IN-LB Inch-Pound Units

SI International System of Units

Externally Bonded Fiber-Reinforced Polymer Systems Design and Construction for Strengthening Masonry Structures—Guide

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Fiber-reinforced polymer (FRP) systems can be used for strengthening masonry structures and masonry elements among other options such as external steel plates, section enlargement with reinforced concrete (RC) overlays or shotcrete, steel bracing, and internal steel reinforcement. FRP systems offer advantages over traditional strengthening techniques: they are lightweight, relatively easy to install, and are corrosion-resistant. Due to the characteristics of FRP materials as well as the behavior of masonry members strengthened with FRP, specific guidance on the use of these systems is needed. This document offers a description of the unique material properties of FRP and committee recommendations on the engineering, construction, and inspection of FRP systems used to strengthen masonry. These guidelines are based on the knowledge gained from experimental research, analytical work, and field applications of FRP systems used to strengthen masonry structures.

Keywords: buildings; columns; confinement; cracking; cyclic loading; detailing; earthquake resistance; fiber-reinforced polymers (FRPs); fibers; flexure; masonry; shear; strengthening; structural analysis; structural design; unreinforced; walls; wind resistance.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Masonry is a type of construction where clay units, concrete masonry units, or natural stones are laid in and bound together by mortar to form a building structure or a component in a structure. Masonry elements can be load-bearing or non-load-bearing. Masonry elements include walls, columns, pilasters, and beams.

Historically, most masonry, until the mid-twentieth century, was unreinforced. Due to damage of unreinforced masonry (URM) in the 1933 Long Beach, CA, earthquake, it was prohibited in seismically active regions, and reinforced masonry (RM) became more prevalent. During the nineteenth century, most of the URM building construction consisted of load-bearing mass-masonry walls. These walls are multi-wythe brick walls connected with brick headers, typically three or four wythes thick at the lowest stories and two wythes thick at the upper stories. From the late 1890s until the mid-1900s, URM was used in many transitional façades. These types of façades consist of steel or reinforced concrete frames that are filled with backup walls supported on spandrel beams, and an outer wythe that in many cases extends the entire building height and is supported only at grade. URM masonry elements were designed to rely on the strength of masonry alone to resist loads.

RM elements use steel reinforcement in grouted cells or embedded in horizontal mortar joints to resist tensile and shear stresses. RM construction became more common in the United States since the 1960s with the development of codes for structural masonry. However, there are examples of older RM structures built in the years following the 1933 Long Beach earthquake as a response to the poor performance of many URM buildings during this earthquake.

Unreinforced structures such as URM are particularly vulnerable to earthquakes and high winds, and many times strengthening is required to resist loads due to these events. Deterioration, change of use, structural modifications, and other factors may also necessitate strengthening of masonry structures or elements. The repair and retrofit/rehabilitation of existing masonry structures have traditionally been accomplished using conventional materials and construction techniques. Externally bonded steel plates, reinforced concrete overlays, installation of steel bars in grouted cells, and post-tensioning are just some of the many traditional techniques available. Fiber-reinforced polymer (FRP) composites have emerged as an alternative to traditional materials for strengthening masonry structures (ACI 440R). FRP materials are lightweight and resistant to corrosion. They exhibit high tensile strength and elastic modulus (carbon FRP), are impact-resistant and have electromagnetic transparency. These materials, which are available in a variety of forms including flat sheets and plates, reinforcing bars, and prestressing tendons of typically round cross section, provide the licensed design professional with flexibility in achieving desired performance.

Advantages of repair or strengthening masonry using FRP composites include easier handling and installation than other strengthening methods with resulting lower installation prices, and minimal dimensional changes to the structure. Disturbance to occupants and loss of usable space are commonly minimized. Dynamic properties of the existing structure remain unchanged because there is little weight addition or stiffness modification.

Disadvantages of using FRP may include inferior performance at elevated temperatures, requirements for protective coatings, degradation of mechanical properties after long-term exposure to certain environmental conditions such as extensive moisture intrusion and frequent freezing-and-thawing cycles, and the relatively higher level of site supervision and inspection required during construction. These disadvantages can typically be addressed by using protection systems suitably designed for the environment as well as testing to confirm the long-term design properties of FRP systems. In addition, due to different textures and uneven surfaces across masonry units and mortar joints, additional effort may be needed to properly prepare the masonry substrate to achieve adequate bond of the FRP system.

1.2—Scope

This guide provides recommendations for the selection and design of FRP systems limited to externally bonded FRP laminates and near-surface-mounted (NSM) FRP bars/strips for increasing or restoring the in-plane and out-of-plane strength of undamaged or damaged URM and RM walls and columns. Infill walls are not included in this guide.

The guide is applicable to masonry structures made of clay bricks, concrete masonry units, and natural stones using conventional types of mortar. The effectiveness of FRP systems is highly dependent on the adequate surface preparation of the masonry substrate. Masonry elements have different textures and uneven surfaces due to units and mortar joints that can affect the effectiveness of FRP systems if the masonry surface is not properly prepared.

For masonry with significant deterioration, questionable mortar bond, as well as cracking, element displacement, or both, traditional repair procedures may be required to be used in combination with FRP strengthening. Procedures and requirements for traditional methods for repair and strengthening of masonry are not covered in this guide. *Assessment and Retrofit of Masonry Structures* (Hamid and Schuller 2019) provides background and guidance for other methods for repair and strengthening.

Before starting the project, the licensed design professional should determine the design basis code (DBC) under which the evaluation, repair, and rehabilitation will be implemented. The DBC will establish the extent of the repairs and rehabilitation, evaluation methods, and design loads. The DBC is the code legally adopted by a jurisdiction, under which the assessments, repairs, and rehabilitations are designed and constructed. Depending on the jurisdiction and project conditions, the DBC can either be the International Existing Building Code (IEBC) or a local existing building code. This guideline does not cover code compliance requirements. Refer to ACI 562 for guidance on how to determine the DBC.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A_c = cross-sectional area of masonry in compression member, in.^{2} (mm^2)
A_e = cross-sectional area of effectively confined masonry section, in.^{2} (mm^2)
A_f = area of FRP external reinforcement, in.^{2} (mm^2)
$A_{f,bar}$ = area of one rectangular or circular FRP bar, in.^{2} (mm^2)
A_n = net cross-sectional area of member, in.^{2} (mm^2)
A_s = area of non-prestressed steel reinforcement, in.^{2} (mm^2)
a_b = smaller cross-section dimension for rectangular FRP bars, in. (mm)
b_b = larger cross-section dimension for rectangular FRP bars, in. (mm)
b_c = short side dimension of compression member, in. (mm)
b_m = width of masonry wall, in. (mm)
C_E = environmental reduction factor
c = distance from extreme compression fiber to the neutral axis, in. (mm)
c_s = distance from extreme compression fiber to the neutral axis at service, in. (mm)
d = distance from extreme compression fiber to centroid of tension reinforcement, in. (mm)
d_b = diameter of an FRP bar, in. (mm)
d_f = effective depth of FRP flexural reinforcement, in. (mm)
d_i = distance from centroid of the i-th layer of longitudinal FRP reinforcement to the extreme compression fiber, in. (mm)
d_v = effective masonry depth for shear calculations, in. (mm)
E_f = tensile modulus of elasticity of FRP, psi (MPa)
E_m = modulus of elasticity of masonry in compression, psi (MPa)
E_s = tensile modulus of elasticity of steel, psi (MPa)
E_2 = slope of linear portion of stress-strain model for FRP-confined masonry, psi (MPa)
e = eccentricity of axial load, in. (mm)
F_i = force in the i-th layer of longitudinal FRP reinforcement, lb (N)
f_a = axial compressive stress due to gravity loads, psi (MPa)
f_{cm}' = compressive strength of confined masonry, psi (MPa)
f_f = stress in FRP reinforcement, psi (MPa)
f_{fd} = design stress of externally bonded FRP reinforcement, psi (MPa)
f_{fe} = effective stress level in the FRP reinforcement; stress attained at section failure, psi (MPa)
f_{fs} = stress in the FRP reinforcement at service, psi (MPa)
f_{fu} = design ultimate tensile strength of FRP, psi (MPa)
f_{fu}^* = ultimate tensile strength of the FRP material as reported by the manufacturer, psi (MPa)
$\overline{f}_{fu}$ = mean tensile strength of FRP reinforcement based on a population of 20 or more tensile tests per ASTM D3039/D3039M, psi (MPa)
f_m = compressive stress of masonry, psi (MPa)
f_m' = specified compressive strength of masonry, psi (MPa)
f_s = stress in the steel reinforcement, psi (MPa)
f_{tm} = average value of the tensile strength of masonry, psi (MPa)
f_y = specified yield strength of non-prestressed steel reinforcement, psi (MPa)
h = effective height of wall or column, in. (mm)
h_c = long side dimension of compression member, in. (mm)
h_{eff} = height to resultant of lateral force, in. (mm)
k = coefficient to calculate the depth to the neutral axis at service
ℓ_{df} = development length of FRP, in. (mm)
ℓ_w = length of the wall, in. (mm)
M_n = nominal flexural strength, in.-lb (N-mm)
M_s = moment due to sustained loads at section, in.-lb (N-mm)
M_u = factored moment at section, in.-lb (N-mm)
n = number of plies of FRP reinforcement
P_n = nominal axial compressive strength of a masonry section, lb (N)
P_s = axial load due to all service loads, lb (N)
P_u = factored axial load, lb (N)
p_{fm}, p_{fv} = force per unit width for surface-mounted FRP systems, lb/in. (N/mm), or force per unit bar for NSM FRP systems, lb/bar (N/bar)
R_n = nominal strength of a masonry member
r = least radius of gyration of a section, in. (mm)
r_c = radius of edges of a prismatic cross section confined with FRP, in. (mm)
S_{DL} = dead load effects
S_H = lateral earth pressure effects
S_{LL} = live load effects
s_f = center-to-center spacing of FRP reinforcement, in. (mm)
T_g = glass-transition temperature, °F (°C)
t = nominal thickness of the wall, in. (mm)
t_f = nominal thickness of one ply of FRP reinforcement, in. (mm)
V_f = nominal shear strength provided by FRP reinforcement, lb (N)
V_n = nominal shear strength, lb (N)
V_u = factored shear force at section, lb (N)
w_f = width of FRP reinforcing plies, in. (mm)

α = angle of application of primary FRP reinforcement direction relative to longitudinal axis of member, degrees

α_L = longitudinal coefficient of thermal expansion, in./in./°F (mm/mm/°C)

α_T = transverse coefficient of thermal expansion, in./in./°F (mm/mm/°C)

β_1 = ratio of the depth of the equivalent rectangular stress block to the depth of the neutral axis, in. (mm)

ε_{bi} = strain in masonry substrate at time of FRP installation (tension is positive), in./in. (mm/mm)

ε_{cmu} = ultimate axial compressive strain of confined masonry, in./in. (mm/mm)

ε_{fd} = debonding strain of externally bonded FRP reinforcement, in./in. (mm/mm)

ε_{fe} = effective strain in FRP reinforcement attained at failure, in./in. (mm/mm)

ε_{fu} = design rupture strain of FRP reinforcement, in./in. (mm/mm)

ε_{fu}^* = ultimate rupture strain of FRP reinforcement as reported by the manufacturer

$\overline{\varepsilon}_{fu}$ = mean rupture strain of FRP reinforcement based on a population of 20 or more tensile tests per ASTM D3039/D3039M, in./in. (mm/mm)

ε_m = compressive strain in masonry, in./in. (mm/mm)

ε_m' = compressive strain of unconfined masonry corresponding to f_m', in./in. (mm/mm); it may be taken as 0.002

ε_{mu} = maximum usable compressive strain in masonry, in./in. (mm/mm)

ε_t' = transition strain in stress-strain curve of FRP confined masonry, in./in. (mm/mm)

ϕ = strength-reduction factor

γ = multiplier of f_m' to determine the intensity of an equivalent rectangular stress distribution for masonry

κ_a = efficiency factor for FRP reinforcement in determination of f_{cm}' (based on geometry of cross section)

κ_b = efficiency factor for FRP reinforcement in determination of ε_{cmu}' (based on geometry of cross section)

κ_m = bond-dependent coefficient for flexure

κ_v = bond-dependent coefficient for shear

κ_{vc} = efficiency factor for FRP reinforcement in determination of f_{cm}' (based on vertical spacing of FRP reinforcement)

κ_ε = efficiency factor equal to 0.55 for FRP strain to account for the difference between observed rupture strain in confinement and rupture strain determined from tensile tests

ρ_g = ratio of area of longitudinal steel reinforcement to cross-sectional area of a compression member ($A_s/(b_c h_c)$)

ρ_s = ratio of steel reinforcement

τ_b = average bond strength for near-surface-mounted FRP bars, psi (MPa)

ω_f = FRP reinforcement index

ψ_f = FRP strength-reduction factor

2.2—Definitions

Please refer to the latest versions of ACI Concrete Terminology and TMS 402/602 for a comprehensive list of definitions. Definitions provided herein complement those resources.

aramid fiber—fiber in which chains of aromatic polyamide molecules are oriented along the fiber axis to exploit the strength of the chemical bond.

aramid fiber-reinforced polymer—composite material comprising a polymer matrix reinforced with aramid fiber cloth, mat, or strands.

carbon fiber—fiber produced by heating organic precursor materials containing a substantial amount of carbon, such as rayon, polyacrylonitrile, or pitch, in an inert environment.

carbon fiber-reinforced polymer—composite material comprising a polymer matrix reinforced with carbon fiber cloth, mat, or strands.

catalyst—substance that accelerates a chemical reaction and enables it to proceed under conditions milder than otherwise required and that is not, itself, permanently changed by the reaction.

creep rupture—breakage of a material under sustained loading at stresses less than the tensile strength.

cross linking—formation of covalent bonds linking one polymer molecule to another.

E-glass—family of glass fibers used in reinforced polymers with a calcium aluminum borosilicate composition and a maximum alkali content of 2.0%.

fabric—two-dimensional network of woven, nonwoven, knitted, or stitched fibers; yarns; or tows.

fiber content—the amount of fiber present in a composite, expressed as a percentage volume fraction or mass fraction of the composite.

fiber fly—short filaments that break off dry fiber tows or yarns during handling and become airborne.

fiber-volume fraction—ratio of the volume of fibers to the volume of the composite containing the fibers.

fire retardant—additive to the resin or a surface coating used to reduce the tendency of a resin to burn.

full cure—period at which components of a thermosetting resin have reacted sufficiently for the resin to produce specified properties.

glass fiber—filament drawn from an inorganic fusion typically comprising silica-based material that has cooled without crystallizing.

glass fiber-reinforced polymer—composite material comprising a polymer matrix reinforced with glass fiber cloth, mat, or strands.

impregnate—to saturate fibers with resin or binder.

initiator—chemical used to start the curing process for unsaturated polyester and vinyl ester resins.

interlaminar shear—force tending to produce a relative displacement along the plane of the interface between two laminae.

intumescent coating—covering that swells, increasing volume and decreasing density, when exposed to fire imparting a degree of passive fire protection.

lamina—single layer of fiber reinforcement.