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In-situ and laboratory based out-of-plane testing of unreinforced clay brick masonry walls strengthened using near surface mounted twisted steel bars

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HIGHLIGHTS

- NSM bonding of TS bars used for strengthening the test walls.
- Full scale cyclic out-of-plane testing of strengthened walls performed.
- Numerous seismic response parameters investigated and reported.
- The flexural strength increase ranged between 143% and 434%.
- Strengthened walls exhibited highly ductile response.

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ABSTRACT

The out-of-plane behaviour of unreinforced masonry (URM) walls strengthened using near surface mounting of twisted steel bars (NSM-TS) was investigated by performing two series of tests, which involved in situ and laboratory based out-of-plane testing of full scale strengthened URM walls. In the first series of testing, two walls were strengthened and tested in situ inside an historic URM house located in Wellington (New Zealand), known to be originally constructed in 1884 and to have undergone several minor periodic alterations. In the second series of testing, the results of in situ testing were further confirmed by performing laboratory based reverse cyclic out-of-plane testing of two slender URM walls that were constructed using vintage solid clay bricks and a low strength hydraulic mortar, replicating typical historic URM construction. Numerous parameters pertaining to the out-of-plane behaviour of NSM-TS strengthened URM walls were investigated, including failure modes, hysteretic response curves, out-of-plane flexural strength, maximum drift, pseudo-ductility, and strain distribution in the NSM-TS bars. Finally, measured performance parameters from the strengthened walls were compared to the corresponding data from the as-built tested walls. It was inferred from the results that the observed flexural strength increase due to NSM-TS strengthening ranged from 143% to 434% when compared to the strength of as-built URM wall.

1. Introduction

Unreinforced masonry (URM) bearing wall buildings in New Zealand were mostly constructed between 1880 and 1930 and being amongst the oldest buildings of the country constitute a significant portion of the country's architectural heritage [1], but the majority of these historic URM buildings are potentially prone to collapse in a moderate to large magnitude earthquake and pose a considerable safety hazard to their occupants. Many instances of URM buildings performing inadequately were observed during the recent 2010/2011 Canterbury (New Zealand) earthquake sequence [1–4], illustrating the seismic risk associated with this building type.

A number of seismic strengthening techniques have been implemented in the past to improve the seismic performance of URM buildings. Amongst such typical applications are the introduction of secondary lateral load resisting frames (steel or concrete), steel reinforced and polymer fibre reinforced shotcreting, diaphragm stiffening, unbonded posttensioning, insertion of steel bars into cored circular cavities located at the centreline of the wall, surface bonding of epoxy impregnated glass fibre reinforced polymer sheets, surface overlay of polymer textile reinforced mortars, and base isolation. A relatively new strengthening technique is the near surface insertion/mounting of high strength twisted

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steel bars (NSM-TS), in which thin slots are cut into the surface of the masonry and the twisted steel (TS) bars are bonded into the slot using either an epoxy or a cementitious grout. The addition of TS bars in URM walls allows the strengthened wall to be designed and to perform as a reinforced masonry wall, where the additionally installed bars restrain the opening of cracks and increase the load carrying capacity and/or ductility of the wall.

Currently, NSM-TS is typically used for non-seismic repairing and strengthening applications that involve NSM bonding of TS bars in mortar bed joints to create deep beams or lintels, stitching across existing cracks, structural tying between intersecting structural walls, and structural tying of veneers to backing walls. The NSM-TS technique is claimed to have numerous advantages, with some of these briefly discussed herein. The NSM-TS technique involves minimal disruption to building function and only minor architectural alteration, which is deemed advantageous for buildings having an exposed brick masonry facade. The application does not increase the seismic weight of the structure and thus requires no additional foundation improvements.

For NSM-TS strengthening of URM walls, at the onset the masonry substrate surface is prepared by grinding any surface undulations and removing dust, paint, oil and/or any loose masonry fragments. Thin surface slots (being 30 mm deep and 4 mm wider than the outer bar diameter) are cut into the masonry surface using a hand held wet circular masonry saw that typically required two closely spaced cuts and removal of the masonry strip formed between these two cuts using a chisel. Additionally, commercially available wet masonry saws can be mounted with an adjustable guide to maintain the depth and alignment of cutting. To reduce the amount of brick cutting, straight slots may be positioned to pass through a maximum number of mortar head joints. This cutting strategy was adopted for the strengthened walls reported herein, and was found to provide adequate bar anchorage. The cut slots are cleaned with an air blower or flushed with water and are left to dry until a saturated surface dry condition is reached. A water based primer can also be sprayed in the slots by using a blow pump to avoid moisture movement between the injected grout and the substrate masonry. An approximately 10 mm thick bead of grout is injected into the back of the slot using a hand held injection gun. The twisted steel reinforcing bars are inserted into the slot by pushing the bars with a finger trowel into the injected bead of grout, and the slot is filled with grout. The slot is concealed by re-pointing using a tinted hydraulic mortar to match the existing masonry bond pattern. Fig. 1a–c shows a typical NSM-TS section and photographs illustrating the strengthening procedure.

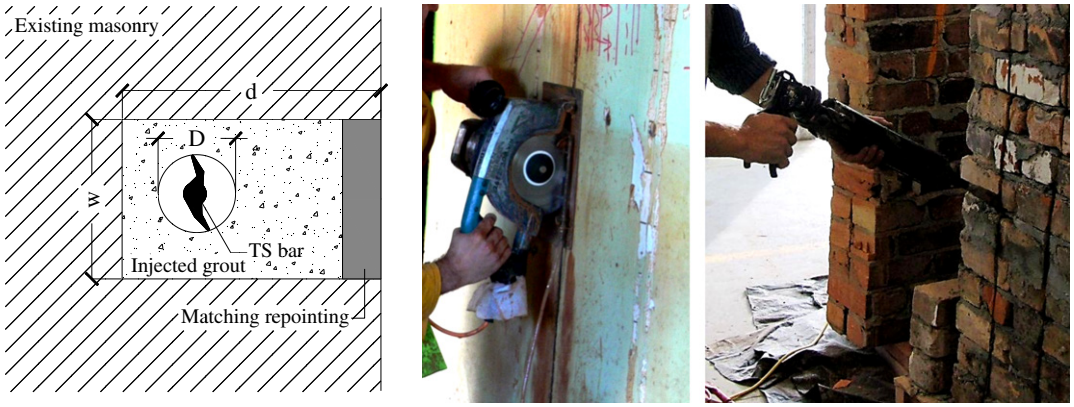
2. Past NSM-TS testing

The use of TS bars to strengthen URM walls dates back to the early 1980s, when the technique was mainly used for the rehabilitation of cavity walls that involved installation of replacement ties between the outer veneer and the backing wall. Research investigating the suitability of NSM-TS for rehabilitation and repair of buildings progressed at a slow rate, with experimental studies mostly focusing on the flexural behaviour of masonry deep beams supporting gravity loading. One such experimental program was undertaken by Stepanek and Czempiel [5] that involved pull out testing and flexural testing of 18 NSM-TS strengthened laboratory built clay brick masonry beams, each being 600 mm deep and 2700 mm long. The test beams were either 250 mm wide (referred to as type A) or 380 mm wide (referred to as type B). The study concluded that an embedment length of 300 mm provided sufficient anchorage to cause the tensile yielding of a 6 mm twisted steel bar, being similar to the results of pull out testing reported by Ismail et al. [6]. The flexural strength increase for type A beams was 124% when TS bars were installed on one face and 143% when TS bars were installed on both faces, whereas the increase in the flexural strength of type B beams for single sided and double sided application was observed to be 181% and 233% respectively. Moreover, the performance of URM arch bridges and masonry vault structures strengthened using a similar bar-grout system has also been extensively investigated [7–9].

Several precedent experimental programs have investigated the out-of-plane behaviour of clay brick masonry walls strengthened using NSM bonding of polymeric strips/bars [10,11]. Italian researchers used NSM bonding of deformed steel bars in mortar bed joints to avoid masonry strength degradation resulting from creep deformation [12,13], which is a typical strengthening intervention for heritage URM buildings located in non-seismic European countries. In a relatively recent research study, the effectiveness of NSM-TS for seismic strengthening of historic clay brick masonry walls was investigated by performing induced diagonal shear testing of strengthened masonry assemblages [6]. This study reported NSM-TS as a potentially viable seismic strengthening technique for in-plane loaded historic URM walls.

3. Material properties

Series 1 testing was conducted on in situ walls located inside a residential house (hereafter referred to as Avon House) situated at 44 Wallace Street Mt. Cook, Wellington, New Zealand. Avon house



(a) typical NSM-TS details (refer Table 3 for values and definition of symbols)

(b) cutting slots

(c) grout injection

Fig. 1. Typical NSM-TS details and application procedure.