OUT-OF-PLANE STRENGTHENING OF UNREINFORCED MASONRY WALLS USING FRP

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Abstract

Unreinforced masonry (URM) structures constitute both a significant portion of the world's heritage buildings and a significant component of the modern residential building stock, and are particularly susceptible to damage from out-of-plane loads such as those generated by earthquakes (Ingham and Griffith 2011). Consequently, there is a considerable need for the development of economical and effective seismic strengthening techniques for URM construction. This study investigates the performance of near surface mounted (NSM) carbon fibre reinforced polymer (CFRP) strengthened clay brick masonry walls under monotonic and cyclic out-of-plane bending with particular attention to the FRP-to-masonry joint behaviour.

Fourteen NSM carbon FRP-to-masonry pull tests were conducted to study the FRP-to-masonry bond behaviour and to investigate the effect that variables such as cyclic loading and FRP strip dimensions have on the debonding resistance of a NSM FRP-to-masonry joint. The pull tests results were then incorporated into a large database of FRP retrofitted masonry pull test results by various researchers over the past 10 years. An empirical model was derived for the intermediate crack (IC) debonding resistance of FRP-to-masonry joints using a large set of test data from the open literature (Kashyap et al. 2012). Further, in order to predict the global load-slip response of FRP-to-masonry pull tests using various local bond-slip relationships two analytical procedures, namely a new generic numerical procedure and a closed-form mathematical solution, were developed which account for the partial-interaction response at the FRP-masonry interface (Kashyap et al. 2011).

Fifteen walls were tested in this study to investigate the behaviour of NSM CFRP retrofitted masonry walls under out-of-plane bending and investigate the IC debonding failure mechanism in them. Also, the effects of typical design variables such as reverse cyclic loading, axial pre-compression, FRP strip spacing and reinforcement ratio on the stiffness, displacement capacity and ultimate strength of FRP retrofitted masonry walls were studied. The test results demonstrated that NSM

CFRP strips designed to fail by IC debonding can provide an increase in strength of up to 20 times the strength of the corresponding unreinforced wall highlighting the effectiveness of the retrofitting scheme used. With respect to the test variables under investigation it was found that FRP strip spacing and reinforcement ratio strongly affect wall performance whereas cyclic loading and vertical pre-compression had little effect.

Finally, a simple design methodology has been developed for masonry walls retrofitted with vertical CFRP strips with IC debonding as the preferred failure mechanism. This design methodology will provide solutions for choosing the FRP strip dimensions (b_p and t_p) and spacing (S). Importantly, the methodology is generic in the sense that it can be used for any type of FRP material and both externally bonded (EB) and NSM retrofit techniques. It also enables the FRP retrofit to be optimised in terms of both the strip spacing and cross-section.

Overall, the results of this study show that the proposed NSM technique is structurally efficient and viable for seismic retrofitting of URM structures. Moreover, implementation of the proposed technique could have a significant impact in strengthening of masonry structures including conservation of the heritage buildings with considerable historical importance.

Statement of Originality

I, Jaya Kashyap certify that this work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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Publications

Journal Papers

Kashyap J, Griffith M, Mohamed Ali MS, and Oehlers D (2011). "Prediction of load-slip behavior of FRP retrofitted masonry." Journal of Composites for construction, 15(6):943–951.

Kashyap J, Willis CR, Griffith MC, Ingham JM, Masia M. (2012). "Debonding resistance of FRP-to-masonry joints", Engineering structures, 41(8):186–198.

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Conference Papers

Kashyap J, Willis CR, and Griffith MC (2011). "Influence of spacing on flexural strength of FRP reinforced masonry walls," Proceedings, 9^{th} Australasian Masonry Conference, Queenstown, New Zealand, 15 – 18 February.

Kashyap J, Griffith MC, and Mohamed Ali MS (2012). "Experimental study on flexural behaviour of FRP retrofitted masonry walls," Proceedings, FRP Composites in Construction (CICE) conference, Rome, Italy, 13-15 June.

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Notation

a	length of the micro-cracking region at the interface
a_d	magnitude of a corresponding to the beginning of macro-cracking
a_{de}	demand acceleration in units of acceleration due to gravity, g
a_{exp}	horizontal acceleration to cause F_{max}
a_u	maximum length of the interface that is softened
a_{URM}	horizontal acceleration to cause F_{URM}
A_{FRP}	total area of FRP used to retrofit a specimen
A_m	cross-sectional area of masonry
A_p	cross-sectional area of FRP plate
b_p	depth of FRP plate/strip
b_f	width of IC debonding failure plane
B	bond force
c	depth of neutral axis in a section
C	statistical coefficient
C_m	masonry compressive force
d_f	depth of IC debonding failure plane
ds/dx	slip strain/ relative slip between FRP and substrate at the interface
E	elastic Modulus of masonry
E_a	elastic modulus of adhesive
E_b	elastic Modulus of brick unit
E_m	elastic Modulus of mortar
E_p	elastic Modulus of FRP
$(EA)_m$	axial rigidity of masonry
$(EA)_p$	axial rigidity of retrofitting plate/strip
f_a	tensile strength of adhesive
f_c	cylinder compressive strength of concrete
f_d	design compressive stress
f_{mc}	compressive strength of masonry
f_{mt}	flexural tensile strength of masonry perpendicular to bed joints
f'_{mt}	characteristic flexural tensile strength of the masonry
f_{rupt}	rupture stress of FRP strip
f_{ut}	flexural tensile strength/ lateral modulus of rupture of brick units

F	applied load for wall
F_{max}	maximum applied load for wall
F_{IC}	applied load at the onset of debonding (wall test)
F_{URM}	unreinforced masonry bending capacity
g	equivalent accelerations
G_f	fracture energy/area beneath bond-slip curve
h_{crack}	crack height
H	wall height
k	interfacial ductility index
k_{mt}	bending moment capacity factor
k_p	perpend factor to allow for the degree of stretcher overlap
l_b	length of the brick unit
L	length of bonded region of the strip/plate
L_{eff}	critical bond length (or effective bond length)
L_{per}	perimeter of the debonding failure plane
m	statistical coefficient
M	moment
M_{ch}	horizontal bending capacity of a section of the masonry
M_{cv}	vertical bending capacity
M_d	design moment
M_{exp}	experimental moment capacity of wall
M_{URM}	bending moment capacity of unreinforced masonry section
M_{pred}	predicted moment capacity of wall
n	statistical coefficient
n_p	number of plates/strips
N	number of tests
N_a	applied axial load
N_s	self-weight of the wall
P	axial force in plate
P_{exp}	experimental IC debonding resistance/bond strength
P_{IC}	predicted IC debonding resistance/bond strength
P_L	axial force in the strip/plate at the crack face
P_{rupt}	tensile rupture capacity of FRP strip
S	horizontal spacing between the vertical FRP strips

S_{max} maximum horizontal strip spacing to avoid horizontal bending failure between strips

t_b/t_d thickness of failure plane surrounding FRP plate/strip

t_m thickness of masonry wall

t_p thickness of FRP plate/strip

u_m displacement of the masonry

u_p displacement of the FRP strip

w_d uniformly distributed lateral load

w_{exp} experimental lateral load capacity of wall

W wall width

x longitudinal position

z lever arm

Z_{d} section modulus of bedded area

Z_p lateral section modulus of the perpends

Z_u lateral section modulus of the masonry units

ρ reinforcement ratio

ρ_b balanced reinforcement ratio

η efficiency factor

Φ capacity reduction factor

δ interfacial slip

δ_1 slip at which τ_{max} occurs

δ_{max} slip at which macro cracking occurs

δ_L slip at the loaded end

Δ global slip (pull tests)/ mid-height wall deflection

ΔL incremental length along FRP strip (equal to strain gauge spacing)

Δ_s change in slip

Δ_{max} maximum slip at loaded end (pull test)

Δ_{ult} maximum mid-height wall deflection

ε strain

$\Delta\varepsilon$ change in strain over length ΔL

ε_{crack} cracking strain of the mortar

ε_{db} strain at onset of debonding

ε_{max} maximum experimental strain

ε_p	interfacial strain of FRP plate/strip
ε_m	interfacial strain of masonry
ε_{rupt}	rupture strain of FRP plate/strip
σ_{exp}	maximum experimental tensile stress
σ_m	axial stress in masonry
σ_p	axial stress in the FRP strip
σ_v	axial stress applied to the walls
γ	specific weight of masonry
τ	interfacial shear stress
τ_b	interfacial shear stress for brick
τ_{avg}	average interfacial shear stress over the strip length ΔL
τ_m	interfacial shear stress for masonry
τ_{mo}	interfacial shear stress for mortar
τ_{max}	maximum FRP-substrate interfacial shear stress
φ_f	IC debonding failure plane aspect ratio
α	$\frac{2(P_{IC}+N_s+N_a)}{\varepsilon_{db}E_m S}$, coefficient
β_o	$\left(1/E_p + A_p/(EA)_m\right)$, constant
β_1	L_{per}/A_p , constant
β_2	$\beta_1\beta_0$, constant
λ	$\sqrt{\frac{\tau_{\max}L_{per}}{\delta_{\max}(EA)_p}}$, constant
λ_1	$\sqrt{\frac{\tau_{\max}\beta_2}{\delta_1}}$, constant
λ_2	$\sqrt{\frac{\tau_{\max}\beta_2}{(\delta_{\max}-\delta_1)}}$, constant
λ_3	$\lambda_2\frac{(\delta_{\max}-\delta_1)}{\delta_{\max}}$, constant

List of Abbreviations

AFRP	Aramid fibre reinforced polymer
AS	Australian Standards
Bond-slip	Interfacial shear-stress/slip relationship
CFRP	Carbon fibre reinforced polymer
CI	Curvature incompatibility
COV	Coefficient of variation
EB	Externally bonded
FRP	Fibre reinforced polymer
GFRP	Glass fibre reinforced polymer
IC	Intermediate crack
LVDT	Linear variable differential transformer
MVG	Magnetic volt gauge
NSM	Near surface mounted
PI	Partial interaction
PE	Plate end
RC	Reinforced concrete
URM	Un-reinforced masonry
UV	ultraviolet