Engineering Structures 118 (2016) 167–177

Contents lists available at ScienceDirect

Engineering Structures

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

# In-plane and out-of-plane testing of unreinforced masonry walls strengthened using polymer textile reinforced mortar

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ARTICLE INFO

*Article history:*
Received 23 November 2011
Revised 16 March 2016
Accepted 16 March 2016
Available online 2 April 2016

*Keywords:*
Seismic strengthening
Structural testing
In-plane
Out-of-plane
Brick masonry
Polymeric composites
Polymer textile

ABSTRACT

Details of an experimental program investigating the structural performance of unreinforced masonry (URM) walls strengthened using two different types of polymer textile reinforced mortar (TRM) is presented. The experimental program involved full scale reversed cyclic in-plane and out-of-plane testing of TRM strengthened URM walls. The testing was performed in two series, with series 1 involving in-plane testing of two (03) pier-spandrel assemblages representing part of a perforated URM wall and series 2 involving out-of-plane testing of three (03) slender walls having no penetrations. To replicate the physical characteristics of historic masonry materials, vintage solid clay bricks and a low strength hydraulic cement mortar were used for construction of the test walls. Numerous structural characteristics pertaining to the seismic behaviour of TRM strengthened historic URM walls were investigated and then compared to those obtained from corresponding as-built tested URM walls. In general, strengthened walls exhibited a ductile behaviour until the polymer textile ruptured in a brittle manner. The strength increment due to TRM strengthening was observed to range from 128% to 136% when the URM test walls were loaded in-plane and from 575% to 786% when the URM test walls were loaded out-of-plane, with a notable increment in deformation capacity and ductility.



## 1. Introduction

Unreinforced masonry load bearing (URM) walls have routinely been documented to exhibit poor seismic performance during moderate to severe earthquakes, resulting in partial or complete collapse of the building [1–5]. The observed poor seismic performance of URM buildings has highlighted the seismic hazard associated with this form of construction, and the need for further investigation to advance the understanding of aspects related to their seismic assessment and improvement.

In the event of an earthquake, gravity loaded URM walls are also subjected to lateral loading either oriented parallel (referred to as in-plane load actions) or oriented perpendicular (referred to as out-of-plane load actions) with respect to their stronger plane, or the URM wall may be subjected to a combination of both lateral load actions. The seismic behaviour of in-plane loaded perforated URM walls (also referred to as URM equivalent frames) is explained by delineating these walls into separate spandrel, joint, and pier elements. Spandrels and piers have been observed to undergo damage more frequently than the joint regions [6], with the failure of pier and spandrel elements being either flexural controlled or shear controlled (or a combination of both). The flexural controlled failure mode is characterised by horizontal cracking at pier tops and bases, flexural vertical cracks at pier-spandrel interfaces, and/or compression crushing at plastic hinge locations (i.e. toe region of piers) that results due to rocking of piers. Sliding along a mortar joint (step joint or bed joint) or diagonal cracking through bricks [7], in either spandrels or piers, are the two most frequently noted shear controlled failure modes in URM frames. Likewise, face-loaded slender URM walls are prone to partial or complete out-of-plane collapse during earthquake, which can result due to flexural failure of the wall and/or wall anchorage failure [8]. Assuming the presence of adequate wall-diaphragm anchorages to provide sufficient lateral restraint, out-of-plane lateral loading causes bending in the wall and depending upon the specifics of the boundary restraints leads to either one-way or two-way bending. Typically, slender historic URM walls with height to thickness ratios greater than 14 are prone to out-of-plane failure when deforming in a one way bending mode [9,10].

A number of seismic strengthening techniques have been implemented in the past to improve the seismic performance of

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http://dx.doi.org/10.1016/j.engstruct.2016.03.041
0141-0296/

URM buildings. Fibre reinforced polymers (FRP) have attracted notable interest from academia and practicing engineers for application to the seismic retrofit of URM buildings owing to their high strength to weight ratio, thinner cross-sections, non-corrosive nature of constituent materials, and their ease of application [11–15]. One typical FRP-based seismic retrofit solution is the full overlay of epoxy impregnated FRP sheets onto the surface of URM walls. However, the technical literature also suggests several challenges/disadvantages associated with the use of organic epoxies in such FRP application [16]. Amongst these disadvantages are their irreversible nature, stiffness incompatibility with historic URM materials, vapour impermeability, and poor performance both at elevated temperatures (typically higher than 60–80 °C) and in alkaline environments [17]. One alternative to overcome these challenges is the use of inorganic cementitious matrices to bond semi-finished or pre-primed dry grid pattern external FRP fabrics, which is typically referred to as a polymer grid pattern textile reinforced mortar (TRM). The TRM strengthening technique is relatively new and is deemed to have several advantages over its counterpart epoxy impregnated FRP overlay, including stiffness compatibility with historic URM materials, flexibility to bend without failure that allows its application over curved surfaces, and relatively higher resistance to elevated temperature and alkali attack, minimal handling problems, and the ability to create a water resistant but vapour permeable layer [18]. However, there exists a paucity of experimental results available in the technical literature on the effectiveness of TRM for seismic strengthening and repairing of perforated URM walls, which motivated the experimental study reported herein. An experimental program involving full scale reversed cyclic in-plane and out-of-plane testing of TRM strengthened URM walls with realistic test boundary conditions was undertaken and numerous parameters pertaining to their seismic performance were investigated. It is noted that the combined effect of in-plane and out-of-plane loading was not investigated. The experimental results from TRM strengthened/repaired test walls were then compared to that from a corresponding as-built test wall and structural improvements in terms of stiffness, strength, ductility, and damping properties were commented on. The experimental results provide proof of the design concept of a relatively new strengthening and repairing system.

### 1.1. Past testing and design guidelines

A number of experimental programs were previously undertaken to investigate the effectiveness of TRM for seismic strengthening of reinforced concrete (RC) structural elements [14,18–22]. Experimental studies have also investigated the effectiveness of TRM systems for restraining the diagonal shear cracking of in-plane loaded URM walls/panels [22–25]. Almeida et al. [26] undertook cyclic shear testing of as built and TRM strengthened URM wallettes and reported the shear strength of TRM strengthened wallettes to be 2.3 times that of as-built URM wallettes. However, quasi-static cyclic testing of full scale as-built URM frame assemblies [27–30] showed that the URM frames exhibit complex behaviour and that the results obtained from testing of individual panels do not accurately represent the seismic behaviour of perforated URM walls. To this end, Augenti et al. [31] performed quasi-static testing of a single perforated URM wall, which was first tested as-built and then repaired using a TRM system. It was concluded that the repair using TRM not only restored the in-plane strength, but also increased the ductility capacity of the wall. The test results from the same set of experiments were then used to develop a nonlinear model to estimate the strength of TRM strengthened URM walls [32].

The cyclic out-of-plane flexural response of small scale TRM retrofitted masonry assemblages has been investigated by performing pseudo-static cyclic out-of-plane testing [33,34], with loading being applied using a three point loading arrangement. Following the above mentioned experimental studies it was reported that TRM is a viable seismic retrofit technique for masonry walls, and a large strength increment was reported for retrofitted masonry assemblages when compared to corresponding as-built tested masonry assemblages. Babaeidarabad et al. [35] performed out-of-plane testing of nine scaled URM walls using an air bag based test setup, of which three walls were tested as-built and six walls were strengthened by applying full overlay of TRM on both faces. It was reported that the flexural strength of the TRM specimens ranged between 2.8 and 7.5 times that of the control URM walls, depending upon the number of grid layers used. The research led to the publication of guidelines for the design of TRM strengthening interventions for concrete and URM buildings [16].

## 2. Experimental program

The experimental program was comprised of two series of tests. Series 1 involved pseudo-static reversed cyclic in-plane testing of two (02) TRM strengthened full scale pier-spandrel assemblages (representing part of a perforated URM wall, also referred to as a URM frame) and series 2 involved reversed cyclic out-of-plane testing of three (03) full scale slender URM walls. Series 2 testing was further performed in two stages, with the first stage involving the testing of walls subjected to reversed cyclic loading up to a drift of roughly 4% and the second stage of testing involving walls loaded in one direction only until the wall collapsed. Because the majority of heritage URM buildings have exposed brickwork on their exterior façade and therefore a strengthening application is only desirable on the interior wall face, the experimental program considered only one sided TRM strengthening, as is the norm for earthquake strengthening of historic URM buildings.

### 2.1. Wall specifications

Test wall dimensions and strengthening details are shown in Table 1. Test walls were given the notation ABX-N or TMX-N, where AB refers to as-built tested walls, TM refers to test walls strengthened using TRM, X denotes the loading direction (I refers to in-plane and O refers to out-of-plane) and N denotes the test number. It should be noted that test assemblage ABI-1 was tested as-built and subsequently repaired by repointing the spandrel cracks and having a single sided TRM full surface overlay applied on the spandrel (the repaired assemblage is referred to as test assemblage TMI-2). Because the piers of assemblage TMI-2 were completely intact at the conclusion of testing, for the construction of test assemblage TMI-3 the existing piers were reused and a new spandrel was reconstructed.

Fig. 1a shows the geometric dimensions of series 1 pier-spandrel assemblages. The test assemblages were constructed over two concrete footings, which were anchored to the laboratory strong floor to avoid lateral sliding of the piers but allow bed joint shear sliding to potentially occur at the pier base. It was observed in previously performed testing of such as-built pier-spandrel URM assemblages [17] that damage was mostly concentrated in the unsupported middle span of the spandrels. Therefore, to limit such damage, the spandrel of both test assemblages was strengthened by applying a full TRM overlay on one face and the piers were left unstrengthened. Fig. 1b shows the geometric dimensions of series 2 test walls, which were strengthened by applying a full TRM overlay on one face.