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Out-of-plane strengthening of unreinforced masonry walls using near surface mounted fibre reinforced polymer strips

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ABSTRACT

The development of cost effective and minimally-invasive seismic retrofit techniques is required for clay brick unreinforced masonry (URM) buildings because of their poor performance in past earthquakes. A laboratory-based experimental program was implemented to address this need, having well-defined but artificial boundary conditions, and utilising constituent construction materials that replicated the characteristics of masonry found in historic URM buildings. The purpose of this experimental program was to investigate the performance of near-surface mounted (NSM) carbon fibre reinforced polymer (CFRP) strips as a seismic retrofit solution for improving the out-of-plane performance of walls in URM buildings. In the experimental testing program nine masonry beams and five full-scale masonry walls were tested. Details of the design methodology for flexural retrofit of URM walls using the NSM CFRP retrofit technique and laboratory test results are reported. The results of the experimental tests confirmed that the NSM CFRP retrofit technique is a minimally-invasive option for seismic strengthening of URM walls to resist out-of-plane earthquake induced lateral forces. Two recent case-study projects that implemented the NSM CFRP technique are also briefly presented.

1. Introduction

One of the most critical deficiencies of historic clay brick unreinforced masonry (URM) buildings is the out-of-plane failure mechanism induced by lateral earthquake loads [1–3]. This failure mechanism is inhibited via the addition of adequate wall-diaphragm connections at the building's roof and floor levels. However, in high and moderate seismic zones the sudden and unstable out-of-plane failure of walls acting in either one-way or two-way bending endangers their vertical load-carrying capacity. Hence, the out-of-plane failure mechanism can result in extensive damage and potential catastrophic collapse, posing a significant life-safety hazard to both building occupants and nearby pedestrians.

In response to the hazard posed by out-of-plane failure of URM walls a number of conventional improvement techniques have been implemented in the past, such as the installation of unbonded posttensioning, the provision of vertical inter-storey wall supports typically in the form of steel or concrete strong-backs (illustrated in Fig. 1a), bonded surface overlays, or application of a shotcrete layer. However, when considering the viability of any retrofit intervention for an historic building it is necessary to appraise the impact on aesthetics, the practicality, time and labour demand of installation, and the cost and mass addition to the structure. These issues may be overcome by using fibre reinforced polymer (FRP) material in the form of near-surface mounted (NSM) FRP bars and strips to strengthen and increase the ductility capacity of URM walls subjected to in-plane and out-of-plane earthquake loading [4–6]. Using the NSM technique provides several advantages over externally bonded (EB) overlay sheet and plate reinforcement which include significantly higher axial strain at debonding, protection from fire and the environment, minimal impact upon the aesthetics of the structure, and reduced construction time [7,8]. These advantages result in the NSM technique being a cost effective and minimally-invasive (see Fig. 1b) option for seismically strengthening URM buildings when compared to other conventional techniques.

A design methodology for NSM FRP when bonded to vintage clay brick multi-leaf URM walls in order to improve flexural capacity of URM wall is proposed and an experimental study was conducted in order to acquire results enabling interrogation of the adequacy of this design methodology. It is intended that the proposed design methodology be incorporated into design guidelines for the out-of-plane seismic strengthening of multi-leaf clay brick URM walls.

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Nomenclature

Roman

a	compression block, mm
a_d	demand acceleration (units of 'g', acceleration normalised by acceleration of gravity)
A_p	cross-sectional area of FRP, mm^2
b_f	width of the groove cut, mm
b_p	width of FRP strip, mm
c	depth of compression block (neutral axis location), mm
C_m	masonry compressive force, kN
d_f	depth of the groove cut, mm
$(EA)_p$	axial stiffness of the FRP, MPa mm^2
E_p	modulus of elasticity of FRP, MPa
E_m	masonry modulus of elasticity, MPa
f'_b	average brick compressive strength, MPa
f_d	the (minimum) design compressive stress on the bed joint at the cross-section under consideration, MPa
f'_{fb}	characteristic flexural bond strength of masonry, MPa
f'_j	average mortar compressive strength, MPa
f'_m	average masonry compressive strength, MPa
f'_p	average plaster compressive strength, MPa
f_{rup}	average brick rupture strength, MPa
f'_{up}	FRP tensile strength, MPa
h_w	height of wall, mm
I_g	gross moment of inertia of a section, mm^4
K_e	effective stiffness, kN/mm
K_{exp}	effective stiffness of the relative cycle, kN/mm
K_g	analytical gross stiffness, kN/mm
l	length of wall, mm
L_b	length of beam, mm
L_{per}	perimeter of the debonding failure plane, mm
M	mid-span moment, kN m
M^*_d	vertical moment demand, kN m
M_{ch}	horizontal bending capacity of the URM wall, kN m/m
M_{exp}	maximum experimentally measured bending moment, kN m
M_{IC}	predicted bending moment, kN m
M_n	nominal moment resistance of wall section, kN m
N_t	overburden weight at mid-section of wall, kN
N_n	nominal axial compression force, kN
P	applied force, kN
P_o	overburden load, kPa
P_{IC}	axial force in the FRP required to cause the onset of intermediate crack (IC) debonding in clay brick masonry, kN
P_u	maximum applied point load, kN
$P_{rupture}$	tensile rupture capacity of FRP, kN
s	design strip spacing, m
t_b	distance from edge of strip to edge of groove cut, mm
t_d	distance from edge of strip to edge of groove cut, mm
t_m	thickness of URM wall, m
T_p	FRP tensile force, kN
t_p	thickness of FRP strip, mm
V_o	maximum applied total lateral force for as-built wall, kN
V_u	maximum applied total lateral force for retrofitted wall, kN
Z_d	section modulus of the bedded area, mm^3/m
Z_u	lateral section modulus of the masonry units, in cubic mm per m length based on the gross cross-section

Greek

Δ	experimentally measured mid-span displacement, mm
γ	specific weight of masonry, kN/m^3
μ	bed-joint coefficient of friction
ε_{db}	FRP debonding strain
ε_m	masonry strain
ε_{db}	rupture strain of FRP
φ_{ch}	strength reduction factor for horizontal bending of masonry in accordance with AS 3700
φ_f	failure plane aspect ratio

1.1. Previous research

Initial experimental validation of NSM FRP as a technique for the seismic improvement of URM buildings involved laboratory testing that focused on strengthening modern single leaf masonry walls, and based on these experimental results an analytical model that predicts the masonry to FRP bond behaviour was developed by Willis et al. [9] and later modified by Kashyap et al. [10]. A companion study was conducted by Dizhur et al. [11] to investigate the bond behaviour of FRP to vintage clay brick masonry and a model predicting the ultimate pull out capacity of the NSM FRP strips was further improved.

Although most URM walls are considered to have supports on at least one vertical edge and one horizontal edge, thus being capable of developing two-way actions [12], most simplified methods for out-of-plane loaded wall analysis and evaluation are focused on

(a) External view showing extensive through-wall anchorage of internal steel strong backs installed for increased out-of-plane wall stability

(b) URM wall following NSM retrofit installation

Fig. 1. Extensive through-wall anchorage of internal steel strong backs and NSM retrofit.