Engineering Structures 50 (2013) 126–136

Contents lists available at SciVerse ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Static cyclic in-plane shear response of damaged masonry walls retrofitted with NSM FRP strips – An experimental evaluation

K.M.C. Konthesingha [a,*], M.J. Masia [a], R.B. Petersen [a], N. Mojsilovic [b], G. Simundic [a], A.W. Page [a]

[a] Centre for Infrastructure Performance and Reliability, School of Engineering, The University of Newcastle, Callaghan, NSW 2308, Australia
[b] Institute of Structural Engineering, Department of Structural, Environmental and Geomatic Engineering, ETH Zurich 8093, Switzerland

ARTICLE INFO

Article history:
Available online 14 December 2012

Keywords:
Masonry
Strengthen/retrofit
Cyclic in-plane shear
NSM
FRP

ABSTRACT

An experimental study was conducted to assess the effect on strength and ductility of retrofitting unreinforced masonry (URM) shear panels with near surface mounted (NSM) carbon fibre reinforced polymer (CFRP) strips. A total of sixteen wall panels, 1200 mm × 1200 mm, were subjected to vertical pre-compression combined with increasing reversing cycles of in-plane lateral displacement. All wall panels were previously tested (prior to retrofitting) under compression and cyclic shear using three different pre-compression levels resulting in various levels of damage. The damaged walls were repaired, retrofitted with NSM FRP strips and retested under pre-compression stress levels of 2.8 MPa, 2 MPa and 1.4 MPa. The retrofitted walls displayed higher displacement capacities compared with URM walls highlighting the effectiveness of retrofitting URM walls under earthquake loading. The ultimate loads were not enhanced due to retrofitting under higher pre-compression levels. However the presence of the reinforcement did restore the ultimate loads to those observed for the original undamaged URM state. This meant that overall, the reinforcement was effective in increasing the energy dissipation capacity of the walls compared to URM. The improvements in the behaviour of the URM walls due to retrofitting were generally similar, irrespective of the amount of damage the URM walls experienced prior to retrofitting. The paper discusses the effect on strength, displacement capacity, energy dissipation and ductility achieved by FRP retrofitting of the damaged (lightly and highly) URM panels compared to the undamaged URM panels under different pre-compression levels. The broader aim of the research is to identify techniques for improving the seismic performance of existing URM walls under in-plane shear loading.

1. Introduction

Due to its high seismic mass, low tensile strength and limited ductility, unreinforced masonry (URM) construction is highly vulnerable to damage from earthquake loading. Fibre reinforced polymer (FRP) strengthening is emerging as an effective seismic retrofitting technique to improve the earthquake resistance of URM walls. This method has several advantages compared with conventional retrofitting techniques. FRP materials have a high strength and stiffness to weight ratio and high durability. Also, there is a minimal loss of usable space due to the strengthening application and it is relatively easy to install [1–4]. In addition to the above advantages, FRP reinforcement will also resist crack propagation [5].

The FRP reinforcement is either externally bonded (EB) to the surface of a wall or inserted into grooves cut into the surface of a wall. The latter is referred to as near surface mounting (NSM). Compared to externally bonded (EB) FRP reinforcement, the NSM technique has several advantages such as: development of higher strain in the FRP before debonding, protection from vandalism and, to some extent, from fire and other environmental influences. It also has a minimal impact on the aesthetics of the structure [6]. The grooves required to be cut into the wall surface may cause cracking planes through the thickness of the wall which is a possible disadvantage of the NSM FRP retrofitting technique.

Numerous research studies have used EB FRP techniques to strengthen/retrofit masonry shear walls under both monotonic and cyclic loading cases [4,7–16]. But only few studies reported the use of the NSM FRP technique for URM shear wall strengthening. Tinazzi and Nanni [17], Tumialan et al. [18], Li et al. [19,20]; Silva et al. [21] and Turco et al. [22] used the NSM strengthening technique with FRP bars (i.e. structural repointing (SR)) to investigate its effectiveness with masonry shear walls. Li et al. [20] conducted their study under a cyclic loading pattern while the other studies listed above used monotonic loading. Petersen [6] and Mahmood and Ingham [16] investigated the use of the NSM FRP strengthening technique with FRP strips in which the strips were embedded into thin slots cut into the surface of the masonry. The tests were conducted under monotonic loading. It was found

* Corresponding author. Tel.: +61 2 4921 6956; fax: +61 2 4921 6991.
E-mail address: Chaminda.Konthesingha@uon.edu.au (K.M.C. Konthesingha).

0141-0296/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engstruct.2012.10.026

that the technique was effective in improving the strength and ductility of URM shear panels which failed by diagonal cracking or bed joint sliding. Considering the FRP strips and bars, thin rectangular FRP strips are more efficient than FRP bars in terms of debonding resistance [23].

To assess the effectiveness of a strengthening technique under earthquake loading, researchers have used either virgin URM panels strengthened using the technique, cracked URM panels repaired and strengthened with a retrofitting technique, or both. Strengthening and retesting previously damaged wall panels is a more representative way to assess the effectiveness of retrofitting techniques in earthquake affected buildings with some damage. Several researchers [9,12,24–27] have used previously cracked wall panels with EB FRP retrofitting to identify the effectiveness of FRP retrofitting under in-plane shear loading. Almusallam and Al-Salloum [24] and Haroun and Ghoneam [25] tested infill wall panels with EB glass FRP (GFRP) and externally coated with a fibre glass composite respectively. ElGawady et al. [12] investigated the effectiveness of EB GFRP and Aramid FRP (AFRP) strengthening of cracked masonry wall panels under cyclic loading. EB CFRP plates were used by Santa-Maria and Alcaino [26] in their study investigating the effectiveness of cracked walls panels with retrofitting. According to their findings, the increase of shear strength and maximum displacement at failure of a previously damaged and repaired wall is similar to that of a wall with no initial damage, with the same amount of CFRP overlays.

However, the current authors were unable to find any published literature on NSM Carbon FRP (CFRP) strengthening in cracked wall panels.

A total of sixteen wall panels were used in the current study. These wall panel specimens were previously tested without reinforcement using the same test apparatus as part of a separate research study [28]. The main objective of the current experimental study was to assess the effectiveness under cyclic in-plane shear loading of the NSM CFRP strip strengthening technique on previously tested wall panels with different levels of damage. In the current paper, the results of tests on retrofitted walls are compared with URM results to evaluate the effect on shear strength, ductility factor, displacement capacity and energy dissipation. Three different pre-compression levels (2.8 MPa, 2 MPa and 1.4 MPa) and three different reinforcing schemes were examined in this study.

2. Experimental study by Mojsilović et al. [28,29]

Mojsilović et al. [28] tested 21 URM wall panels under vertical pre-compression combined with cyclic in-plane shear to investigate the effects of a damp proof course (DPC) layer incorporated near the base of the walls. Three different pre-compression levels were used to cover all possible failure modes such as sliding, diagonal shear and compression (toe crushing) failure. However, only sliding and toe crushing were observed. Two different DPC layer positions, as well as no DPC, were investigated. The DPC was placed either between the first two courses of masonry (Series A) or between the concrete footing beam and first masonry course (Series B). In addition, three control specimens with the same dimensions and without a DPC were tested (Series C). The specimens were first subjected to the vertical pre-compression load which was kept constant during the test and then subjected to increasing reversing cycles of in-plane shear displacement applied via a steel beam at the top of the wall. The apparatus used was the same as that used for the current study and described in Section 3.3 below, except that sliding along the base of the wall was not prevented in the Mojsilović et al. [28] tests. Specimen designation for the Mojsilović et al. [28] study is summarised in Table 1.

Table 1
Specimen designation and test program [28].

Series	Pre-compression stress (MPa)		
	0.7	1.4	2.8
A	A3 (3 specimens)	A1 (3 specimens)	A2 (3 specimens)
B	B3 (3 specimens)	B1 (3 specimens)	B2 (3 specimens)
C	C3	C1	C2

Of the 21 panels, 16 panels remained in a state which allowed them to be reused for the current research, albeit having suffered various degrees of damage. The damaged walls were divided into two categories namely highly damaged (HD) and lightly damaged (LD). This distinction was relatively easy to make as it corresponded roughly to the level of pre-compression stress used in the Mojsilović et al. [28] study. Walls tested at the highest level of pre-compression (2.8 MPa) failed primarily in a compression mode resulting in predominantly vertical cracks distributed throughout the walls in addition to crushing of the masonry at the corners of the walls. These walls were identified as highly damaged (Fig. 1a). The sliding recorded at the DPC level was negligible for these panels (between −1.5 mm and 0.6 mm on average [29]). Wall B1–2 (tested under 1.4 MPa pre-compression) also displayed a predominantly compression failure mode with negligible sliding along the bottom (−1.9 mm minimum and 0.7 mm maximum [29]) (Fig. 1b) and was also considered to be in the highly damaged category. The remaining walls were classified as lightly damaged. These walls included three walls tested at a pre-compression of 1.4 MPa and six walls tested at 0.7 MPa. The lightly damaged walls (Fig. 1c) failed predominantly by sliding at the base with some minor corner crushing and so did not display cracking through the centre of the wall typical of the highly damaged specimens.

3. Experimental program

In the current study, the sixteen wall panels from the study of Mojsilović et al. [28] were grouped as shown in Table 2. Walls previously tested under pre-compression 2.8 MPa (highly damaged category) were repaired, retrofitted and retested under the same pre-compression stress to assess the effectiveness of the various retrofitting techniques in restoring and/or improving the performance of the walls compared to the previous URM tests. The walls previously tested under pre-compression 0.7 MPa (lightly damaged category) were repaired, retrofitted and retested under 2.8 MPa pre-compression to allow comparison with the highly damaged walls with the view to assessing the influence that the degree of damage has on the effectiveness of retrofitting. There was little point to retesting any walls at 0.7 MPa pre-compression as this level of compressive stress was observed by Mojsilović et al. [28] to result in sliding and/or rocking failures for URM walls. Therefore, retrofitted walls tested at this compressive stress would also be expected to rock (for all tests in the current study, the specimens were prevented from sliding at the base of the wall as described in Section 3.3 below) leading to a trivial outcome in terms of the effectiveness of retrofitting.

Wall B1-2 was retested under 1.4 MPa pre-compression after repairing and retrofitting with Scheme 3 (see Section 3.2 below). Due to its compression failure with negligible sliding in the previous study [29], the previous test result for wall B1-2 was used as the URM result for comparison with the retrofitted result at this pre-compression level.

The remaining three specimens previously tested under 1.4 MPa pre-compression were repaired and retested under 2.0 MPa pre-compression without retrofitting. These results were used as the URM test results under 2.0 MPa pre-compression. Of