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Shear strengthening of un-reinforced concrete masonry walls with fabric-reinforced-cementitious-matrix

Saman Babaeidarabad *, Diana Arboleda, Giovanni Loreto, Antonio Nanni

Department of Civil, Architectural, and Environmental Engineering, University of Miami, Miami, FL 33146, USA

HIGHLIGHTS

- The effectiveness of FRCM composite for strengthening of masonry walls was investigated.
- A total of nine concrete masonry wall panels, 1.2 m × 1.2 m in size, were tested under diagonal compression.
- FRCM and FRP strengthened walls were compared after normalizing the data.
- The experimental results were also compared with analytical model predictions.

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ABSTRACT

In this paper, the in-plane behavior of un-reinforced concrete masonry walls externally strengthened with a fabric-reinforced cementitious matrix (FRCM) system is investigated. The experimental program consists of testing nine un-reinforced concrete masonry walls strengthened on both sides with two different FRCM schemes (one and four reinforcement fabrics). The analytical model as per ACI 549-13 is used to predict the shear capacity of the strengthened walls. The effects of design limitations in the approach proposed by ACI 549-13 are also discussed. Finally, experimental data from other research programs using fiber-reinforced polymer (FRP) composites are presented to demonstrate that when normalized shear capacity is related to a calibrated reinforcement ratio, the two overlay strengthening technologies match well.

1. Introduction

Masonry is one of the oldest construction materials. Un-reinforced masonry (URM) walls are a widespread construction practice around the world, but are not well-suited to withstand in-plane loading and may exhibit brittle failure followed by scattering of debris. Retrofitting masonry walls with techniques such as externally-bonded fiber reinforced polymer (FRP) and near surface mounted (NSM) FRP bars effectively enhances shear capacity and pseudo-ductility, and controls the scatter of fragments which can be a threat to life [1–7]. Depending on the masonry's physical and mechanical properties, the failure modes of URM walls subjected to in-plane loading as identified by tests [1–11], ACI 440-10 [12], and ASCE 41 [13], are: diagonal tensile cracking, joint sliding, and toe crushing. Diagonal tensile cracking typically occurs with the formation of a single diagonal crack through concrete masonry units. Shear sliding can form along a single mortar bed joint or along multi-bed and head joints in a step format. Toe crushing failure may occur at the compressed corners.

Grando et al. [1] and Tumialan [10] performed experiments by applying diagonal compression to concrete masonry walls retrofitted with externally-bonded glass FRP (GFRP) laminates or GFRP NSM bars in the mortar joints. Results showed a remarkable enhancement in shear capacity. Likewise, Li et al. [2] carried out an experimental program on concrete masonry walls under diagonal compression after strengthening them with different schemes of GFRP NSM bars or GFRP strips. Strengthened walls showed significantly improved in-plane behavior in terms of load carrying capacity and pseudo-ductility. Yu et al. [11] tested under diagonal compression concrete block walls strengthened externally with different amounts of GFRP grid-reinforced polyurea. The results again showed considerable improvements in shear capacity.

The popularity of FRP stems from its lightweight, simplicity of application, and availability in different forms such as pre-cured laminates, sheets, grids, and bars [12,14]. Despite improvement in terms of strength and pseudo-ductility, the externally-bonded FRP technology has some limitations: inability to install FRP on damp

* Corresponding author. Tel.: +1 732 298 4859.
E-mail addresses: s.babaeidarabad@umiami.edu (S. Babaeidarabad), d.arboleda@umiami.edu (D. Arboleda), giovanni.loreto.gl@gmail.com (G. Loreto), nanni@miami.edu (A. Nanni).

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Nomenclature

A_f	area of mesh reinforcement by unit width, mm^2/mm (in^2/in)
A_m	interface loading area between steel shoe and wall, mm^2 (in^2)
A_n	net area cross-sectional of masonry wall, mm^2 (in^2)
E_f^*	tensile modulus of elasticity of the un-cracked FRCM specimen, GPa (ksi)
E_f	tensile modulus of elasticity of the cracked FRCM specimen and other strengthening system, MPa (ksi)
E_m	modulus of elasticity of masonry wall, MPa (ksi)
f_c	compressive strength of mortar, MPa (psi)
f_{ft}	transition stress corresponding to the transition point, MPa (psi)
f_{fu}	ultimate tensile strength of FRCM, MPa (ksi)
f_{fv}	design tensile strength of FRCM shear reinforcement, MPa (ksi)
f'_m	compressive strength of masonry, MPa (psi)
f'_t	tensile strength of masonry, MPa (psi)
G	shear modulus of rigidity of masonry wall, GPa (ksi)
h	concrete block height, mm (in)
H	wall height, mm (in)
L	wall length in the direction of the shear force, mm (in)
n	number of fabric layers
P	applied load (geometrically 1.414 times the shear force in a square wall, kN (kip)
t	wall thickness, mm (in)
V_c	masonry wall shear capacity due to compression failure, kN (kip)
V_{dt}	masonry wall shear capacity due to diagonal tension failure, kN (kip)
V_f	contribution of FRCM to nominal shear strength of the wall, kN (kip)
V_m	contribution of masonry to nominal shear strength of the wall, kN (kip)
V_n	nominal shear strength, kN (kip)
V_{sf}	masonry wall shear friction capacity, kN (kip)
V_{ss}	masonry wall shear sliding capacity, kN (kip)
w	length of concrete block, mm (in)
θ	inclined angle between horizontal and main diagonal of wall, deg
μ	pseudo-ductility of masonry wall
μ_0	coefficient of internal shear friction in mortar joint
μ_m	modified coefficient of internal shear friction in mortar joint
γ_{cr}	shear strain at cracking, mm/mm (in/in)
γ_u	shear strain of the masonry at ultimate, mm/mm (in/in)
ε_{ft}	transition strain corresponding to the transition point, mm/mm (in/in)
ε_{fu}	ultimate tensile strain of the FRCM, mm/mm (in/in)
ε_{fv}	design tensile strain of FRCM shear reinforcement, mm/mm (in/in)
σ_c	principal compression stress at the center of wall induced by diagonal forces, MPa (psi)
σ_t	principal tension stress at the center of wall induced by diagonal forces, MPa (psi)
τ_0	shear bond strength in mortar joint, MPa (psi)
$\tau_{0,m}$	modified shear bond strength in mortar joint, MPa (psi)
τ_{cr}	shear stress at cracking, MPa (psi)
τ_u	shear stress of the masonry at ultimate, MPa (psi)
Φ_v	strength reduction factor for shear
ω_f	calibrated reinforcement ratio
ρ	the ratio between area of FRCM/FRP reinforcement and net area of URM walls

substrate; poor behavior of the resin at temperatures above its glass transition temperature; and, lack of vapor permeability, which may cause damage to the substrate [14–17]. An opportunity exists to complement FRP systems with an alternative that replaces the organic binder (e.g., epoxy) with an inorganic one (e.g., cementitious mortar) [15–17]. Accordingly, fabric-reinforced cementitious matrix (FRCM) has emerged as an innovative external retrofit technology. FRCM was introduced in previous studies [16–21] for both new construction and repair (the topical area of interest in this paper) under various terms, namely: textile reinforced mortar (TRM), textile reinforced concrete (TRC), cementitious matrix-grid (CMG), or inorganic matrix-grid (IMG) composite.

Parisi et al. [3] and Prota et al. [21] performed comprehensive experimental studies on tuff masonry under diagonal compression after externally strengthening with FRCM. Their experimental results showed that retrofitted walls achieved higher shear strength and pseudo-ductility. Papanicolaou et al. [16,17] studied the effectiveness of FRCM to retrofit perforated clay brick/solid stone block walls subjected to in-plane and out-of-plane cyclic loading. Results showed again that FRCM provided substantial enhancements in terms of shear capacity and pseudo-ductility, proportionally to the number of reinforcement layers. Babaeidarabad et al. [22–24] tested clay brick masonry walls strengthened with carbon-FRCM reinforcement under diagonal compression and out-of-plane loading. Retrofitted walls showed significant enhancements in terms of strength and pseudo-ductility.

This paper presents an experimental program where un-reinforced concrete masonry walls were externally retrofitted on both sides with carbon-FRCM and subjected to diagonal compression. FRCM consists of a sequence of one or four layers of carbon fabric applied to the wall surface through a mortar reinforced with short fibers. The mortar is made of combinations of Portland cement, silica fume and fly ash acting as the inorganic binder plus silica sand. The fabric consists of primary direction and secondary direction strands where polymeric coatings are applied to the fibers only to enhance the long-term durability and to prevent problems associated with handling and installation [15]. Results of this project are compared with the existing experimental database obtained on concrete masonry walls strengthened with FRP under the same test setup configuration showing that the two overlay strengthening technologies are comparable and provide similar results. Following ACI 549-13 [25] provisions, shear capacity is calculated for both prediction and design.

2. Experimental program

2.1. Specimens

Nine un-reinforced concrete masonry walls, 1220 by 1220 by 92 mm (48 by 48 by 3.63 in), were fabricated in a running bond pattern by a professional mason to ensure compliance with good construction practices. Six walls were externally strengthened with 1-ply and 4-ply FRCM covering both faces of the wall. In accordance to the requirements of AC434-13 [26], 1-ply and 4-ply were tested as the possible extreme amounts of reinforcement. A 4-ply FRCM system was selected as the highest level of reinforcement possible.

2.2. Material characterization

The nominal dimensions of the concrete blocks used in the construction of the walls were 102 by 203 by 406 mm (4 by 8 by 16 in), with a net area of 24,322 mm^2 (37.7 in^2). Four prisms were built with three stacked concrete blocks match-cured with the walls. Testing (ASTM C1314-12 [27]) resulted in an average net-area compressive strength of 19.5 MPa (2823 psi) and a coefficient of variation (C.O.V) of