IN-LB	Inch-Pound Units
SI	International System of Units

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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.

CONTENTS

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 (Triantafillou 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 Standardizaton (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)		