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Guide for the Design and Construction of Externally Bonded Fiber-Reinforced Polymer Systems for Strengthening Unreinforced Masonry Structures

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Fiber-reinforced polymer (FRP) systems are an option to consider for strengthening unreinforced masonry (URM) structures. Traditional strengthening systems include external steel plates, reinforced concrete (RC) overlays, span shortening with steel subframing or bracing, and internal steel reinforcement. Relative to traditional systems, features of FRP systems include high tensile strength, light weight, ease of construction, and resistance to corrosion. This guide offers general information on FRP systems use, a description of their unique material properties, and recommendations for the design, construction, and inspection of FRP systems for strengthening URM structures. These guidelines are based on knowledge gained from a comprehensive review of experimental and analytical investigations and field applications.

Keywords: buildings; cracking; cyclic loading; detailing; earthquake resistance; fiber-reinforced polymers; fibers; flexure; masonry; shear; structural analysis;structural design; unreinforced.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Masonry is a generic term used to describe a type of construction where clay, or concrete masonry units, or natural stones are bonded together to form a load-bearing structure or a component in a structure. Non-load-bearing masonry includes partitions and veneers.

Although masonry is used in flexural applications such as retaining walls, roof and floor beams, and lintels, it is more frequently used in load-bearing walls primarily resisting compression loads. Reinforced and unreinforced masonry (URM) walls have been used in constructing structural load-bearing components. In buildings, masonry walls can serve effectively as part of the lateral load-resisting system to resist wind and earthquake loads. Infill masonry walls play a significant role in enhancing in-plane stiffness and shear resistance of both reinforced concrete (RC) and steel frames, if properly connected to the structural frame.

Unreinforced masonry structures have shown their vulnerability to major events such as earthquakes, severe wind, blast, and impact. In addition, factors such as change in occupancy, deterioration, or an increase in lateral-load demand, may create the need to perform structural retrofit. ACI 530 covers the design and construction of new masonry; the repair, retrofitting, and rehabilitation of masonry structures are not included in that code.

The repair and retrofit/rehabilitation of existing masonry structures have traditionally been accomplished using conventional materials and construction techniques. Externally bonded steel plates, RC overlays, grouted cell reinforcements, and post-tensioning are just some of the many traditional techniques available. Fiber-reinforced polymer (FRP) (ACI 440R) composites have emerged as an alternative to traditional materials for strengthening masonry structures. Fiber-reinforced polymer materials are lightweight and noncorrosive. They exhibit high tensile strength and elastic modulus (carbon FRP), and are impact resistant with electromagnetic transparency. These materials, which are available in a variety of forms, including flat sheets and plates and reinforcing bars and prestressing tendons of typically round cross section, provide the licensed design professional with flexibility in achieving desired performance. Fiber-reinforced polymer systems can be used in seismic, wind, or blast strengthening of URM structural elements.

Advantages of retrofitting masonry using FRP composites include easier handling and installation with resulting lower installation prices, and minimal changes to the structure's appearance. Disturbance to occupants and loss of usable space are also minimized. Dynamic properties of the existing structure remain unchanged because there is little weight addition or stiffness modification. Disadvantages of using FRP may include diminished performance at elevated temperatures, requirement for protective coatings, degradation of mechanical properties after long-term exposure to certain environmental conditions such as extensive moisture intrusion and frequent wet freezing-and-thawing cycles, and the relatively higher level of site supervision and inspection required.

1.2—Scope

This guideline provides information on the selection and design of FRP systems limited to externally bonded FRP laminates and near-surface-mounted FRP bars/strips for increasing the in-plane and out-of-plane strength of existing ungrouted, grouted, or partially grouted URM walls; infill walls are not included in this guide. The guide is applicable to URM structures made of clay bricks, concrete masonry units, and natural stones using conventional types of mortar.

For masonry with significant deterioration, questionable mortar bond, and cracking and/or element displacement, traditional procedures may be required as well as FRP strengthening. The evaluation for the need to apply traditional modes of strengthening is not covered in this guide.

CHAPTER 2—NOTATION AND DEFINITIONS

ACI provides a comprehensive list of notation and definitions through an online resource, "ACI Concrete Terminology," http://terminology.concrete.org. Definitions provided herein complement that resource.

2.1—Notation

A_f = cross-sectional area of FRP reinforcement, in.^{2} (mm^2)
$A_{f,bar}$ = area of one rectangular and/or circular FRP bar, in.^{2} (mm^2)
A_n = area of net mortared/grouted section, in.^{2} (mm^2)
a_b = smallest dimension of a FRP rectangular bar, in. (mm)
b_b = largest dimension of a FRP rectangular bar, in. (mm)
C_E = environmental reduction factor
c = distance from the fiber of maximum compressive strain to the neutral axis, in. (mm)
c_s = distance from the fiber of maximum compressive strain to the neutral axis at service limit state, in. (mm)
D = dead load effect
d_b = diameter of a FRP bar, in. (mm)
d_f = effective depth of FRP flexural reinforcement, in. (mm)
d_i = distance of force F_i measured from the extreme compression fiber, in. (mm)
E_f = tensile modulus of elasticity of FRP, psi (MPa)
E_s = tensile modulus of elasticity of steel, psi (MPa)
e = eccentricity of axial load, in. (mm)
F_i = force acting on the i-th FRP strip, lb (N)
f_a = axial compressive stress due to gravity loads, psi (MPa)
f'_{dt} = specified masonry diagonal tension strength, psi (MPa)
f_f = stress in the FRP reinforcement, psi (MPa)
f_{fe} = effective stress level in the FRP reinforcement, 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 ultimate tensile strength of FRP reinforcement based on a population of 20 or more tensile tests per ASTM D3039/D3039M, psi (MPa)
f'_m = specified masonry compressive strength, psi (MPa)
f_{tm} = average value of the tensile strength of masonry, psi (MPa)
H = lateral earth pressure effect
h = effective height of the wall, in. (mm)
h_{eff} = height to resultant of lateral force, in. (mm)
k = coefficient accounting for the boundary conditions of the wall
L = length of the wall, in. (mm)
ℓ_d = development length, in. (mm)
M_n = nominal flexural strength, in.-lb (N-mm)
M_s = moment due to sustained loads, in.-lb (N-mm)
M_u = factored moment, in.-lb (N-mm)
n = number of plies of FRP laminates, and number of circular and rectangular bars, or both