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Shaking table test of fibre reinforced masonry walls under out-of-plane loading

Razieh Sistani Nezhad, Mohammad Z. Kabir *, Mehdi Banazadeh

Department of Civil Environmental Engineering, Amirkabir University of Technology, Tehran Polytechnic, Hafez Ave., P.O. Box 15875-4413, Tehran, Iran

HIGHLIGHTS

- The out-of-plane dynamic behaviour of FRP-reinforced and unreinforced masonry walls is presented.
- Displacement capacity, base shear, fundamental frequency and energy absorption are compared.
- The crack pattern and micro damage of specimens are discussed.
- GFRP strips improved wall performance significantly.

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ABSTRACT

The present paper describes an experimental procedure to study the effect of retrofitting technique using fibre reinforced composites on the out-of-plane seismic performance of masonry walls. For this purpose, three "I" shaped half scale bearing masonry walls were tested under scaled versions of Bam, Kobe and Northridge earthquake horizontal components using one degree shaking table equipment. Each specimen is loaded axially by a concrete beam to simulate the effect of scaling; also two transverse walls are used to prevent overturning of the main wall against out-of-plane loads. The subject of this study is mainly about dynamic response of FRP strengthened masonry walls in terms of fundamental frequency, displacement capacity, shear strength, crack patterns and energy absorption. Experimental results revealed that FRP reinforcement can significantly improve masonry walls performance.

1. Introduction

Advantages of masonry construction such as low cost, accessibility to natural materials, fire resistance, etc. encourage people to widely use these construction techniques in developing countries. For decades, seismic provisions have not been considered during the construction of numerous masonry buildings. These structures have experienced intensive damage due to the low tensile strength and heavy weight that induce high inertia forces. Severe damage of masonry walls as the main load bearing members of masonry buildings can result in total collapse of these structures. Because of the lower mass, durability and aesthetic compatibility, externally bonded FRP technique is one of the most profitable retrofitting methods [1]. Fibre reinforced polymers were used to increase the in plane shear resistance [2–9], and the out-of-plane flexural strength of the masonry walls [10–16]. Two examples of in-plane and out-of-plane damages of masonry walls due to earthquake are illustrated in Fig. 1.

Load bearing structural wall resists against lateral loads induced by wind and specially earthquake in addition to the gravity loads. Overall performance of masonry buildings is significantly influenced by the behaviour of these bearing structural walls as the main components. One of the most important approaches to access the overall response of such building is to study the constituent behaviour experimentally. However, due to difficulties of full-scale testing of masonry buildings such as space and test limitations, reduced-scale testing of specimens has been found as an alternative strategy [17,18]. This method needs different scale factors for various quantities to simulate the dynamic response of real structures in both elastic and inelastic range [19].

Kasparik et al. conducted a dynamic in-plane test on 5 reduced-scale partially grouted concrete block masonry walls that strengthened with three different reinforcement bars. The specimens were tested under 1940 El Centro, California earthquake. Each wall experienced a constant compression load axially exerted on the top of the wall. The results were shown that this type of

* Corresponding author.
E-mail addresses: razieh.sistaninejad@aut.ac.ir (R. Sistani Nezhad), mzkabir@aut.ac.ir (M.Z. Kabir), mbanazadeh@aut.ac.ir (M. Banazadeh).

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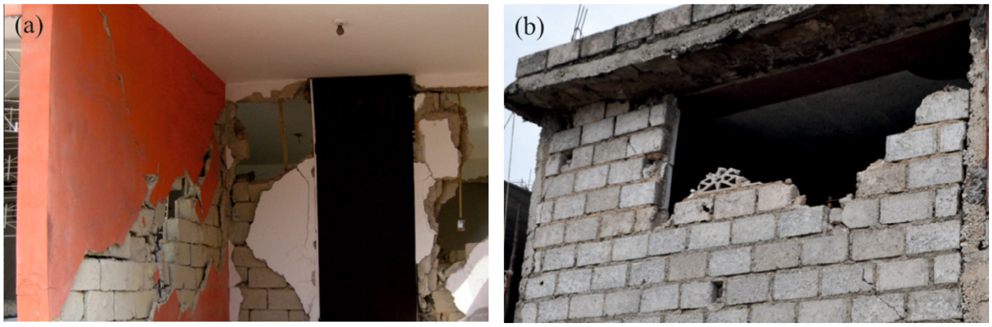

Fig. 1. Two dominant damages of masonry walls: a) in-plane diagonal cracks; b) out-of-plane collapse.

reinforcement has less cost compared with conventional fully grouted reinforced concrete block walls. Yield strength, period shift and some other parameters as stiffness and seismic force degradation were examined [18].

Based on a series of shaking table tests on lightly reinforced, fully grouted masonry walls, Mojiri et al. investigated the plastic hinge zones and the equivalent lengths of plastic hinges and also different energy components of shear masonry walls dissipated by shake table, wall and the external mass system. In addition, depending on the geometry and seismic demands of each wall, displacement ductility levels were obtained [20].

Wigth et al. studied the performance of post-tensioned concrete masonry walls against in-plane seismic loads. To study the effectiveness of this construction technique, two walls with window and door openings were tested first. Finally a one story square masonry building was tested to investigate the simultaneous effect of wall corners and openings on the seismic response of these structures. The failure modes of the walls show vertical cracks around the window opening and compressive crushing of masonry on the bottom corners. Results show that residual strains are low because of tendons energy absorption and self-center ability of post-tensioned masonry structures [21].

A scaled prototype of a 3-story RC frame with masonry infill was studied by Koutromanos et al. on a shake table under NS components of Gilroy and El Centro earthquakes. The effect of engineered cementations composite (ECC) material on the seismic performance of the building was investigated by retrofitting of one bottom story wall. Another strengthening technique was used after damaging of second story walls. In this step, epoxy was injected into cracked mortar joints and glass fibre reinforced polymer overlays were covered the walls. Considerable enhancement of the base shear capacity of the building shows the effectiveness of these techniques [22].

Bairrão et al. reported on the testing of a limestone masonry building with two different reinforcement type, polymeric grids for horizontal reinforcement at the first step and vertical polymeric grids and fibre-added mortar for the next step. Results showed that the local and global behaviour of the building improved by adding polymeric grids vertically and fibre-added mortar [23]. Shaking table tests were also performed to study the seismic performance of hollow brick partitions [24].

Tu et al. investigated out-of-plane behaviour of masonry infills in RC frames by shaking table test on four full-scale one story specimens. Each specimen was loaded under excitations with increasing amplitude until collapse. Results showed that boundary elements as concrete columns and masonry thickness can increase out-of-plane resistance of masonry panels significantly [25].

Lourenço et al. conducted shake table testing of two 1:2 scale masonry buildings. In this study, a new construction system was proposed. In this system, masonry bonds consisting of continuing vertical joints and connections were established using steel truss reinforcement and frogged ends of concrete blocks. In-plane and out-of-plane behaviour of masonry walls in terms of crack initiation, lateral drifts and failure modes were reported [26].

Out-of-plane performance of masonry members was addressed by a few researchers. One reason is the difficulty of considering wall interaction with the remainder of the building and also the fragile nature of out-of-plane collapse.

Out-of-plane seismic response of a U-shaped tuff masonry wall was studied on the shaking table in Rome, Italy by Al Shawa et al. 34 shake table excitations were applied to an assemblage of masonry façade and two transverse walls. Experimental results show that the specimen behaves as a rigid member undergoing rocking motion at the base and vertical cracks between main façade and transverse walls happened because of poor transversal bond [27].

Costa et al. conducted a shaking table study to evaluate out-of-plane performance of a full scale stone masonry façade. Recorded acceleration and displacements were reported in this study. As observed in this experimental work, one-sided rocking happened before collapse and finally overturning happened [28].

While in-plane performance of FRP strengthened masonry walls has been extensively studied by researchers, there are not considerable reports are available in literature on the effect of retrofitting on out-of-plane dynamic behaviour of these walls. This paper describes observations and results of out-of-plane shaking table tests on three "I" shaped masonry walls, one of them strengthened by unidirectional glass fibre reinforced strips. First a summary of shaking table tests performed on masonry constructions and details of the test setup and specimens is presented. Input excitations of the shaking table categorized in three phases are then summarized. In addition, test results in the scope of base shear, displacement capacity and fundamental frequency are presented. Moreover, the behaviour of reinforced masonry specimen is compared to the unreinforced control specimens and the effectiveness of strengthening with GFRP composites is studied. Finally, the load-displacement curves of reinforced and unreinforced specimens under progressive harmonic load are plotted and compared with each other. Out-of-plane performance of unreinforced masonry wall is improved by adding glass fibres as expected.

2. Experimental program

2.1. Test setup

In this study, dynamic behaviour of masonry walls and the effect of fibre reinforced polymer on the out-of-plane performance of masonry specimens were examined. For this purpose, a series of shaking table tests on the 1:2 scaled masonry walls were conducted at the laboratory of the Earthquake and Structure Research Center of Amirkabir University of Technology. This shaking table consists of four main parts including power pack, deck, hydraulic jack and control system. It can simulate harmonic waves up to 20 Hz frequency and 1.5 g acceleration and also earthquake motions in the acceptable range of frequency. The table with