigid block mechanism into the sliding at the brick-to-mortar joint close to the applied force. The overall deformation was improved and the ultimate strength was increased almost 10 times with respect to the unstrengthened specimens. In case of basalt FRCM, failure mode was rupture of fabrics followed by separation of the vault into blocks. However, the ultimate capacity was improved more than eight times with respect to the unstrengthened specimens.

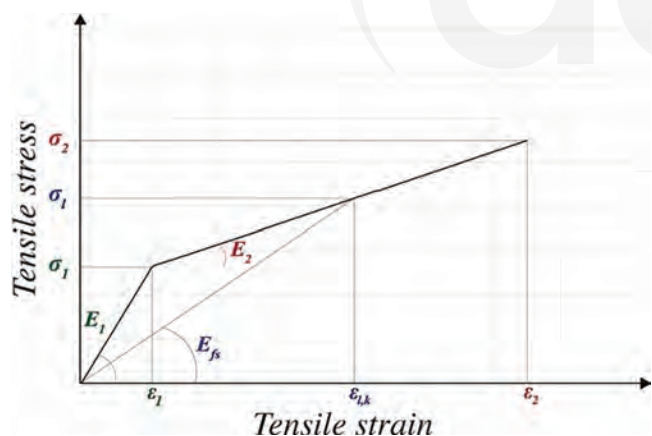


Fig. 3.4.3d—Tensile behavior of the FRCM/SRG-system.

Hojdys and Krajewski (2014b) performed monotonic tests on barrel vaults strengthened at their extrados with strips of carbon and glass FRCM systems. Results showed that failure mode depended on the reinforcement type and ratio: after cracking of the mortar joints (which were reflected in the FRCM), the specimen strengthened with glass FRCM failed due to fabric rupture, while the slippage of the fabric along a mortar joint was observed in case of carbon FRCM-strengthened specimen. Ultimate capacity was increased almost six times for glass FRCM/SRG and eight times for carbon FRCM-strengthened specimens. In both cases, the FRCM controlled crack propagation.

Garmendia et al. (2011) tested six stone masonry arches under monotonic loading applied at each quarter of the span. Three of the arches were strengthened at the extrados with a double layer of basalt FRCM. The FRCM delayed the formation of hinges at the intrados, and the failure occurred by fabric rupture (and consequent rigid-block mechanism), debonding of the FRCM from the substrate, or crushing of the masonry. Increase in terms of ultimate capacity was recorded up to 10 times higher with respect to the unstrengthened specimens. In Garmendia et al. (2014), an additional six arches were tested—three of them were strengthened only at their intrados and the remaining three at both intrados and extrados. In the case of strengthening only at the intrados, collapse was due to combination of sliding of the voussoir and debonding of the reinforcing system from the substrate. In the case of strengthening on both surfaces (intrados and extrados), tests showed better results in terms of ultimate capacity, and the failure mode was crushing of the voussoir. Combining the results of the joint studies, specimens strengthened at their extrados had the best performance in terms of displacement capacity, while those strengthened at both sides achieved the highest ultimate capacity. In Garmendia et al. (2015), basalt FRCM and SRG were applied on brick masonry barrel vaults with a hydraulic-lime based matrix. Comparing the results of basalt FRCM with SRG, similar results in terms of ultimate capacity increase (approximately five times higher than the unstrengthened specimens) and failure mode (both exhibited a final mechanism) were observed, but the SRG allowed much higher displacements at keystone than FRCM.

Alecci et al. (2016b) tested 1:2-scale brick masonry arches strengthened at the extrados with PBO FRCM under mono-

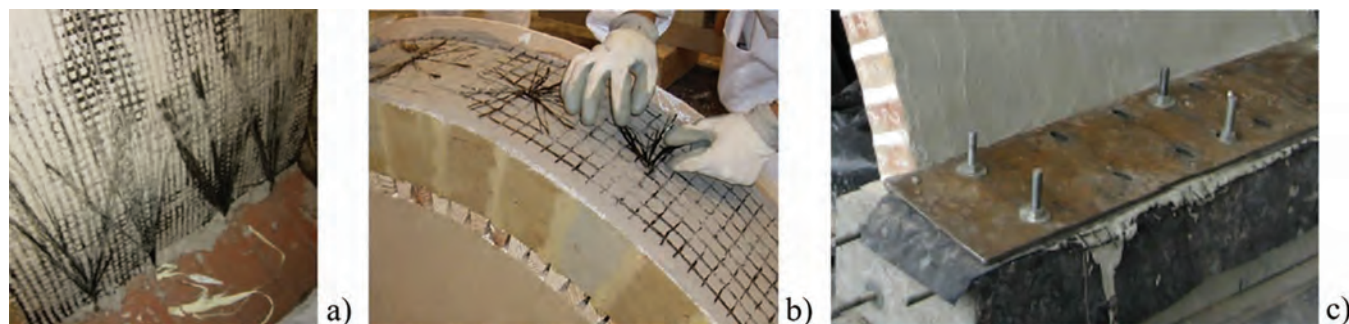


Fig. 3.4.4a—Detail of anchors: (a) connectors placed at ends (Girardello et al. 2013); (b) along fabric distribution (Garmendia et al. 2011); and (c) anchoring with metal plates (Hojdys and Krajewski 2014a).

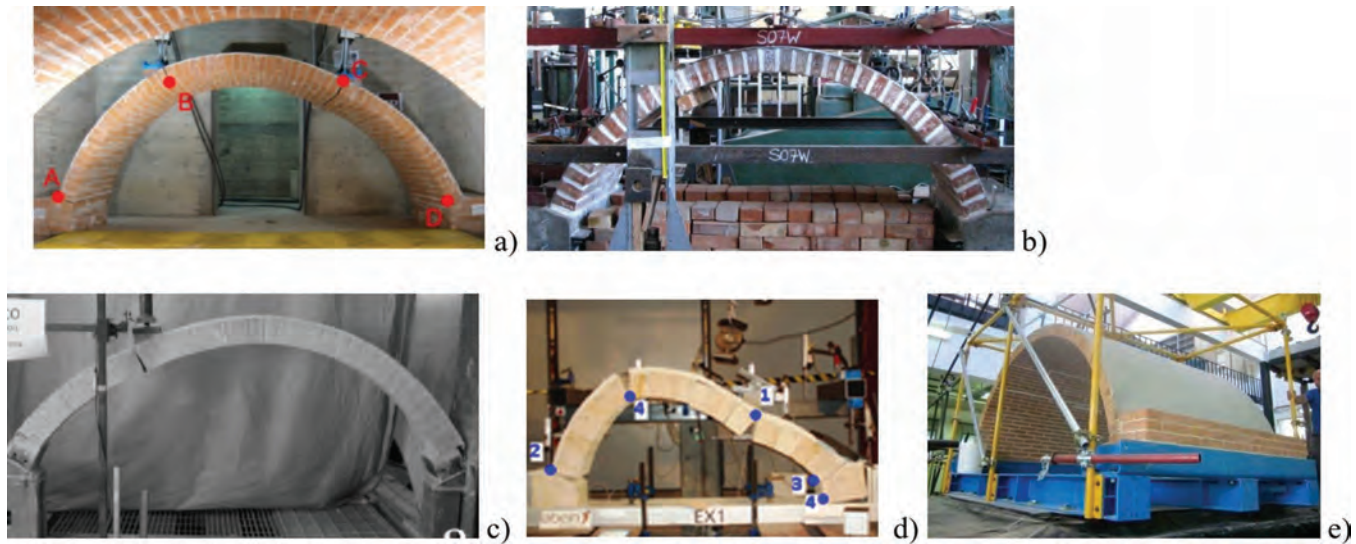


Fig. 3.4.4b—Test setups applied to strengthened arch/vault specimens: (a) cyclic tests (Girardello et al. 2013); (b), (c), and (d) monotonic tests (Hojdys and Krajewski [2014a]; Alecci et al. [2017a]; Garmendia et al. [2011], respectively); and (e) dynamic tests (Giamundo et al. 2016).

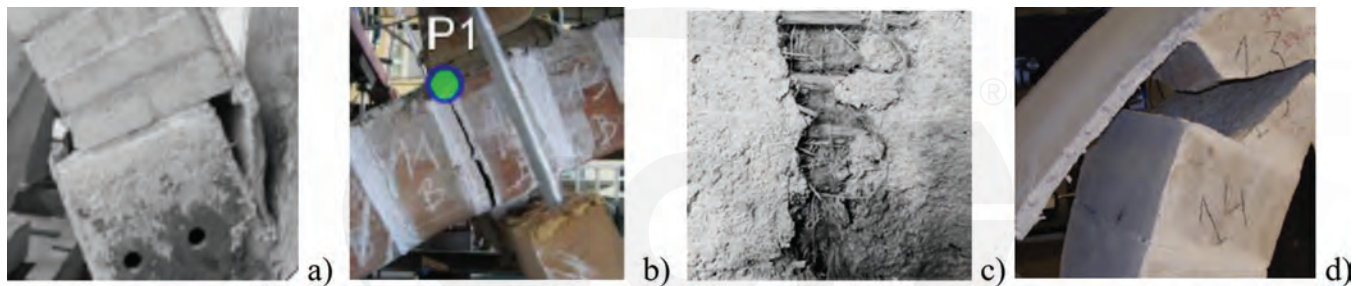


Fig. 3.4.4c—Localized failure detected on strengthened specimens: (a) sliding at abutments (Alecci et al. 2016b); (b) plastic hinge rotation (Hojdys and Krajewski 2014a); (c) matrix failure (Alecci et al. 2017b); and (d) matrix detachment (Garmendia et al. 2011).

tonic load applied at a quarter of the span. Ultimate strength, stiffness, and displacement capacity increased approximately 8, 2, and 15 times, respectively. The failure mode was sliding and rotation at the abutments and consequent debonding of the composite system from the substrate. In Alecci et al. (2017a), the study also included a basalt FRCM with lime-based mortar. Hinge formation was forewarned by preliminary cracking of the matrix, and the failure was due to slipping of the fabric until failure, which occurred without debonding at mortar-substrate interface. Peak load and displacement were increased approximately 5 and 20 times, respectively. The performance of PBO FRCM strengthened arch was compared with unreinforced specimens and arches strengthened with carbon FRCM (Alecci et al. 2017b). Although carbon FRCM/SRG exhibited a maximum load 1.3 times higher than that of PBO FRCM, applications with PBO can be considered more effective, as its reinforcement ratio was more than three times lower compared to carbon. In both cases, the debonding of the FRCM and the subsequent failure of masonry close to the loaded section were observed.

In De Santis et al. (2017, 2018b) laboratory tests on full-scale specimens of brick vaults provided with buttress walls

and fill were performed before and after retrofitting with SRG or basalt FRCM composites, which were applied either at the extrados or at the intrados. Test outcomes showed the effectiveness of the strengthening systems investigated in enhancing both the ultimate strength and displacement capacity as well as the important role played by mechanical connectors, which were installed in the abutments for extrados reinforcements and along the arch barrel for the SRG intrados one to delay end debonding and intermediate debonding, respectively.

Shake table tests were carried out on barrel brick masonry vaults retrofitted with basalt FRCM after preliminary damage, with a combination of localized repointing and grouting. The FRCM was applied on the entire extrados surface (Giamundo et al. 2015, 2016; Ramaglia et al. 2017). Results obtained after intervention showed an increase of the peak acceleration up to 2.5 times, corresponding to the same displacement achieved before retrofitting, and less steep variations for both natural frequency decay (increase) and damping ratio (decrease). Slight damage occurred at high load capacity (PGA of approximately 12 m/s^2), resulting in both minor stiffening and significant capacity increase with a minimal added mass.

3.4.5 Elevated temperature performance—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 affect the tenability conditions in a building during the early stages of a fire. Fabric-reinforced cementitious matrix systems exhibit a good performance in terms of fire response, if compared to FRPs, as the inorganic matrix is inherently noncombustible, nontoxic, and nonflaming (Maroudas and Papanicolaou 2017; Tlaji et al. 2018). Nevertheless, the deterioration of the mechanical properties of the constituent materials should be carefully considered in the design of the strengthened structural member exposed to fire and reference should be made to the general building code to satisfy fire provisions.

Performance of FRCM exposed to elevated temperatures in tension and bending was studied (Kulas et al. 2011; Colombo et al. 2011; Triantafillou et al. 2017). The effect of high temperatures on the bond performance of FRCM/SRG composite materials applied to masonry substrates has been investigated (Maroudas and Papanicolaou 2017; Triantafillou et al. 2017), highlighting that the performance of FRCM-reinforced masonry structures may strongly depend upon the fiber material of the fabric, presence of coating, and matrix composition. Research aimed at comparing the performance of members strengthened with an FRCM system against FRP systems was performed (Bisby et al. 2009, 2011) to investigate the idea that FRCM can provide retention of mechanical and bond properties at elevated temperatures. Steady-state flexural tests were performed on commercially available FRCM-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, indicating that they may be considered an attractive option for fire-safe structural strengthening. Another appealing application of FRCM can be in warm climates or industrial environments. Additional tests are needed to define upper service temperature limits for FRCM. Very limited literature exists on the performance of SRG under elevated temperature, which suggests ensuring a suitable protection to the steel cords/wires if exposure to elevated temperatures is expected.

3.5—Examples of commercially available FRCM/SRG systems

Numerous FRCM/SRG systems are currently commercially available. Aiming at providing an overview of the main properties of the existing FRCM/SRG composites, this section collects information on some representative FRCM systems, most of which were tested within a round robin test initiative organized in 2016–2017 by the RILEM Technical Committee 250-CSM (de Felice et al. 2018a) Composites for the Sustainable strengthening of Masonry, involving 19 research institution and 11 industrial suppliers (de Felice et al. 2018a; Lignola et al. 2017; Carozzi et al. 2017; Leone et al. 2017; Caggegi et al. 2017; De Santis et al. 2017b). A total of 30 FRCM/SRG composites were investigated, covering the most common systems for the strengthening of masonry

structural members. Table 3.5 collects the main properties of the FRCM/SRG systems tested within this experimental activity. Each system is identified by a letter (A for aramid, B for basalt, C for carbon, G for glass, P for PBO, and S for steel) and a progressive number. The geometric properties (surface mass density γ_s , design thickness t_f , grid spacing i) and the mechanical properties provided by technical data sheets (tensile strength f_t and tensile modulus of elasticity E_t) are listed for the fabrics, which are also shown in Fig. 3.5a through 3.5e. As for the matrixes, the table collects the compressive strength $f_{c,mat}$ and the Young's modulus in compression E_{mat} (from technical data sheet).

Within the round robin test, direct tensile tests on bare fabric specimens and on FRCM/SRG coupons were carried out with a clamping grip setup. Shear bond tests on brick masonry prisms manufactured with clay bricks (having 15 MPa [2176 psi] compressive strength and 5.8 GPa [841 ksi] Young's modulus) and lime-based mortar (having 5 MPa compressive strength) were carried out as well. Aiming at giving an overview of the different behavior of FRCM/SRG systems, Fig. 3.5f through 3.5h show the response curves of some FRCM/SRG systems tested within this investigation. Note that in the graphs of direct tensile tests on FRCM/SRG coupons and of shear bond tests the stress was calculated as the load divided by the cross-sectional area of the fabric.

Figure 3.5f shows that all bare textiles employed presented an elastic-brittle behavior, with elastic modulus ranging between 50 GPa (glass 25 x 25 mm) textile and 225 GPa (PBO 15 x 15 mm) (7252 and 32,634 ksi, respectively). The axial stress versus axial strain responses of corresponding FRCM and SRG coupons (Fig. 3.5g) show, in general, a trilinear behavior according to Fig. 3.3a. The behavior observed for the PBO FRCM is different from that of other materials due to the mechanical properties of the matrix employed, which cracked at an applied load associated to very high tensile stress in the fibers. This response was observed only in some PBO FRCM coupons, whereas the remaining specimens, not reported for the sake of brevity, provided a trilinear stress-strain response (Caggegi et al. 2017).

Figure 3.5h shows the axial stress versus loaded end slip response curves of different FRCM composites, obtained from single-lap shear bond tests. The curves clearly differ in terms of stiffness, peak axial stress, and post-peak response, depending on fabric properties and architecture, matrix properties, and fabric-to-matrix interaction. Different failure modes were also exhibited by different FRCM systems. Because the bonded length plays an important role in the response obtained, the results depicted should be carefully compared. Details on the role of the bonded length and on the expected stress-slip response can be found in D'Antino et al. (2014).

It is worth noting that test outcomes may be affected by setup details; boundary conditions; manufacturing and curing; and fabric properties and architecture, matrix characteristics, and fabric-to-matrix interaction. The results presented in this section, therefore, cannot be considered representative of all possible FRCM systems but can be extrapolated to systems different from those included in the

Table 3.5—Properties of some commercially available FRCM/SRG systems*

Fabric material	System	Fabric properties						Matrix properties		
		γ_s , g/m ²	t_f , mm	i , mm	Notes	f_b , MPa	E_b , GPa	Type	$f_{c,mat}$, MPa	E_{mat} , GPa
Aramid	A1	51	0.033	—	Dry, uniaxial	3151	101	Lime	10	—
	A2	197	0.033	—	Dry, quadriaxial	3151	101	Lime	10	—
Basalt	B1	220	0.033	25 x 25	Coated	—	—	Cement	35	—
	B2	220	0.033	25 x 25	Coated	—	—	Pozzolan and lime	12	10
	B3	350	0.058	25 x 25	Coated	3200†	90†	Pozzolan and lime	15	—
	B4	250	0.039	6 x 6	Coated	1538	89	Cement	15	10
Carbon	C1	270	0.063	30 x 30	Coated	—	—	Pozzolan and lime	12	10
	C2	270	0.063	30 x 30	Coated	—	—	Cement	35	—
	C3	170	0.047	10 x 10	Dry	4800†	240†	Lime	6	—
	C4	168	0.047	10 x 10	Dry	4800†	240†	Fiber reinforced cement, polymers	20	7
	C5	200	0.048	15 x 15	Dry	2500	230	Cement	16	16
	C6	170	0.047	20 x 20	Coated	4700†	240†	Cement	25	15
	C7	280	0.157	15	Coated, uniaxial	2778	185	Cement	52	27
	C8	80	0.044	20 x 20	Coated	3000	200	Cement	52	27
Glass	G1	218	0.040	15 x 15	Coated	2100	84	Lime	10	—
	G2	300	0.06	12 x 12	Dry	1200	65	Lime	6	—
	G3	250	0.050	25 x 25	Coated	2000†	70†	Pozzolan and lime	15	—
	G4	250	0.031 warp 0.050 weft	15 x 18	Coated, with aramid bundles	1700 warp 1160 weft	90 warp 70 weft	Lime and geobinder	15	9
	G5	220	0.048 warp 0.062 weft	15 x 15	Dry	1300	65	Pozzolan and lime	18	16
	G7	190 warp 170 weft	0.056 warp 0.052 weft	17 x 12	Coated	1911 warp 1742 weft	45 warp 38 weft	Fiber reinforced, cement	22	7
	G8	225	0.035	25 x 25	Coated	1286	72	Pozzolan and lime	15	8
PBO	P1	44	0.014	15 x 15	Dry	5800†	270†	Fiber reinforced cement, polymers	20	7
Steel	S1	670	0.084	6.35	Galvanized steel cords, uniaxial	2800	190	Lime and geopolymer	15	9
	S2	670	0.084	6.35	Galvanized steel cords, Uniaxial	2800	190	Cement and geobinder	55	25
	S3	1500	0.188	3.18	Stainless steel cords, Uniaxial	2165	190	Pozzolan and lime	6	-
	S4	1057	0.138	5.0	Stainless steel ropes, Uniaxial	1522	200	Fiber reinforced cement, polymers	25	10

*Most of these systems were tested within a RILEM TC 250-CSM round robin test (de Felice et al. 2018a).

†Data referred to individual wire.

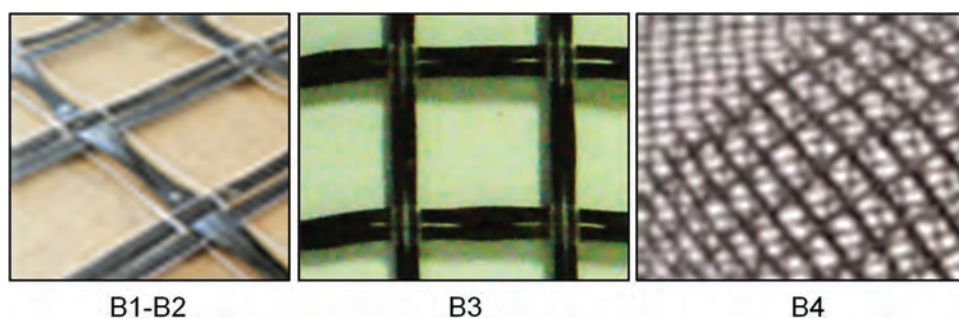


Fig. 3.5a—Basalt fabrics tested within a RILEM TC 250-CSM Round Robin Test.

RRT initiative. The FRCM properties reported are not to be directly used for design, but that acceptance parameters and corresponding design values need to be determined starting from test results, as clarified in Chapter 5.

CHAPTER 4—FIELD APPLICATION EXAMPLES

In the last decade, FRCM/SRG composite systems have been used for the static and seismic retrofitting of masonry walls, arches and vaults, as well as for the confinement

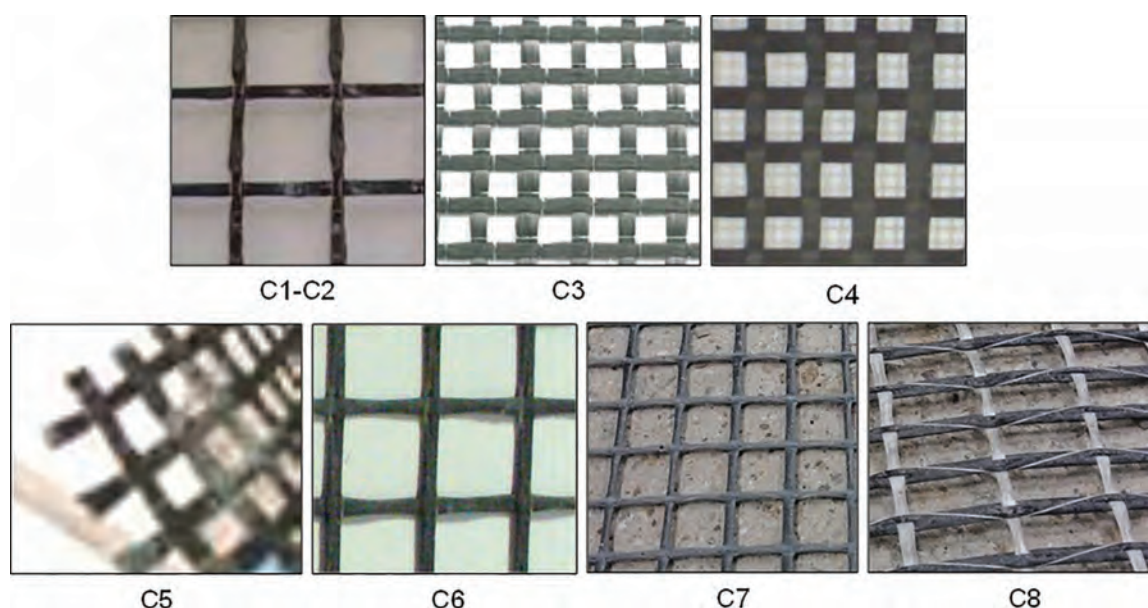


Fig. 3.5b—Carbon fabrics tested within a RILEM TC 250-CSM round robin test (C1 to C6) and other examples of commercially available carbon fabrics (C7 and C8).

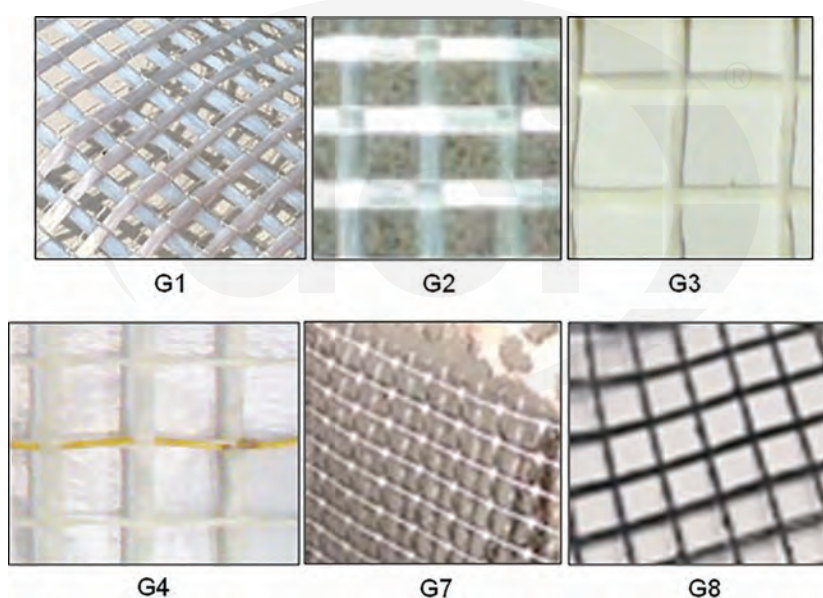


Fig. 3.5c—Glass fabrics tested within a RILEM TC 250-CSM round robin test.

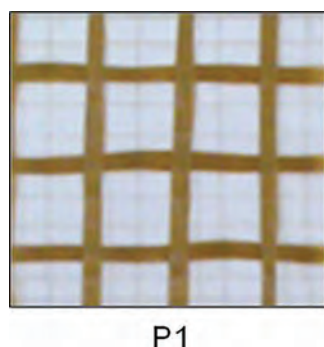


Fig. 3.5d—PBO fabric tested within a RILEM TC 250-CSM round robin test.

of masonry columns. In this section, several case studies provide evidence of FRCM/SRG potentials as a repair/strengthening technology for masonry structures.

4.1—Application procedure

Application procedures of FRCM/SRG composites are that they are commonly bonded to masonry structural elements by covering their entire surface (Fig. 4.1a) or by means of vertical or horizontal (or both) strips (Fig. 4.1b). The choice of the layout of the composite reinforcement depends upon the type of the element needing strengthening (Mantegazza et al. 2006), geometric and mechanical features of the FRCM/SRG (such as architecture and material of the fabric, type of mortar, tensile and bond strength, curing conditions), and the type of masonry making up the substrate

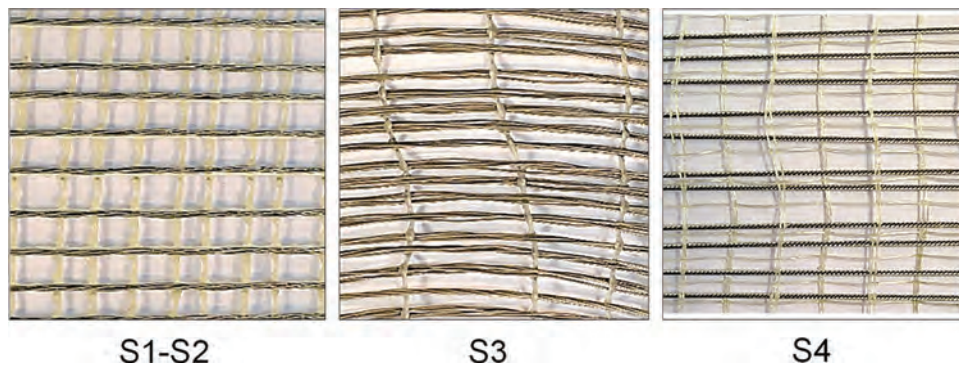


Fig. 3.5e—Steel fabrics tested within a RILEM TC 250-CSM round robin test.

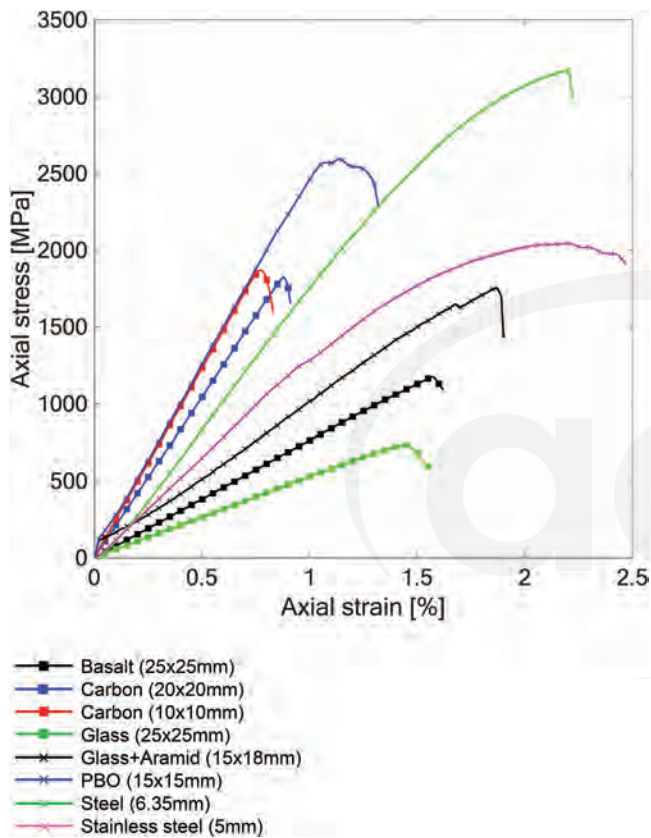


Fig. 3.5f—Axial stress-axial strain response curves of the fabrics tested within a RILEM TC 250-CSM round robin test (the curves are obtained as the average of five specimens tested in the same laboratory).

(for example, structures made up of weak rubble-stone masonry are typically reinforced by applying the FRM/ SRG systems to their entire surfaces, whereas in the case of regular blocks masonry, the strengthening system is bonded by means of discrete strips). Bidirectional fabrics made of glass, basalt, carbon, or polyparaphenylene benzobisoxazole (PBO) (either dry, coated, or impregnated) fabrics are typically applied covering the entire element surface, whereas unidirectional (either dry, such as stainless, or coated, such as galvanized) steel fabrics are installed by means of discrete strips. Furthermore, in the case of walls and arched structures, either only one side (intrados or extrados for arches and vaults) or both sides of the element can be reinforced,

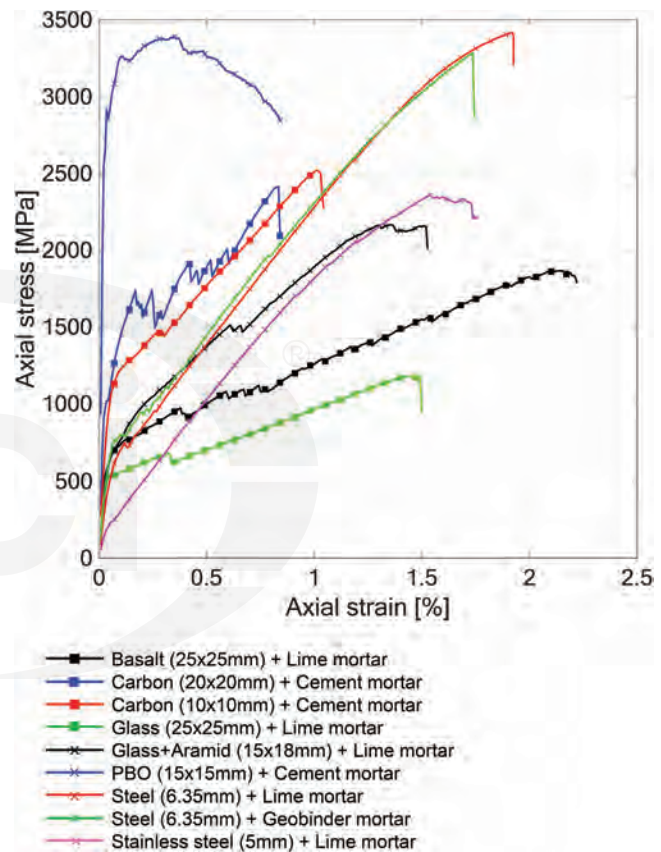


Fig. 3.5g—Axial stress-axial strain response curves of FRM/ SRG coupons tested within a RILEM TC 250-CSM round robin test (the curves are obtained as the average of five specimens tested in the same laboratory).

depending mainly on loading conditions (intensity and direction) and on the characteristics of the cross section of the element itself.

The application of an FRM/ SRG system should be executed very carefully because proper installation and adequate curing conditions for the mortar matrixes are crucial for the effectiveness of the strengthening work. The recommendations provided by the manufacturer should be followed carefully for FRM/ SRG installation. As a general indication, this latter is made according to the following steps. Once the existing plaster has been removed, the undamaged substrate should be carefully cleaned and prepared, taking

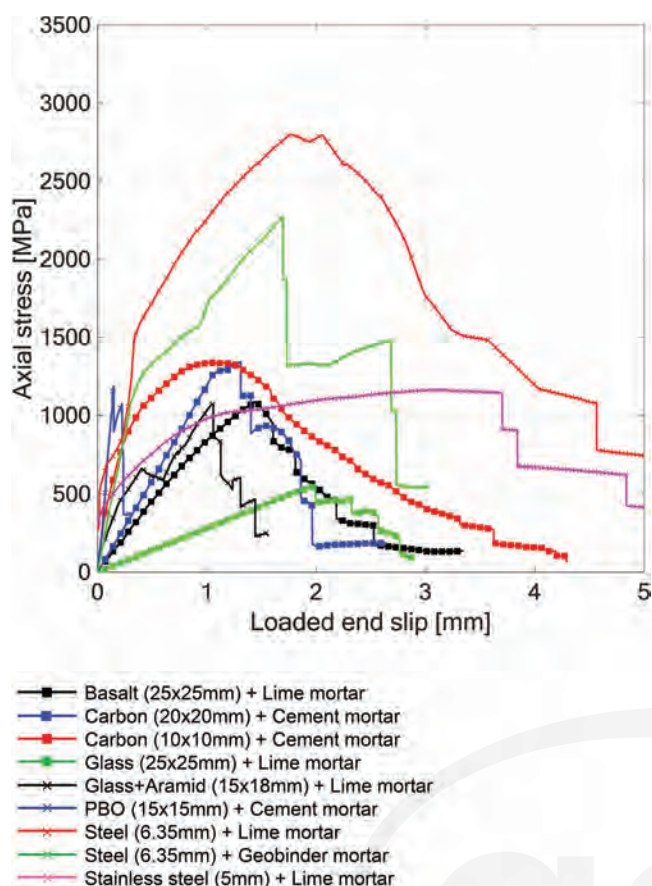


Fig. 3.5h—Axial stress-loaded end slip response curves of shear bond tests performed within a RILEM TC 250-CSM round robin test (the curves are obtained as the average of five specimens tested in the same laboratory).

away any dust or other things that could negatively influence the adhesion of the system.

If the substrate is damaged or uneven, it is typically necessary to improve the quality of masonry through grout injections or by replacing the damaged blocks with intact ones, or both, to remove any superficial residues, to restore mortar joints, and to artificially improve the roughness of the substrate's surface. Once the masonry surface is clean, a first layer of mortar (typically 0.12 to 0.2 in. [3 to 5 mm] thick) is spread by hand (Fig. 4.1a(a) and 4.1b(a)). While the matrix is still wet, the fabric is applied upon the first layer of mortar by pressing with a spreader (to ensure the embedment of the fabric itself within the matrix) (Fig. 4.1a(b) and 4.1b(b)) and then it is fully covered by a final protective smoothing (typically 0.12 in. [3 mm] thick) (Fig. 4.1a(e) and 4.1b(e)). This latter operation should be done making sure to give a constant thickness to the matrix. It must be noted that, during the embedding of the fabric, it is very important to check that the mortar comes out of the spaces between the fabric rovings in order to provide a better adhesion between the first and the second layer of mortar. In some instances, the mortar is applied by the shotcrete method for both the first mortar layer and the layer covering the fabric, after the fabric is applied over the first mortar layer. The same requirements for overall FRCM thickness apply.

The connection between the reinforcing system and the substrate could be commonly improved by using specific connectors (typically made up of fibers) inserted within the masonry just before the application of the final covering layer of mortar. If the reinforcement layout is made of discrete fabric strips, connectors are inserted in correspondence of the intersection between two transverse strips

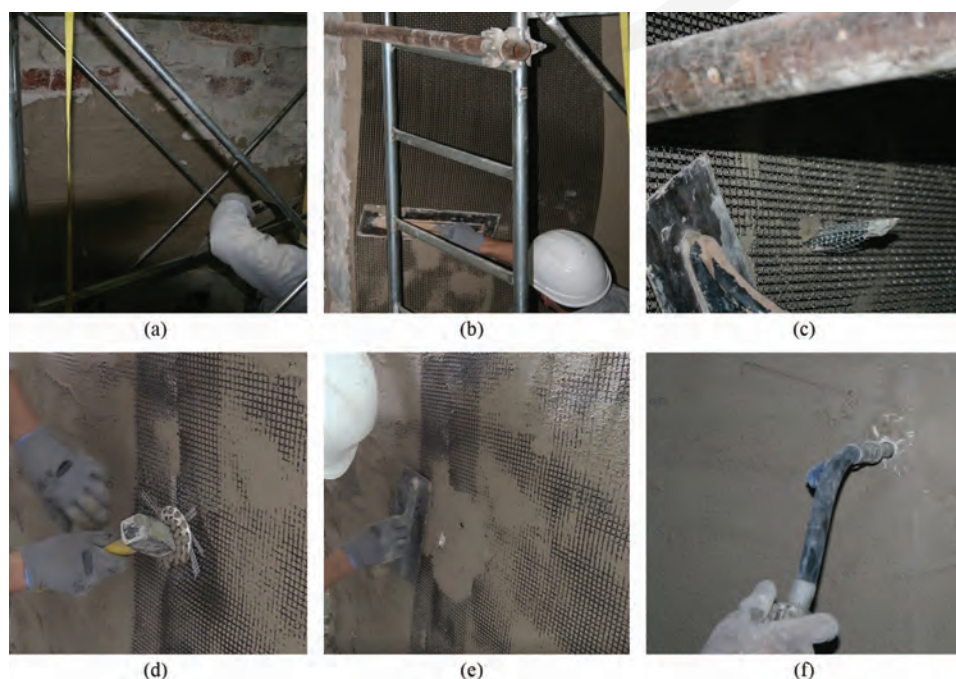


Fig. 4.1a—Application steps of a FRCM system (bidirectional fiber-basalt fabric within a lime-based mortar matrix) upon the entire surface of a masonry wall: (a) spreading of the first layer of mortar; (b) application of the fabric upon the first layer of mortar; (c) and (d) insertion of the steel connector; (e) spreading of the cover layer of mortar; and (f) injection of the grout within the connector.

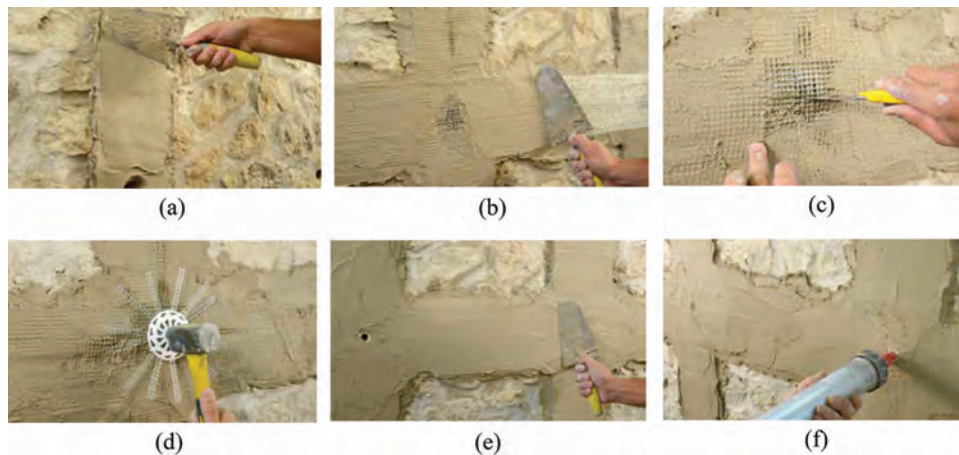


Fig. 4.1b—Application steps of a SRG system (unidirectional steel fabric within a lime-based mortar matrix) by means of discrete strips on the surface of a rubble stones masonry wall: (a) spreading of the first layer of mortar; (b) application of the fabric upon the first layer of mortar; (c) and (d) insertion of the steel connector; (e) spreading of the cover layer of mortar; (f) injection of the grout within the connector (courtesy of Kerakoll).



Fig. 4.2a—Strengthening of walls belonging to a damaged brick masonry building in Milan, Italy: (a) improving of the quality of masonry; and (b) application of the fabric (courtesy of TCS).

(Fig. 4.1b(c),(d), and (f)), whereas in the case of uniformly distributed reinforcement, they are installed with a specific spacing as in the design (Fig. 4.1a(c), (d), and (f)).

Other features, such as the anchorage and overlapping lengths and the spacing between the strips (in the case of discrete reinforcement), should be properly decided upon by the designer.

4.2—Strengthening of masonry walls

FRCM/SRG systems are applied, either for the in-plane and out-of-plane strengthening of load-bearing walls (refer to Chapters 7 and 8) or, more in general, for the seismic retrofitting of masonry buildings, preventing local collapse mechanisms (by means of reinforced bond beams, specific connectors, or FRCM/SRG external bond strips) (refer to Chapters 7 and 8).

As stated in Section 4.1, FRCM/SRGs are commonly bonded to masonry walls by covering their entire surface or by means of vertical or horizontal (or both) strips, following the application steps shown in Fig. 4.1a and 4.1b. Either only one side or both sides of the wall can be reinforced, depending mainly on loading conditions (intensity and

direction) and on the characteristics of the cross section of the wall itself. For instance, single-wythe walls loaded in one main direction (which rarely happens for earthquake loading but may be the case for wind) could be reinforced on one side only. Differently, applications to both sides and with transverse connectors appear preferable for multi-leaf/wythe walls, in which failure may occur by wythe separation, or for walls with low mechanical properties (for example, irregular rubble stone masonry with weak or deteriorated lime mortar), in which collapse may be due to disaggregation.

An application example of FRCM applied to the entire surface of a masonry wall for its in-plane and out-of-plane strengthening is shown in Fig. 4.2a, dealing with a retrofit intervention on a damaged brick masonry building in Milan, Italy. The system is made up of an unbalanced bidirectional fabric (0.6 x 0.4 in. [15 x 10 mm] and having a mass per unit area of 6.53 lb/ft² [275 g/m²]) of glass fabric (coated with an alkali-resistant [AR] material) applied to the wall through a lime-based mortar (Fig. 4.2a(a)). Helicoidal steel bars (embedded within a fluid hydraulic-lime grout) were also inserted into the wall to improve its quality (Fig. 4.2a(b)).



Fig. 4.2b—Retrofitting intervention with SRG on the application of unidirectional galvanized steel fabrics using lime based mortar and installation of mechanical connectors (courtesy of Kerakoll).

Figure 4.2b shows a consolidation intervention of an historical building in L'Aquila, Italy. The intervention deals with the in-plane and out-of-plane strengthening of rubble-stone masonry and tuff masonry load-bearing walls. The SRG composite system consists of a unidirectional steel fabric, made up of four galvanized steel cords per inch (4 cords per in. [1.57 cords per cm]) fixed to a fiberglass micro-fabric to facilitate installation, placed within a lime-based mortar layer (Fig. 4.2a(a)). The fabric has a total mass per unit area of 15.90 lb/ft² (670 g/m²) and an equivalent thickness of 0.0033 in. (0.084 mm). In this case, the reinforcement was applied on either the internal or the external face of the wall by means of both horizontal and vertical discrete strips (approximately 12 in. [300 mm] wide) arranged with a constant spacing (of approximately 1.1 yd [1 m]) (Fig. 4.2b(b)). The vertical strips were anchored below the base of the wall (not shown in the picture) to ensure the effectiveness of the reinforcement for the enhancement of the flexural strength under in-plane (lateral) loads. Moreover, to provide better adhesion between the reinforcement and the substrate and to create transverse connections within the wall, mechanical connectors made of steel fabric were inserted into the masonry at the intersection of the strips (Fig. 4.2b).

Another example of masonry walls reinforced with FRCM (against either in-plane or out-of-plane loads) is shown in Fig. 4.2c. The strengthening intervention was made in Casino Ciolina, an historical masonry building in L'Aquila,



Fig. 4.2c—Strengthening of masonry walls with FRCM, Casino Ciolina, L'Aquila, Italy: application of a bidirectional glass fabric with lime-based mortar and spreading of the last layer of mortar (courtesy of Cingoli).

Italy. The walls of the structure are made up mainly of a rubble-stone masonry, having a masonry pattern typical of the centre Italy's old buildings. Before the installation of the FRCM composite, injections with a lime-based grout were done to consolidate the masonry substrate. The strengthening system consists of a bidirectional fiberglass fabric (1 x 1 in. [25 x 25 mm]), embedded within a lime-based mortar layer.



Fig. 4.2d—Common solution for the FRCM-strengthening of masonry walls against in-plane loads, Italy. System used: bidirectional fiberglass fabric (1 x 1 in. [25 x 25 mm], 5.34 lb/ft² [225 g/m²] mass per unit area), embedded within an inorganic matrix (courtesy of Mapei).



Fig. 4.2e—Strengthening of a tuff masonry wall (Italy). System used: multi-axial aramid-fiber grid (4.27 lb/ft² [180 g/m²] mass per unit area), applied with a lime-based mortar (courtesy of Sacen).

The fabric has a mass per unit area of 5.34 lb/ft² (225 g/m²) and was applied through strips having a width of 1 yd (0.9 m). To guarantee the continuity of the reinforcement, the fabric strips were overlapped over a sufficient length.

The abovementioned reinforcing system was also applied to increase the in-plane strength of an internal load-bearing wall of a masonry building in Italy (refer to Fig. 4.2d). The consolidation intervention shown in Fig. 4.2d represents a solution commonly adopted to increase either the in-plane flexural or shear strength of masonry walls by using FRCM systems, in which the reinforcing system is bonded to the entire surface of the wall.

The layout pattern shown in Fig. 4.2d (FRCM/SRG systems applied to the entire surface of the wall) can be achieved by using fabrics of several types of materials, such as aramid and carbon (Fig. 4.2e and 4.2f).

The consolidation intervention illustrated in Fig. 4.2g consists in the seismic retrofitting of a damaged masonry building in San Marino, in which load-bearing walls were reinforced against either in-plane or out-of-plane actions. As regards the in-plane strengthening, discrete fabric strips were applied along the two diagonal of walls (Fig. 4.2g(a)), whereas to improve the out of plane flexural strength,

discrete vertical strips were bonded to the walls along the entire height of the structure (Fig. 4.2g(b)). External fabric bond strips were also applied at each floor level of the structure (Fig. 4.2g); this latter intervention is commonly used to protect old masonry buildings against local collapse mechanisms, improving the connection between orthogonal façade walls, preventing their overturning, and ensuring a global response of the structure under seismic actions. The SRG system applied for the intervention consists of a unidirectional galvanized ultra-high-strength steel fabric, made up of about 12.8 cords per in. (5 cords per cm), embedded within a pozzolan and cement mortar layer (Fig. 4.2g(c)). The fabric has a mass per unit area of 52.21 lb/ft² (2200 g/m²), a theoretical thickness of 0.0094 in. (0.24 mm) and is applied through strips 3.94 in. (100 mm) wide.

Another seismic retrofitting intervention of masonry structures against local collapse mechanism is shown in Fig. 4.2h. Horizontal fabric bond strips were applied either to the external Fig. 4.2h(a)) or the internal Fig. 4.2h(b)) surface of the façade walls, aiming to make the structure exhibit a global response under the earthquake load. More precisely, the goal of the external horizontal strips (bonded at each floor level of the building) was to create a continuous connection



Fig. 4.2f—Strengthening of masonry walls by using a bidirectional carbon-fiber grid (0.6 x 0.6 in. [15 x 15 mm], having a mass per unit area of 4.03 lb/ft² [170 g/m²] and an equivalent thickness of 0.0018 in. [0.047 mm]), applied with a fiber-reinforced pozzolan and cement mortar (courtesy of G&P Intech).



Fig. 4.2g—Seismic retrofitting of a damaged masonry building in San Marino: (a) in-plane and (b) out-of-plane strengthening of masonry walls; and (c) SRG details (courtesy of Kimia).

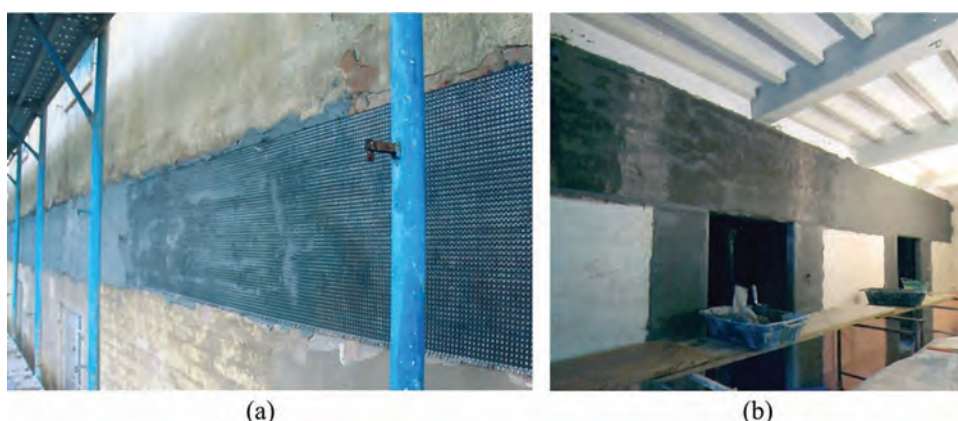


Fig. 4.2h—Seismic retrofitting of a residential building in San Prospero, Italy: horizontal carbon fiber fabric strips applied either on the (a) external or (b) internal surface of façade walls (courtesy of Ruredil).

between orthogonal façade walls, whereas the internal ones were necessary to tie up two parallel façade walls in order to prevent their out-of-plane overturning. The composite reinforcing system used for the retrofitting of the structure is made up of a carbon fiber fabric (0.4 x 0.4 in. [10 x 10 mm]) strips applied by means of a pozzolan and cement mortar.

The fabric has a mass per unit area of 3.99 lb/ft² (168 g/m²), a theoretical thickness of 0.0018 in. (0.047 mm), and was applied through strips having a width of 23.6 in. (600 mm).

The installation of masonry bond beams (placed on the top of the walls) is another kind of seismic retrofitting intervention of masonry buildings that prevents the occurrence of

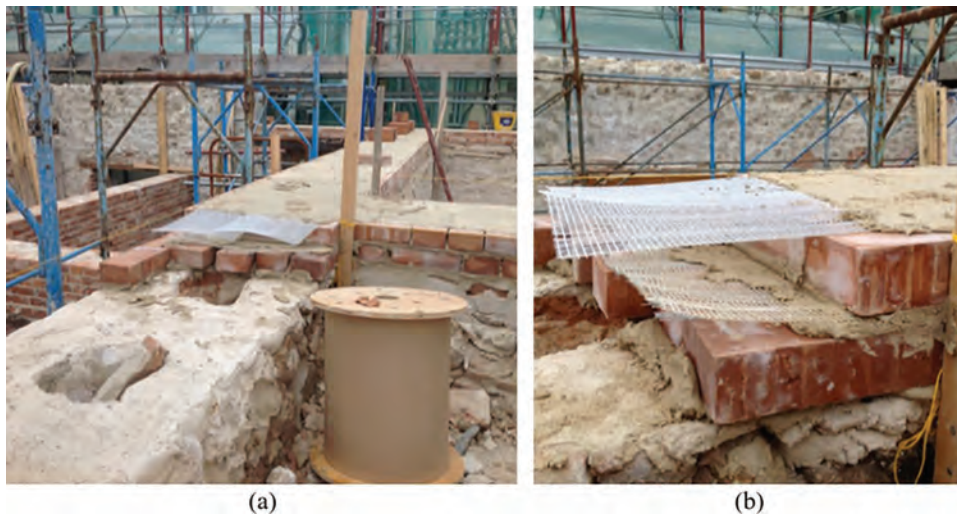


Fig. 4.2i—Historic building in L'Aquila, Italy: construction of a reinforced crowning-beam by means of SRG (courtesy of Sac).

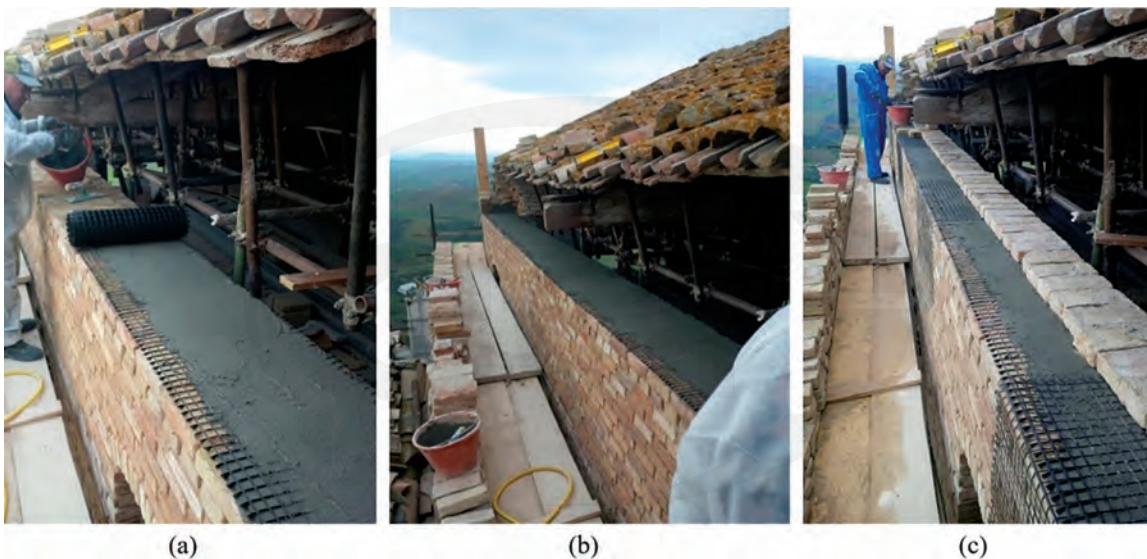


Fig. 4.2j—Building of a reinforced bond beam in lime-brick masonry, Italy: (a) application of the first layer of mortar and fabric; (b) coverage of the fabric through the second layer of mortar and application of the upper layer of bricks (courtesy of Mapei).

local collapse mechanisms (such as the out-of-plane overturning of façade walls) by connecting the perimeter walls of the structure. FRCM/SRG systems are commonly applied into mortar bed joints of crowning beams in order to increase their in plane and out of plane flexural capacity. In Fig. 4.2i, the steps for the building of a bond beam in an historic masonry building in Italy are shown; the structure is located in the city center of L'Aquila and is a typical Italian ancient masonry building. The brick masonry beam was built in order to crown a vault and to carry the horizontal thrust transmitted by the low-weight beams (carrying the vault itself). The brickwork was reinforced with a unidirectional steel fabric (having a total mass per unit area of 15.90 lb/ft^2 (670 g/m^2)), made up of four steel cords per inch (4.28 cords per in. [$1.67 \text{ cords per cm}$]) fixed to a fiberglass microfabric, embedded within a lime-based matrix (Fig. 4.2i(b),(c)). The

fabric was installed in all the bed joints for the entire width of the crowning beam (Fig. 4.2i).

Another case of masonry crowning-beams reinforced with SRG systems is illustrated in Fig. 4.2j. In this case, the reinforcing system consists of a bidirectional fiberglass fabric ($1 \times 1 \text{ in. [25 x 25 mm]}$), applied with a lime- and pozzolan and cement mortar. The fabric has a mass per unit area of 5.34 lb/ft^2 (225 g/m^2).

4.3—Strengthening of masonry arches and vaults

FRCM/SRG reinforcing systems are also often used for the retrofitting of masonry curved structural members, such as arches and vaults, providing an increase of their capacity in bearing unsymmetrical service loads, support displacements, and seismic actions (refer to Chapter 9). These systems can be applied either on the entire surface of the vault (FRCM systems) or by means of discrete strips (typically SRG



Fig. 4.3a—Application steps of a SRG system upon the extrados of a double curvature vault: (a) preparing of the vault surface; (b) cutting of the fabric strips; (c) wetting of the vault surface; (d) and (e) application of the fabric strips upon the first mortar layer; (f) preparation of the end connectors; (g) spreading of the top mortar layer; (h) installation of the transversal set of fabric strips; and (i) construction of buttresses and filling with granular material (courtesy of Cingoli).

systems but also sometimes FRM systems in either PBO or carbon fabrics), and either at the extrados or at the intrados. The installation at the extrados is more expensive and slower because it requires that the flooring and the fill are removed; on the other hand, it allows substitution of the existing filling material with a lighter one to build side buttresses or backing in solid brickwork (useful to constrain the deflection of the vault), to insert tie-bars (which allow to prevent the relative movement of the side walls supporting the vault), and, finally, to preserve any paintings at the intrados. The application at the intrados is faster because it can be accessible from below, but the curvature of the surface may reduce the effectiveness of the composite, requiring the installation of mechanical pins to prevent premature detachment.

In Fig. 4.3a, the steps of the installation of a SRG system at the extrados of a brick masonry vault are shown; the images refer to a consolidation intervention of Casino Ciolina, an historical building in L'Aquila, Italy.

After the shoring up of the vault with props from below, the fill material was removed, mortar joints were repointed, dislocated bricks were restored, and holes were drilled in the side walls for the installation of the end connectors. After that, the surface of the vault was cleaned and its roughness was improved artificially (Fig. 4.3a(a)). Then, the strips of fabric consisting in 12 in. (300 mm) wide unidirectional steel fabric strips, made up of 12 steel cords per inch (4.72 cords per cm), having a surface mass density of 47.5 lb/ft²

(2000 g/m²) and a design thickness of 0.01 in. (0.254 mm) were cut to size (Fig. 4.3a(b)), and the surface of the vault was wet with water and then the first layer of lime-based mortar was installed. Each textile strip was installed making sure that the sheet is perfectly incorporated into the matrix by pressing with a spreader. Each strip was then prepared at the ends and inserted continuously into the apposite holes in the abutments and then a fluid lime grout was injected to complete installation. After the spread of the first layer of lime-based mortar (approximately 0.2 in. [5 mm] thick), each fabric strip was applied (ensuring the full protrusion of the mortar between the cords) (Fig. 4.3a(d) and (e)), the end connectors were performed and inserted in their apposite holes in the abutments, and then the grout was injected to complete the system (Fig. 4.3a(f)). Once the strips were covered by the second layer of mortar (about 0.2 in. [5 mm] thick) (Fig. 4.3a(g)), the steps shown in Fig. 4.3a(d) through (g) were repeated for a second transverse set of strips (usually performed in vaults with double curvature) (Fig. 4.3a(h)). To complete the consolidation intervention, tie-bars were installed, side buttresses or backings were built, and new fill material (for example, expanded clay) was placed (Fig. 4.3a(i)).

Figure 4.3b shows a strengthening intervention on a double curvature masonry vault of S. Andrea hospital in Vercelli, Italy. The vault was reinforced by discrete fabric strips at the extrados of the vault surface. The



Fig. 4.3b—Strengthening intervention on a double curvature masonry vault of S. Andrea hospital in Vercelli, Italy, with PBO FRCM (courtesy of Cerutti).



Fig. 4.3c—Seismic retrofitting of the stable of Santa Apollinare's fortress in Marsciano, Italy: strengthening of a masonry vault (courtesy of Kimia).

composite reinforcing system consists of unidirectional PBO FRCM fiber open fabric strips (10 in. [250 mm] wide), embedded within a pozzolan and cement mortar matrix with short fibers. The fabric has a mass per unit area of 1.04 lb/ft² (44 g/m²) and an equivalent thickness amounting to 0.0011 in. (0.028 mm). After cleaning and preparation of the substrate, the system was bonded to the surface of the vault; for each strip of reinforcement, the first layer of mortar (0.12 in. [3 mm] thick) and then the fabric strip were laid by pressing on the mortar (ensuring that the mortar comes out of the spaces between the fibers) (Fig. 4.3b(a)). After that, before the attainment of the complete maturation of the bed layer of mortar, the top mortar layer was applied to fully

cover the PBO strip. Then, the second set of transverse fabric strips was laid following the same procedure just described. The pozzolan and cement mortar matrix used is particularly suitable for the application on masonry structures, thanks to its chemical-physical compatibility with the substrate. The consolidation intervention was concluded by building side buttresses in solid brickwork.

The same layout of reinforcement was adopted for the strengthening of a single curvature masonry belonging to the stable of Santa Apollinare fortress (Fig. 4.3c). The SRG system consisted in a unidirectional steel fabric, made up of about 12.82 cords per in. (5 cords per cm), embedded within a pozzolan and cement mortar layer. The fabric has a

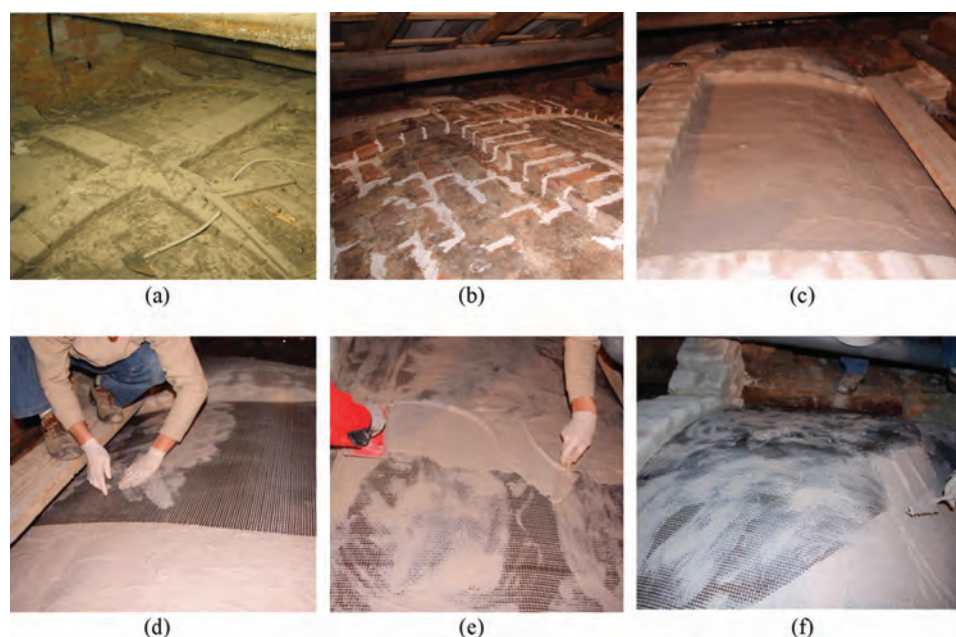


Fig. 4.3d—Strengthening of the extrados of a double-curve masonry vault, Italy: (a) pre-intervention state of the vault; (b) cleaning of the substrate; (c) to (f) application of the FRCM system (courtesy of Mapei).



Fig. 4.3e—Strengthening intervention on the double curvature masonry bricks vault of S. Peter Apostle's Church in Giglio Island, Italy: (a) anchoring of the fabric; and (b) spreading of the primer (promoter of adhesion of the fabric to the matrix) (courtesy of Ardea).

mass per unit area of 52.21 lb/ft² (2200 g/m²), a theoretical thickness of 0.0094 in. (0.24 mm), and was applied through strips having a width of 4 in. (100 mm). In this case, no side buttresses were built to constrain the deflection of the vault.

A case of a double-curve masonry vault reinforced at the extrados is shown in Fig. 4.3d, dealing with a consolidation intervention of an ancient masonry building in Italy. In the figure, all the main steps for the application of the FRCM system upon the vault surface are illustrated. At first, the substrate was cleaned by removing dust and the masonry joints were restored (Fig. 4.3d(b)); then, the first layer of lime- and pozzolan and cement mortar was spread (Fig. 4.3d(c)) and the fabric, consisting of a basalt fiber fabric 0.24 x 0.24 in. (6 x 6 mm) with a mass per unit area of 5.93 lb/ft² (250 g/m²), was accurately applied by hand to the entire surface of the vault, ensuring the embedment of the fabric

itself within the matrix (Fig. 4.3d(d)). Finally, the second layer of mortar was applied using a spreader (Fig. 4.3d(e) and (f)).

Another strengthening intervention, in which the reinforcement is applied on the entire extrados surface of a masonry vault, is illustrated in Fig. 4.3e. The double curvature masonry bricks vault belongs to St. Peter Apostle's Church placed in Giglio Island, Italy. The reinforcement consists of a bidirectional carbon fiber fabric (0.3 x 0.3 in. [8 x 8 mm]) applied to totally cover the extrados of the vault by means of lime-based mortar. The fabric has a mass per unit area of 4.75 lb/ft² (200 g/m²) and an equivalent thickness of 0.0022 in. (0.056 mm). After the removal of the detached mortar between bricks, the vault surface was cleaned by aspiration, dusting and washing and wetted to spread the first layer of lime-based mortar (approximately



Fig. 4.3f—Strengthening of the masonry vaults of Santa Marta's Church (courtesy of S&P).



Fig. 4.3g—Strengthening of the intrados surface of a masonry vault, Italy. FRCM system is made up of a bidirectional fiber-glass fabric (1 x 1 in. [25 x 25 mm], 5.31 lb/ft² (225 g/m²) mass per unit area) and cement-based mortar (courtesy of Mapei).



Fig. 4.3h—Strengthening of a masonry vault in L'Aquila, Italy. SRG system used: unidirectional galvanized steel fiber sheet (having a mass per unit area of 52.24 lb/ft² [2200 g/m²] and an equivalent thickness of 0.0106 in. [0.27 mm]), applied with a lime-based mortar (courtesy of G&P Intech).

0.16 in. [4 mm] thick). After about an hour, a specific primer (promoter of adhesion of the fabric to the matrix) was spread using a brush. Then, two layers of fabric were laid, one along the direction of vault's meridians and the other along the parallels' direction. The former was made up of discrete strips and the latter consisted of a total coverage of the vault surface (by means of sheets overlapped for a length of 8 to 10 in. [200 to 250 mm]). To anchor the reinforcement and to avoid its detachment from the substrate, specific connectors

consisting of carbon bars (about 12 in. [300 mm] long) with a diameter of 0.4 in. (10 mm) combined with carbon fiber strips (2 in. [50 mm] wide and with a mass per unit area of 7.12 lb/ft² [300 g/m²]) were applied (Fig. 4.3e(a)). Finally, a second layer of primer (Fig. 4.3e(b)) and mortar (0.08 to 0.12 in. [2 to 3 mm] thick) were applied to complete the reinforcing system.

Vaults are also reinforced at the intrados, as shown in Fig. 4.3f through 4.3h. Figure 4.3f deals with the strengthening



Fig. 4.3i—Strengthening intervention on a masonry dome of Sinanpasa Madrasa, Bursa, Turkey (courtesy of TICEM).

ening of the masonry vaults of Santa Marta's Church. The church's main vault is composed of a tuff masonry (approximately 11 in. [280 mm] thick) and has a 32.8 ft (10 m) span over irregular stonewalls. This consolidation intervention was necessary because the vault presented deflection and important longitudinal cracks both in the central part and at the supports. The FRCM system adopted consists of a carbon fiber fabric with high strength, applied to totally cover both the intrados and the extrados surface of the vault by means of lime-based mortar. The total thickness of the FRCM on both the vault surfaces amounts to 0.8 in. (20 mm). The fabric has a mass per unit area of 1.89 lb/ft² (80 g/m²) and an equivalent thickness of 0.0017 in. (0.044 mm).

An application of FRCM on a masonry dome on the masonry dome of Sinanpasa Madrasa, Bursa, Turkey is shown in Fig. 4.3i. Structural cracks up to 0.24 in. (6 mm) were determined before intervention. Thirteen domes of the structure were strengthened by using FRCM. The fabric has mass per unit area of 7.83 lb/ft² (330 g/m²). The glass fiber fabric was used with appropriate overlapping. Natural hydraulic lime based thixotropic mortar was used as matrix. Yarns along four directions in fabric helped to distribute and transfer the loads due to structural and physical effects on dome.

4.4—Confinement of masonry columns

FRCM/SRG systems also represented an alternative technique to strengthen masonry columns (refer to [Chapter 8](#)). Thanks to their confinement action, these systems allow to increase both the axial strength and ductility (deformation capacity) of masonry columns, respecting the aesthetic, conservation, and restoration requirements, and, overall,



Fig. 4.4a—Seismic retrofit of a nursery in Zocca, Italy: confinement of columns (courtesy of Ruredil).

without adding significant mass (that increase seismic action and static demand to the foundation systems) and with minimum stiffness increase.

In Fig. 4.4a, a strengthening intervention dealing with the confinement of the columns of a nursery in Zocca, Italy, is illustrated. A jacketing of the columns was made by uniformly applying the FRCM system on their whole surface. The system consisted of bidirectional PBO fiber fabric strips (39.3 in. [1000 mm] wide), applied by means of pozzolan and cement mortar. The fabric has a mass per unit area of 1.04 lb/ft² (44 g/m²) and an equivalent thickness of 0.00056 in. (0.014 mm). This reinforcing system is real-



Fig. 4.4b—Columns confinement of a stable in Ravenna, Italy (courtesy of Kerakoll).



Fig. 4.4c—FRCM/SRG strengthening of masonry columns of the ex-bowling facility in Ravenna, Italy (courtesy of Kerakoll).

ized using non-toxic materials, allows transpiration, and it is highly resistant to thermal excursions.

Another example of brick masonry column confinement is shown in Fig. 4.4b, in which a strengthening intervention of a stable in Ravenna, Italy, is illustrated. The SRG reinforcing system, consisting in a steel fabric embedded within a lime-based mortar matrix, was bonded to the entire surface of the column. The fabric was made up of unidirectional galvanized high-strength steel cords (four cords per inch)

with a surface mass density of 15.90 lb/ft² (670 g/m²) and an equivalent thickness of 0.0033 in. (0.084 mm).

The same reinforcing system was adopted in Ravenna, Italy, to strengthen the brickwork columns of the ex-bowling facility (Fig. 4.4c).

CHAPTER 5—MATERIAL CHARACTERISTICS AND SYSTEM QUALIFICATION

The qualification of a FRCM/SRG system is based on a test plan that provides data on material properties, force, and deformation limit states, including failure modes, according to prescribed test protocols and procedures.

The qualification parameters should be considered representative only of the system that underwent the experimental tests and cannot be extended or extrapolated to different systems. Experimental outcomes are sensitive to fabric properties and architecture, matrix characteristics, interaction between matrix and fabric, as well as to the number of fabric layers embedded within the FRCM/SRG composite. Changing even one of these parameters corresponds to changing the FRCM/SRG system. In this case, therefore, the new FRCM system needs to undergo another qualification process.

5.1—Experimental tests for material characterization

Different experimental methods are available to determine the mechanical properties of FRCM/SRG composite materials and their constituents (fabrics and matrixes) that are used in the design of FRCM reinforcements. The test protocols are described in this section.

5.1.1 Experimental tests for the mechanical characterization of fabric (required by RILEM acceptance procedure)—These tests are carried out for the mechanical characterization of fabrics using a universal testing machine with suitable capacity. Bare fabric specimens shall have the same conditions (including coating and preimpregnation) of the

fabrics embedded within the mortar matrix in FRCM/SRG composites and the same number of yarns of the textile strip used in the shear bond test (Refer to Section 5.1.4.). Fabric specimens have a width not larger than the wedges of the testing machine and a net length (for example, excluding the gripping areas) at least five times the width to avoid the edge effects (Fig. 5.1.1a).

The specimen is clamped by the wedges of a universal testing machine with sufficient lateral pressure to avoid slippage within the grips. Aluminum, steel, or fiber-reinforced polymer (FRP) tabs with a suitable thickness (not less than 0.0787 in. [2 mm]), length (not less than 2 in. [50 mm]), and width (equal to the specimen width) are applied with epoxy resins at both ends of the fabric strip to prevent premature fiber rupture or damage. During the installation of the tabs and the placement of specimens in the test frame, alignment of the fabric with the axis of the actuator is of utmost importance to prevent non-uniform distribution of the load.

The load is applied under displacement control and a rate of 0.02 in./min (0.5 mm/min) or less is recommended. The load and strain in the specimen shall be recorded (a minimum gauge length of 1 in. (25 mm) is recommended to measure the displacement). The effective tensile modulus of elasticity of the fabric, E_t , is calculated as the secant modulus between 20 and 60 percent of the maximum stress, in accordance with Eq. (5.1.1).

$$E_t = 0.4f_{t,max}/(\epsilon_{t@0.6f_{t,max}} - \epsilon_{t@0.2f_{t,max}}) \quad (5.1.1)$$

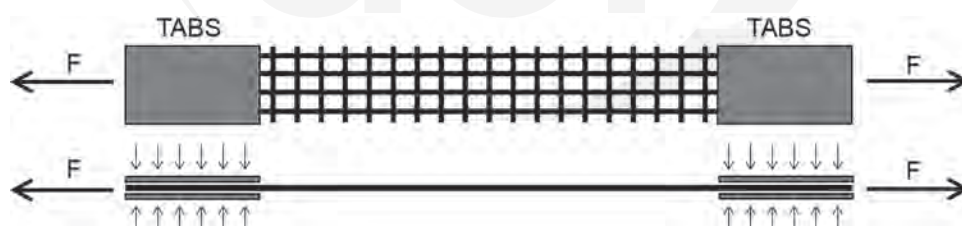


Fig. 5.1.1a—Experimental setup for direct tensile tests on bare fabric specimens.

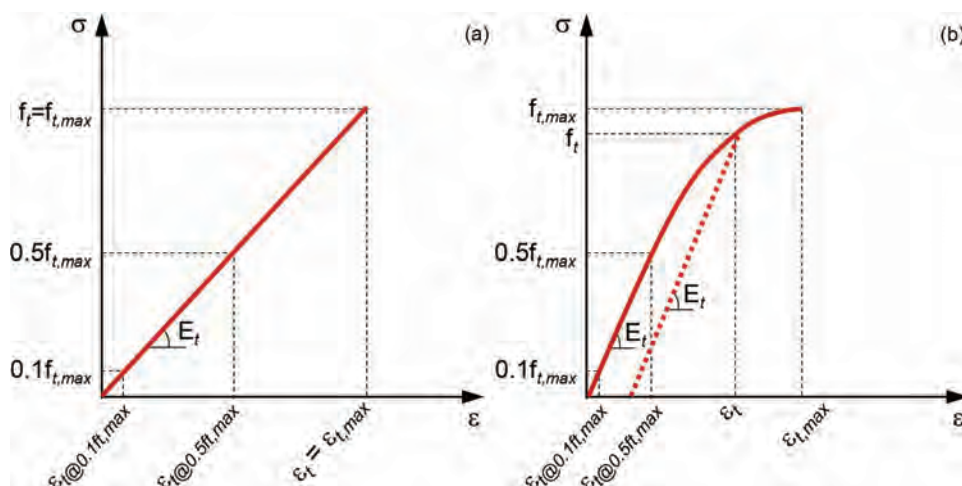


Fig. 5.1.1b—Expected tensile stress versus tensile strain curve obtained in direct tensile tests of fabric exhibiting a. (a) linear and (b) nonlinear behavior.

The tensile strength of the fabric, f_t , and the corresponding strain, ϵ_t , are equal to $f_{t,max}$ and $\epsilon_{t,max}$, respectively, if the fabric exhibits a linear behavior up to failure (Fig. 5.1.1b(a)). If the stress-strain behavior is nonlinear, as it may happen for steel fabrics, the tensile strength f_t is determined as the minimum of $f_{t,max}$ and the tensile strength obtained through offset method per ASTM E8/E8M with specific offset value equal to 0.2 percent. The ultimate strain ϵ_t corresponds to f_t in the axial stress versus axial strain response curve (Fig. 5.1.1b(b)). A minimum of nine tests is recommended.

The following mechanical properties are determined through a direct tensile test on a fabric specimen:

- a) f_t —tensile strength of fabric, psi (MPa)
- b) ϵ_t —ultimate strain of fabric, in./in. (mm/mm)
- c) E_t —tensile modulus of elasticity of fabric, psi (MPa)

These properties are used for ULS design verifications. Design is based on the properties of the FRCM/SRG in the primary direction only. For load conditions resulting in forces other than in the primary direction, the forces should be decomposed.

5.1.2 Experimental tests for the mechanical characterization of mortar matrix—The following mechanical properties of mortar matrixes are determined in accordance with the specified standard test methods:

			
f_{mc}	compressive strength of mortar (psi) from compression test (ASTM C109/C109M)	$f_{c,mat}$	Compressive strength of mortar (MPa) from compression test (Eurocode EN 998-2 and EN 12190)
		E_{mat}	Modulus of elasticity of mortar (MPa) from compression test (Eurocode EN 998-2 and EN 13412)
		$f_{t,mat}$	Tensile strength of mortar (MPa) from three-point bending test (Eurocode EN 196-1)

5.1.3 Direct tensile tests on FRCM/SRG coupons—The tensile behavior of FRCM/SRG composite materials is investigated through direct tensile tests on prismatic specimens (coupons), which can be either manufactured separately or obtained by cutting them from a larger FRCM/SRG panel (Fig. 5.1.3a). Two gripping mechanisms—clevis grip and clamping grip—can be used according to different test methods. In the clevis grip tests described in the ICC-ES Acceptance Criteria **AC434**, steel plates are adhered to the coupon at each end, and the tensile load is transferred through the clevis to end plates. In the clamping grip tests described in RILEM TC 232-TDT (**Brameshuber 2016**), the ends of the coupon are gripped within bolted steel plates that apply a lateral pressure to the specimen, and the load is transferred by friction.

	
Annex A of the ICC-ES Acceptance Criteria AC434 provides instructions to perform tensile tests with a clevis grip method. Steel plates are adhered to the end of the coupon using high-end epoxies and are connected to the test frame through clevises, which allow rotation (Fig. 5.1.3b.a1). The axial load is transferred to the specimen through shear stresses with no lateral pressure. For the tabs, a width equal to that of the coupon, a length of at least 4 in. and a thickness of at least one-sixteenth inch are recommended. As for the coupons, an appropriate thickness should be determined on the base of the number of fabric layers. It is also recommended that the specimen should have at least three yarns, and the width should be at least four times the thickness.	RILEM TC 232-TDT Recommendation (Brameshuber 2016) provides fundamental instructions to perform tensile tests with a clamping grip method. The recommendation, developed for TRC composites, has been widely used also for the mechanical characterization of FRCM/SRG strengthening systems. The description provided below is based both on the research carried out on TRC (RILEM TC 232-TDT recommendation [Brameshuber 2016]) and on the studies devoted to FRCM/SRG testing (De Santis et al. 2017a). Steel plates are bolted to the end of the coupon and are clamped by the wedges of the testing machine, with a suitable gripping mechanism that allows for rotation in two perpendicular planes (Fig.
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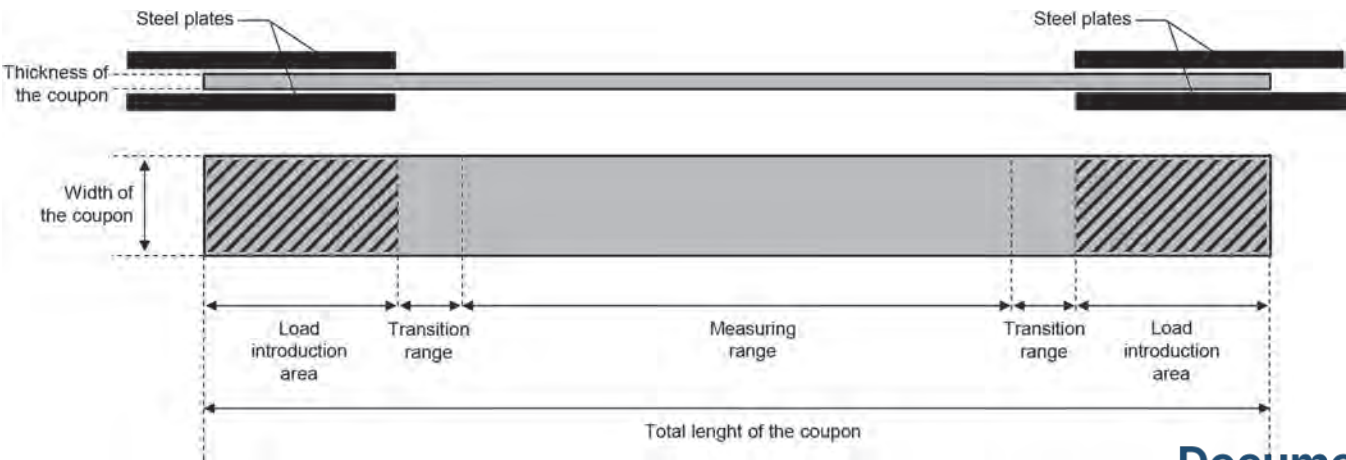


Fig. 5.1.3a—FRCM/SRG coupon specimen for direct tensile tests.

The test is conducted in displacement control. Load and deformation of the specimen are recorded, and the stress is calculated as the load divided by the cross-sectional area of the fabric in the loaded direction. The displacement is measured by an extensometer over the monitoring length, which is recommended to be more than 2 in. to include at least one transverse crack of the FRCM/SRG matrix. A minimum of twenty specimens is required. Note that the minimum number of FRCM coupons is larger than that of bare textile specimens due to the wider expected variability.	5.1.3b.b1). A hydraulic grip is also allowed, and the pressure has to be adjusted in order to prevent slippage between the plate and the specimen. A rubber sheet is placed between the steel plates and the coupon to avoid stress concentrations. To ensure a homogeneous stress distribution and prevent excessive crushing damage of the mortar, the specimen is reinforced in the gripping areas with FRP wrapping. The load is transferred to the specimen by friction over a load introduction length of at least 125 mm, which can be increased for FRCM/SRG systems with low fiber-to-matrix bond. Recommended minimum dimensions for the specimens are 500 mm [19.68 in.] total length, 60 mm [2.36 in.] width and 6 mm [0.24 in.] thickness. The load is applied under displacement control and recorded by a load cell. The stress is calculated as the load divided by the cross-sectional area of the fabric. The strain is recorded by strain or displacement transducers over a suitable base length, which excludes the transition range to prevent the measurement from being affected by edge effect near the gripping area. The measuring range should at least include a transverse crack of the FRCM/SRG matrix. The final crack should develop within the measurement range in order to consider the result of the test reliable until failure. Otherwise, it is valid up to the beginning of crack localization.	The expected tensile stress versus tensile strain response curve shows an initial uncracked stage, followed by a crack development stage and a cracked stage (Fig. 5.1.3b.a2). The ultimate tensile strength f_{fu} is the maximum stress achieved during the test. The stiffness in the cracked portion, E_f, is calculated in the $0.60f_{fu}$ to $0.90f_{fu}$ range, as shown in Fig. 5.1.3b.a2 and expressed in Eq. (5.1.a1). $E_f = (0.9f_{fu} - 0.6f_{fu}) / (\epsilon_f @ 0.90f_{fu} - \epsilon_f @ 0.60f_{fu}) \quad (5.1.3a1)$ The ultimate tensile strain ϵ_{fu} is calculated in accordance with Eq. (5.1.3a2) $\epsilon_{fu} = \epsilon_f @ 0.6f_{fu} + 0.4f_{fu} / E_f \quad (5.1.3a2)$ Finally, the stiffness of uncracked FRCM/SRG, E_f^*, is the slope of the uncracked portion of the curve. In direct tensile tests with clevis grip method, failure may take place either by tensile rupture of the fabric or through slippage of the fabric within the matrix. Thus, the test represents application of FRCM/SRG materials without additional anchorage. The load is transferred from the tabs to the matrix and from the matrix to the fabric at both sides of the coupon, whereas, in structural applications, the load is transferred from the substrate to the matrix and from the matrix to the fabric only on one side. Test results are affected by the length of the tabs, when failure mode is slippage of the fabric within the matrix.	The expected tensile stress versus tensile strain response curve shows an initial uncracked stage, followed by a crack development stage and a cracked stage. The ultimate tensile strength f_{fu} is the maximum stress attained in the test. The ultimate tensile strain ϵ_{fu} is the strain corresponding to a stress of f_{fu}. The stiffness in the uncracked stage, E_1, and in the cracked stage, E_2, are determined as the slope of the curve in the uncracked stage and in the cracked stage, respectively (Fig. 5.1.3b.b2). In direct tensile tests with clamping grip method, failure takes place by tensile rupture of the fibers, provided that sufficient lateral pressure is applied in the gripping areas that prevents fabric-to-matrix slippage. In this sense, test results depend upon the lateral pressure applied to the coupon in the load introduction area. No information is provided on the fabric-to-matrix bond, and the boundary conditions experienced by the FRCM/SRG material do not reproduce the actual stress state faced in the field.
		The following mechanical properties are determined through a direct tensile test on a FRCM/SRG coupon performed according to ICC-ES Acceptance Criteria AC434. Note that the stress is referred to the cross-sectional area of the fabric and that E_f and E_f^* tensile modules of elasticity are calculated on the tensile stress versus tensile strain response curve.	The following mechanical properties are determined through a direct tensile test on a FRCM/SRG coupon performed according to RILEM TC 232-TDT Recommendation (Brameshuber 2016). Note that the stress is referred to the cross-sectional area of the fabric and that E_1 and E_2 tensile modules of elasticity are calculated on the tensile stress vs tensile strain response curve (De Santis et al. 2017a).
		$f_{fu} =$ ultimate tensile strength of FRCM/SRG, psi	$f_{fu} =$ ultimate tensile strength of FRCM/SRG, MPa
		$\epsilon_{fu} =$ ultimate tensile strain of FRCM/SRG, in./in.	$\epsilon_{fu} =$ ultimate tensile strain of FRCM/SRG, mm/mm
		$E_f^* =$ stiffness of uncracked FRCM/SRG, psi	$E_1 =$ stiffness of uncracked FRCM/SRG, MPa
		$E_f =$ stiffness of cracked FRCM/SRG, psi	$E_2 =$ stiffness of cracked FRCM/SRG, MPa

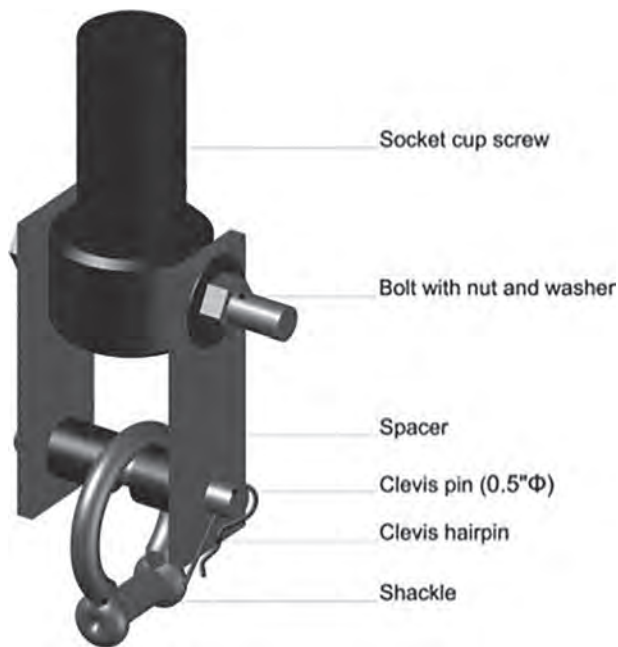


Fig. 5.1.3b.a1—Gripping mechanism for direct tensile test on FRCM/SRG specimens (AC434).

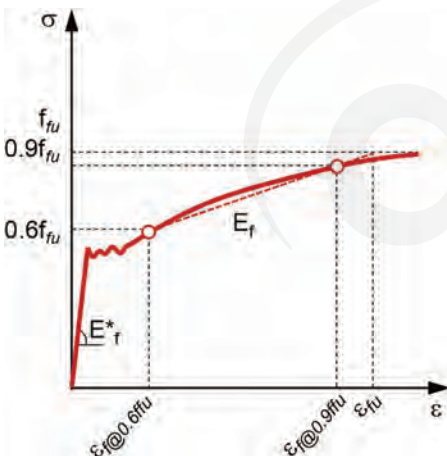


Fig. 5.1.3b.a2—Expected tensile stress versus tensile strain curve of a FRCM/SRG coupon (AC434).

It should be considered that, for both test methods, the measurement of the strain may be influenced by the number of cracks that develop within the gauge length of the extensometer. The number of cracks depends on the properties of the FRCM/SRG composite (including tensile strength of the matrix, stiffness of fabric and matrix, fabric-matrix bond characteristics, and fabric architecture). Furthermore, sensitivity of inorganic matrixes to possible local defects (for example, microcracks due to handling/installation) introduces an additional variability in the results.

Due to the different boundary conditions, the stiffness of the cracked FRCM/SRG and the peak stress attained at failure are higher if a clamping grip is used with respect to those determined with a clevis grip (Fig. 5.1.3c) (Arboleda et al. 2016).

For modeling the tensile behavior of FRCM/SRG systems within advanced structural analysis approaches, a bilinear

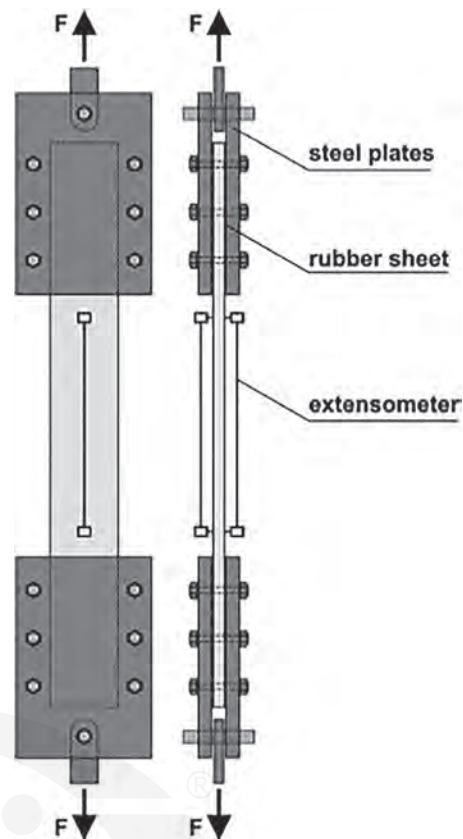


Fig. 5.1.3b.b1—Experimental setup for direct tensile test on FRCM/SRG specimens (RILEM TC 232-TDT [Bramshuber 2016] recommendation).

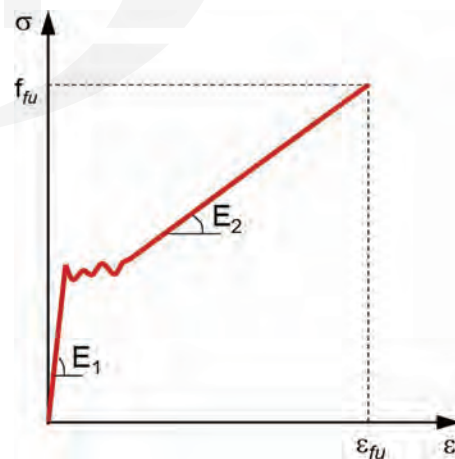


Fig. 5.1.3b.b2—Expected tensile stress versus tensile strain curve of a FRCM/SRG coupon tested according to RILEM TC 232-TDT recommendation.

or a trilinear (Fig. 5.1.3d) constitutive relationship can be defined based on the test results. Indications on how to determine the coordinates (strain and stress) of the transition points can be found in the literature (De Santis et al. 2017a). However, for design purposes, as shown in the present document, the FRCM/SRG material can be considered as linear elastic to failure. This is the simplest constitutive relationship and provides conservative results. Moreover, depends upon a limited number of parameters, which

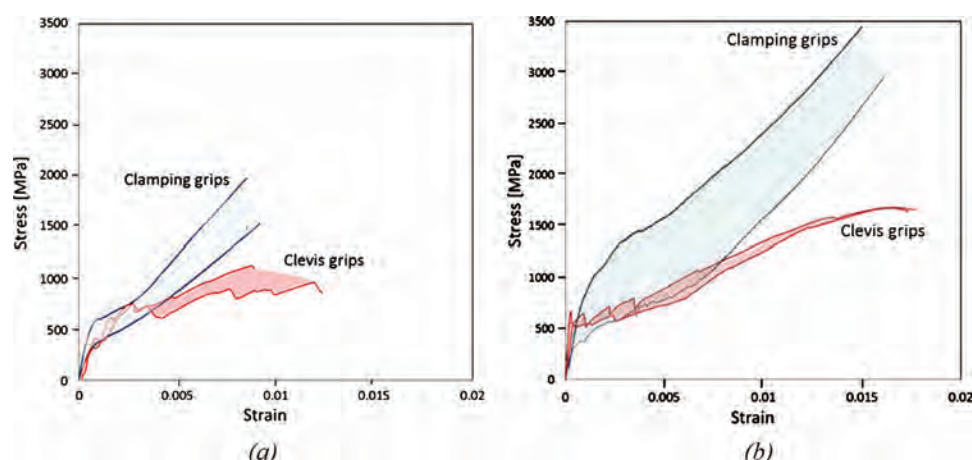


Fig. 5.1.3c—Comparison between expected tensile stress versus tensile strain curves of (a) a PBO and (b) carbon FRCM/SRG coupon obtained from direct tensile tests performed with the clamping grip method and with the clevis grip method (Arboleda et al. 2016).

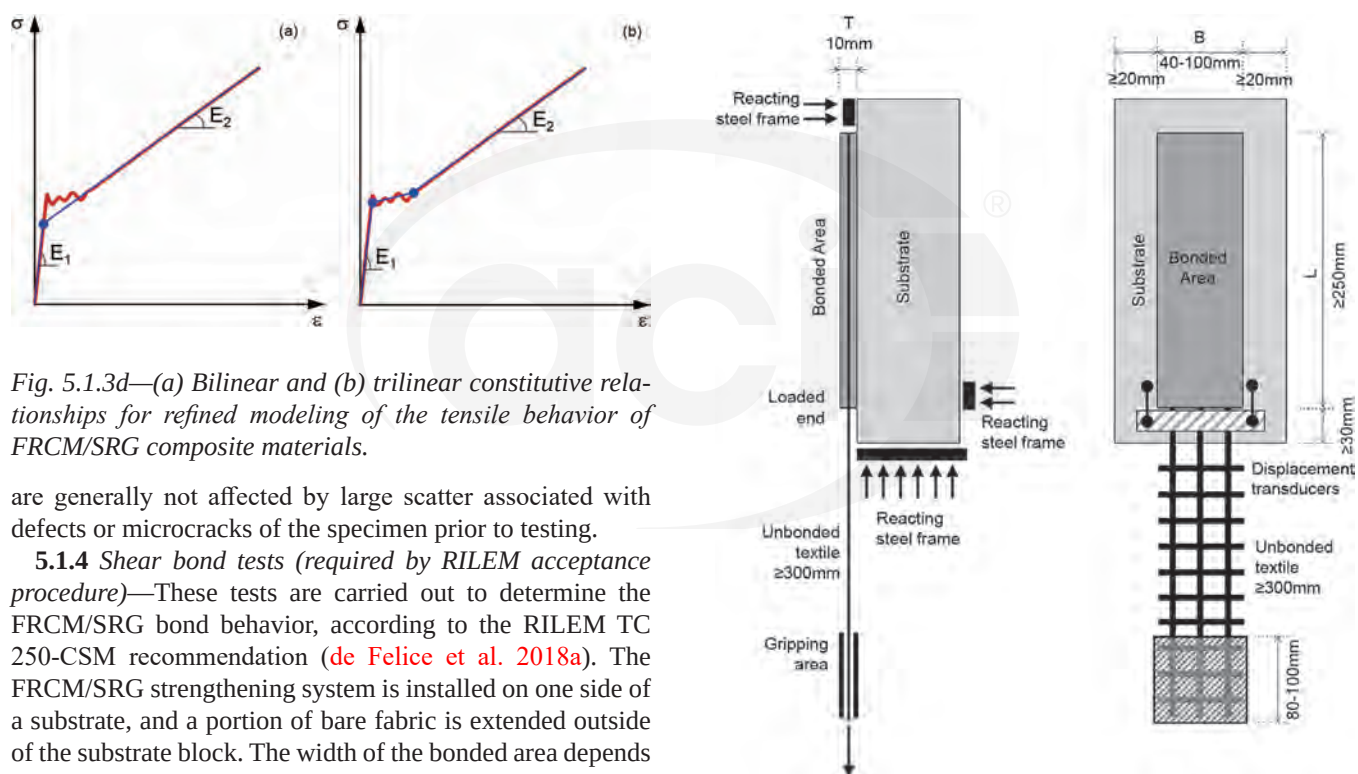


Fig. 5.1.3d—(a) Bilinear and (b) trilinear constitutive relationships for refined modeling of the tensile behavior of FRCM/SRG composite materials.

are generally not affected by large scatter associated with defects or microcracks of the specimen prior to testing.

5.1.4 Shear bond tests (required by RILEM acceptance procedure)—These tests are carried out to determine the FRCM/SRG bond behavior, according to the RILEM TC 250-CSM recommendation (de Felice et al. 2018a). The FRCM/SRG strengthening system is installed on one side of a substrate, and a portion of bare fabric is extended outside of the substrate block. The width of the bonded area depends on the grid spacing. The width should include at least three fiber rovings (or cords in case of SRG) and should be in a range of 1.6 to 4 in. (40 to 100 mm). The bonded area should not be close to the edges of the substrate prism to avoid spalling and edge effects. A bonded length of 12 in. (300 mm) is recommended.

The experimental investigations available in the scientific literature (D'Antino et al. 2014; Lignola et al. 2017; Carozzi et al. 2017; Leone et al. 2017; Caggegi et al. 2017; De Santis et al. 2017b, 2018a) suggest that a bonded length of 2 in. (300 mm) is longer than the effective bond length, thus ensuring that the FRCM/SRG-to-substrate load transfer capacity is fully exploited. On the other hand, it is also noted that, in case of failure by textile slippage, the fabric-to-mortar friction (interlocking) that is activated where the fabric has debonded from the matrix contributes to the substrate-to-

Fig. 5.1.4a—Experimental setup of single-lap shear bond test (RILEM TC 250-CSM recommendation).

composite load transfer capacity and, therefore, longer bond length could lead to higher peak loads.

Tests are performed with a universal testing machine in single-lap shear setup. The specimen is constrained by a stiffened steel frame, while the loaded end of the unbonded fabric is clamped by the wedges of the testing machine and pulled away (Fig. 5.1.4a). The application of metallic or FRP tabs is recommended to prevent fabric damage or sliding in the gripping area. The test is conducted under machine stroke displacement control (displacement rate of 0.006 to 0.012 in./min [0.15 to 0.30 mm/min]). The applied load is recorded by a load cell. The axial stress is

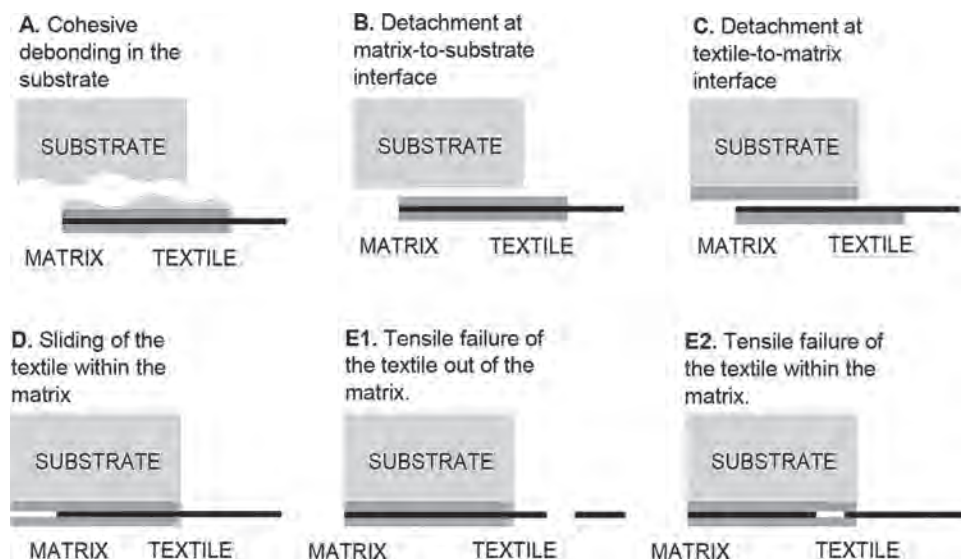


Fig. 5.1.4b—Failure modes in single-lap shear bond test (RILEM TC 250-CSM recommendation).

obtained by dividing the applied load over the cross-sectional area of the fabric. The relative displacement between fabric and substrate at the loaded end of the bonded area (generally named as slip) is measured by displacement transducers. A minimum of five tests is recommended.

The main test result is the axial stress-slip relationship. The peak axial stress f_{fb} is the maximum axial stress value attained in the shear bond test. Different failure modes may take place, including: (A) debonding with cohesive failure of the substrate; (B) detachment at the matrix-to-substrate; (C) detachment at the fabric-to-matrix interface; (D) fabric slippage within the matrix, with or without cracking of the outer mortar layer; (E1) tensile rupture of the fabric out of the bonded area; and (E2) tensile rupture of the fabric within the matrix with telescopic failure of the bundle (Fig. 5.1.4b). As described in the recommendation of RILEM TC 250-CSM (de Felice et al. 2018a), failure mode A usually occurs when a strong matrix is bonded to a weak substrate, failure mode B usually takes place on relatively smooth surfaces, failure mode C is often exhibited by FRCC/SRG systems comprising fabrics with small grid/cord spacing, and failure mode D usually takes place as a result of a weak fabric-to-matrix bond/interlocking. Finally, FRCC/SRG systems comprising relatively weak fabrics with small equivalent thickness may exhibit failure mode E1 (generally when fiber bundles are provided with preimpregnation or coating) or failure mode E2 (when dry fabrics are used).

The shear bond test method provides a characterization of the FRCC/SRG bond behavior for the bond critical structural applications, in which the effectiveness of the externally bonded (EB) FRCC/SRG reinforcement system relies on the FRCC/SRG-to-substrate load transfer capacity. However, it should be considered that some applications, such as the confinement of columns, are generally not affected by the substrate-to-FRCC/SRG load transfer capacity, and failure may occur either by the tensile rupture of the fabric or by detachment/opening of the jacket at the overlap. Moreover, the substrate-to-FRCC/SRG load transfer capacity provided

by the single-lap shear bond test is referred to an end plate debonding failure, because only one end of the composite is loaded, whereas in a typical application, the load is applied to both ends of the composite and a stress-free end of the composite is not typically observed in practice. For this reason, a coefficient $\alpha_1 \geq 1$ should be considered, as explained in the following sections, for structural applications depending on the boundary conditions experienced by the EB FRCC/SRG composite reinforcement.

The applications that include mechanical pins or connectors are generally not bond-critical because detachment is prevented and failure is expected to occur by tensile rupture of the fabric. However, only limited scientific literature is available and, therefore, the increase in the bond strength provided by connectors is not expressly considered in the present guide.

5.2—Determination of qualification parameters

This section illustrates the procedures to determine the qualification parameters of FRCC/SRG composite materials, which are used in the following sections to calculate the design strength of reinforced structural members (including walls, vaults, and columns). The two qualification approaches (ACI and RILEM) are based on different assumptions, and characteristic values are associated with different percentiles. Therefore, direct comparison between the qualification parameters should not be carried out.

Likewise, design methods are developed on the base of the assumptions made in the qualification process and are not expected to provide identical results. For instance, ACI's design values of material properties coincide with the characteristic values, and a strength reduction factor ϕ is used to reduce the design strength of the structural member. RILEM differs in that the design strength values of the materials are calculated as the characteristic values divided by a partial strength coefficient γ . Therefore, the design strength of the structural members calculated according to ACI or RILEM approaches are not necessarily expected to be the

same. Finally, the partial coefficients applied to the external loads differ and, therefore, the safety levels (ratio between design capacity and demand) are not necessarily expected to coincide.

	
The main design parameters of FRCM/SRG composite materials are the stiffness E_f and the design tensile strain ε_{fd}. The stiffness to be used for design, E_f, is the average value of the stiffness of cracked FRCM/SRG (Eq. (5.2a1)). $E_f = \langle E_f \rangle \quad (5.2a1)$ The design values of the strain ε_{fd} is defined as the average value $\langle \varepsilon_{fu} \rangle$, minus one standard deviation Δ_ε, which are provided by the direct tensile tests performed in accordance with ICC-ES Acceptance Criteria AC434 (Eq. (5.2a2)). $\varepsilon_{fd} = \langle \varepsilon_{fu} \rangle - \Delta_\varepsilon \quad (5.2a2)$ The design tensile strain ε_{fd}, shall be limited to ε_{lim}, in accordance with Eq. (5.2a3) $\varepsilon_{fd} \leq \varepsilon_{lim} \quad (5.2a3)$ The limit strain ε_{lim}, is introduced to prevent excessive damage in the structural member reinforced with FRCM/SRG. The value to be assumed for ε_{lim} depends on the specific reinforcement applications and is provided in the dedicated sections. <i>cont. next column</i>	The main design parameters of FRCM/SRG composite materials are the tensile modulus of elasticity, E_f, the ultimate tensile strain of the fabric, ε_{tk}, and the maximum tensile strain in the fabric attained in the bond test, ε_{fb}. The latter is derived by combining the results of FRCM/SRG-to-substrate shear bond tests and of direct tensile tests on bare textile specimens as shown in Fig. 5.2b. The method originates from the debate within the working group of the Italian National Research Council (CNR) set for the development of guidelines for the qualification of FRCM composites. The idea of combining the results of shear bond tests with tensile tests was originally proposed in Ascione et al. (2015) with reference to tensile tests on FRCM coupons, and then updated with reference to bare textiles in the light of the fact that the stress state and the crack pattern of FRCM coupons does not effectively represent those experienced in structural applications, due to the different boundary conditions. The use of tensile tests on bare textiles also provides more robust results since the modulus of elasticity of textiles generally exhibits lower scatter than that of FRCM coupons, which is very sensitive to cracking. <i>cont. next column</i>

The design value of the elastic modulus, E_f , is therefore the average value of the tensile modulus of elasticity of the fabric (Eq. (5.2b1)).

$$E_f = \langle E_f \rangle \quad (5.2b1)$$

The characteristic value of the tensile strength of the fabric, f_{tk} , is obtained as the average value $\langle f_t \rangle$, minus k_n times the standard deviation Δ_σ , which are provided by the tensile tests on bare fabrics as described in Section 5.1.3 (Eq. (5.2b2))

$$f_{tk} = \langle f_t \rangle - k_n \Delta_\sigma \quad (5.2b2)$$

where k_n is a fractile coefficient that depends on the number of tested specimens, defined in Annex D of Eurocode 0 (EN 1990:2002-02) ($k_n = 1.92$ for 10 specimens). The corresponding ultimate tensile strain in the fabric is given in accordance with Eq. (5.2b3).

$$\varepsilon_{tk} = f_{tk} / E_f \quad (5.2b3)$$

The characteristic value of maximum axial stress in the textile attained in the bond test, f_{fbk} , is obtained as the average value $\langle f_{fb} \rangle$, minus k_n times the standard deviation Δf , which are provided by the shear bond tests performed in accordance with RILEM TC 250-CSM recommendation (de Felice et al. 2018a) (Eq. (5.2b4)).

$$f_{fbk} = \langle f_{fb} \rangle - k_n \Delta f \quad (5.2.b4)$$

where $k_n = 2.33$ for five specimens. The corresponding maximum tensile strain in the fabric attained in the bond test, ϵ_{fb} , (Fig. 5.2.b) is obtained in accordance with Eq. (5.2b5).

$$\epsilon_{fb} = f_{fbk} / E_f \quad (5.2.b5)$$

Experimental tests on reinforced structural members (refer to Chapter 3) show that the behavior of FRCM/SRG systems at failure is generally in between the end debonding and the tensile rupture of the fibers. On the one hand, the detachment of the FRCM/SRG composite from the substrate may take place in an intermediate section at a higher stress in the fabric than that attained in the shear bond test. On the other hand, due to local stress concentration or uneven redistribution of the load among the fiber bundles, the tensile strength of the fabric may not be fully exploited.

Accordingly, the design value of the strain in the FRCM/SRG composite material, ϵ_{fd} , is calculated in accordance with Eq. (5.2b6)

$$\epsilon_{fd} = \frac{1}{\gamma_m} \min(\alpha_1 \epsilon_{fb}; \epsilon_{tk} / \alpha_2) \quad (5.2.b6)$$

where the coefficients α_1 and α_2 are calibrated by comparison between experimental results and average theoretical data and, therefore, vary depending on the specific applications. Their values are provided in the next chapters for each specific design application.

The partial safety factor on the design axial strain of the FRCM/SRG composite material is $\gamma_M = 1.5$.

The effective tensile strain level in the FRCM/SRG composite material, ϵ_{fe} , should be limited to the design tensile strain of the FRCM/SRG composite material. The effective tensile stress level in the FRCM/SRG reinforcement, f_{fe} , is calculated in accordance with Eq. (5.2a4) (Fig. 5.2a).

$$f_{fe} = E_f \cdot \epsilon_{fe}, \text{ where } \epsilon_{fe} = \epsilon_{fd} \leq \epsilon_{lim} \quad (5.2a4)$$

The effective tensile strain level in the FRCM/SRG composite material, ϵ_{fe} , should be limited to the design tensile strain of the FRCM/SRG composite material. The effective tensile stress level in the FRCM/SRG reinforcement, f_{fe} , is calculated in accordance with Eq. (5.2b7).

$$f_{fe} = E_f \cdot \epsilon_{fe}, \text{ where } \epsilon_{fe} \leq \epsilon_{fd} \quad (5.2.b7)$$

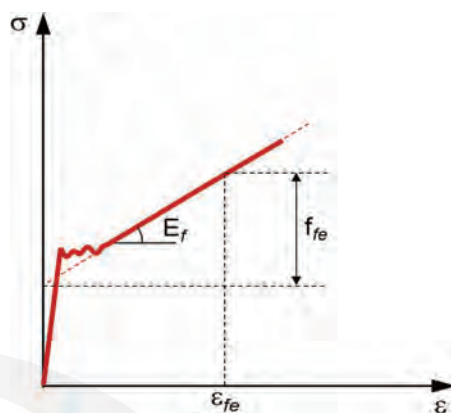


Fig. 5.2a—Identification of effective tensile stress level of the FRCM/SRG composite material.

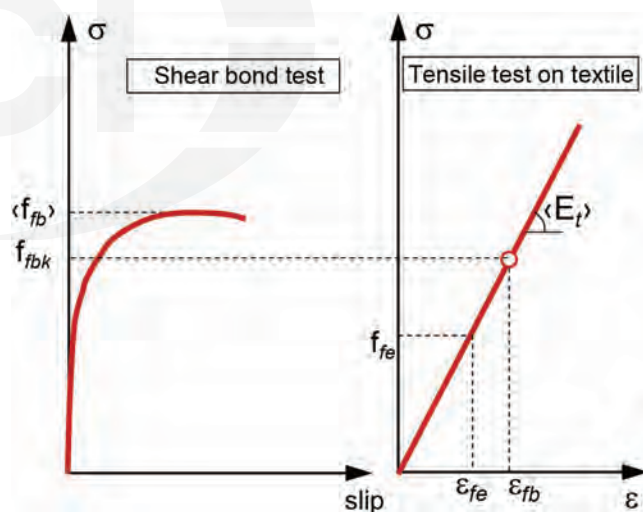


Fig. 5.2b—Identification of characteristic maximum tensile strain in the FRCM/SRG composite material attained in the bond test.

CHAPTER 6—GENERAL DESIGN CONSIDERATIONS

FRCM and SRG composites are particularly suitable for the externally bonded (EB) strengthening of existing masonry structures. In unreinforced masonry, damage or collapse is generally caused by the lack of tensile strength and by the consequent onset of a failure mechanism associated with either overturning, flexure, shear, leaf/wythe separation, or disaggregation. FRCM/SRG systems provide the masonry structural member with tensile resistance.

enhancing its ultimate strength and improving its displacement capacity. Thanks to the high strength of FRCM/SRG composites, the required increase of structural capacity is, in most cases, achievable with one ply of fabric, with the only exception being confinement of columns, which are often wrapped with more plies. FRCM/SRG composites are also particularly effective for seismic retrofitting, because their limited thickness ensures that the mass increase is negligible and because they do not noticeably modify the dynamic properties of the structure. The use of mortar matrixes, whose stiffness is comparable to that of masonry, makes FRCM/SRG reinforcements mechanically compatible with masonry substrates, with a relatively easy, versatile (capability of adapting to various shapes and layouts), and cost-efficient installation in the construction site, even on wet or irregular surfaces. FRCM/SRG composites with lime-based mortars comply with the principles of conservation required for applications to architectural heritage, as they ensure chemical compatibility, vapor permeability, and reversibility (possibility of being removed with no damage to the original substrate).

The broad range of commercially available FRCM/SRG systems (including being characterized by different values of tensile strength and modulus of elasticity, surface mass density, design thickness, grid spacing, and fabric architecture) makes it possible to grade the reinforcement design; it allows the licensed design professional (LDP) to adopt the suitable the fabric type and mortar matrix type, the amount of design the fabric cross section, and to select either and designate a continuous (full coverage) or a discrete (horizontal, and vertical strips, or both) layout.

Masonry walls may be reinforced with FRCM/SRG composites to enhance the out-of-plane flexural strength. FRCM/SRG composites may be applied to the entire surface of the wall or in vertical and horizontal strips, depending on fabric architecture and tensile strength of the FRCM/SRG, as well as on the loading conditions foreseen in the design (vertical/horizontal bending). The out-of-plane bending resistance of the wall may be increased by up to three to four times, and the lower the compressive loads, the higher the flexural strength enhancement attained after FRCM/SRG reinforcement. FRCM/SRG composites can also be used to build reinforced masonry crowning beams (which provide the structure with a box-type behavior), or to realize transverse connectors (to prevent leaf/wythe separation in multi-leaf walls) or long connectors/strips (to prevent nearly rigid body overturning mechanisms).

Masonry walls may be reinforced with FRCM/SRG composites to increase their in-plane strength. The reinforcement is usually applied to the entire surface of the wall, preferably to both sides. Applications to one side only could also be designed, which require particular care for the assessment of the effects of asymmetry/eccentricity. Transverse connections may be also included in the design of the in-plane reinforcement to improve the substrate-to-FRCM/SRG load transfer capacity and provide the additional benefit that the in-plane shear strength of the wall can be increased up to about two to three times, especially in the

case of thin walls. Transverse connections can also enhance the mechanical properties of the masonry wall, which may lead to even larger increases of the shear strength, especially for relatively weak masonry walls.

The confinement of masonry columns with FRCM/SRG is an effective technique for increasing the compressive strength, which is based on the limitation of the lateral deformation. It is commonly accomplished by the application of a jacket made with one or more plies of fabric. The increase in the compressive strength is usually about 10 to 20 percent and strongly depends on the confining pressure provided by the FRCM/SRG jacket, which, in its turn, is related to the stiffness and strength of the FRCM/SRG system, the shape of the cross section of the column, and the mechanical properties of the masonry.

External bonded FRCM/SRG systems are also used to strengthen and repair arches and vaults. As for the case of the walls, the reinforcement supplies the lack in tensile strength of masonry, providing a significant increase in the load-carrying capacity. The reinforcement prevents the opening of the cracks in the vault, restraining the onset of a four-hinge collapse mechanism. The FRCM/SRG can be applied either to the extrados or to the intrados of the vault, providing an increase in the ultimate strength up to five times that of the unreinforced vault.

The following chapters provide guide for the design of the reinforcement and the assessment of the ultimate strength of FRCM/SRG-strengthened masonry walls under out-of-plane and in-plane loads, of columns, and of masonry arches and vaults.

6.1—Design philosophy

6.1.1 Design principles—The design philosophy is based on limit-state design principles to provide acceptable safety levels and is consistent with existing criteria, guides, and codes as listed below.

	
Acceptance criteria for masonry and concrete strengthening using FRCM and SRG composite systems – ICC-ES Acceptance Criteria AC434	RILEM TC 233 and RILEM TC 250 (de Felice et al. 2018a) recommendations

This guide can be used to design the FRCM/SRG strengthening system for existing individual masonry walls subject to in-plane and out-of-plane loads resulting from wind and earthquakes (ASCE 41; Eurocode 6 [EN 1996:1995-02]). The LDP designing the FRCM/SRG strengthening system for individual walls should evaluate the effect wall strengthening has on the overall structure. If appropriate, a global analysis of the overall structure should be performed (ASCE 41; Eurocode 6 [EN 1996:1995-02]). In strengthening of masonry members, the relationship between each element and the entire structure is particularly relevant. Specifically, the in-plane rigidity of floor diaphragms and the stiffness of the connections between the floor diaphragms and

the walls, as well as among intersecting walls themselves, can be critical to the global behavior of the building.

To evaluate the nominal strength of FRCM/SRG-strengthened masonry, all possible failure modes with associated strains and stresses in each material should be assessed. Material properties such as compressive and tensile strength, elastic modulus in compression, and shear strength of existing masonry, should preferably be determined by in-place tests or laboratory tests on extracted samples. If these are unavailable, conventional material properties of existing masonry may be obtained from available guidelines, including

	
ASCE 41 and TMS 402/602-16	Eurocode 6 – Design of Masonry Structures (Eurocode 6 [EN 1996:1995-02])

Dimensions of the masonry elements should be obtained from the existing drawings, field measurements, or both. If there are uncertainties regarding existing material strengths or substrate conditions, the licensed design professional (LDP) may wish to incorporate more conservative strength reduction factors than those discussed in this guide.

6.1.2 Design strength—

	
FRCM/SRG-strengthening of masonry members should be proportioned so that the design strength equals or exceeds the required strength. Design strength is the nominal strength multiplied by the strength reduction factor ϕ , as determined from a reliability-based calibration study that accounts for uncertainties in materials, fabrications, construction details, and geometric properties. If such a detailed reliability study is not available, the use of strength reduction factors ϵ as specified by TMS 402 is recommended. If there are uncertainties regarding existing material strengths or substrate conditions, the design professional may wish to incorporate more conservative strength reduction factors than those discussed in this guide.	FRCM/SRG strengthening of masonry members should be proportioned so that the design strength equals or exceeds the required strength. Design strength is the characteristic (5 percent fractile) strength divided by the partial coefficient γ , as determined from a reliability-based calibration study that accounts for uncertainties in materials, fabrications, construction details, and geometric properties. If there are uncertainties regarding existing material strengths or substrate conditions, the design professional may wish to incorporate more conservative partial coefficients than those discussed in this guide.

6.1.3 Required strength—The required strength should be determined in accordance with the strength design load combinations of the existing building code. The “existing building code” refers to the code adopted by a jurisdiction that regulates existing buildings. When the “existing building code does not provide factored load combinations, the FRCM/SRG-strengthening of masonry members should be designed to resist the combination of loads specified in

ASCE 7 (ACI) or Eurocode 6 (EN 1996:1995-02) (RILEM) for strength design. Members subject to compressive axial load should be designed for the factored moment accompanying the factored axial load.

6.2—Strengthening limits

For masonry structural members, FRCM/SRG strengthening limits are imposed to guard against failure of the strengthened element should the FRCM/SRG reinforcement become ineffective due to damage, vandalism, or other causes (ACI 440.2R). These limitations ensure that the masonry member, typically a gravity-load-carrying element, can resist sustained loads typically expressed as dead loads and a portion of the live loads without the contribution of the FRCM/SRG system.

In the case of masonry strengthening, FRCM/SRG systems are usually installed to increase the strength of URM or reinforced masonry walls subjected to special loading events such as earthquake, high wind, and blast loads. These loads are rare and typically not sustained. The probability of simultaneous occurrence of damage to FRCM/SRG—for example, from vandalism or exposure to high temperatures and high short-term loads such as that from earthquake or wind—is low; therefore, a strengthening limit for these applications is unnecessary. However, for cases of walls that are part of the primary lateral-load-resisting system, the LDP should evaluate the impact of the loss of FRCM/SRG strengthening in the global behavior of the structure. The evaluation should also consider that walls that are part of the lateral-load-resisting system can be subject to out-of-plane load, in addition to in-plane loads.

	
There are two cases, however, in which the strengthening limits should be considered. These cases include masonry elements that are subject to sustained loads such as columns resisting gravity loads and walls resisting out-of-plane loads due to earth pressure. For walls resisting out-of-plane loads due to earth pressures, the strength of the existing wall should be sufficient to meet the limitation given in the following	
$(\phi R_n)_{existing}^3 (0.9D + 1.15H)_{new}$	

6.3—FRCM/SRG design properties

FRCM/SRG design properties as described in this guide are obtained from tests performed in accordance to