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Out-of-plane shaking table tests on unreinforced masonry panels in RC frames

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ABSTRACT

Shaking table tests were conducted on four full-scale single-story structures to investigate the out-of-plane behavior of unreinforced masonry (URM) panels in RC frames. Specimens included one pure frame, two frames with confined masonry panels of different thicknesses, and one with infill panels. Every specimen was subjected to single-axis ground motions with the intensity magnified each cycle until the structure exhibited severe damage. With strong boundary restraints, the confined masonry panels exhibited notable resistance to out-of-plane inertial forces via the arching mechanism. Infill panels also showed arching at low motion intensity, but separated from the boundary frames at higher intensity and collapsed under the inertial force caused by their self-weight. Wall thickness/slenderness was found to have a significant influence on out-of-plane strength and stiffness. An analytical model for the out-of-plane behavior of confined masonry panels in accordance with the rocking mechanism is also presented. Comparison with experimental results showed that this model affords accurate and conservative estimates for force and deformation capacities. It also suggests that the out-of-plane deformation capacity of a confined masonry panel is proportional to its thickness.

1. Introduction

Confined masonry (CM) consists of pre-laid unreinforced masonry (URM) panels surrounded by cast-in-place reinforced concrete (RC) boundary frames. As shown in Fig. 1, the vertical edges between the panel and boundary columns were toothed as shear keys. The post-cast boundary frame also provided panel confinement after shrinkage of the concrete. CM is an economical choice of construction for low-rise housing in Asian countries, such as China [1], Indonesia [2], India [3], and Taiwan. It is also widely used in most Latin-American countries like Mexico [4–6] and Chile [7] and in European countries like Italy and Slovenia [8]. Comparing with traditional URM buildings, CM have been reported to have better seismic performance during strong earthquakes, including the 1985 Central Chile earthquake ($M_s = 7.8$) [7] and the recent Sumatra earthquake ($M_s = 7.6$) [2].

In Taiwan, URM panels made of clay brick are the most common type of partition in low-rise RC buildings. In the 1970s and 1980s, most URM panels employed confined masonry. The masonry panels are double wythe (200–240 mm) with English bond. Unlike the typical CM that usually has small tie columns with dimensions corresponding to the panel thickness (150–200 mm), CMs in Taiwan have larger boundary columns and beams (250–300 mm). After the 1990s, CM buildings are limited to a height of 10 m or three stories by the building code. Therefore, post-laid URM panels that were in-filled in pre-constructed RC buildings became the popular choice. The post-laid panel type is mostly considered a nonstructural element and so is single wythe (100–120 mm) using only a stretcher bond. However, such panels have a poor boundary connection with the frame, particularly at the top edge, where there is usually a gap between the panel and top beam owing to difficulties during construction.

The in-plane performance of URM panels in RC frames has attracted considerable interest in seismic research. CM panels were found to provide fair in-plane shear capacity and ductility [1,3,6,8]. However, during the 1999 Chi-Chi earthquake in Taiwan, more than 50% of typical CM school and street-side buildings were severely damaged [9,10]. It was found that these buildings only had partitions in one direction; the full in-plane strength of panels was not exploited since the building will fail along the direction with no partitions, as shown in Fig. 2. Fig. 3 shows the structural system of a typical school building. It consists of classrooms arranged along a single corridor and divided by URM partitions, leaving the longitudinal elevations as openings. Therefore, school buildings usually collapse along the longitudinal direction, that is, the out-of-plane direction for the URM partitions. In these cases, the

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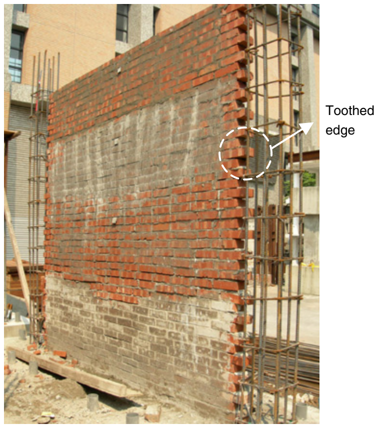

Fig. 1. An under-construction confined masonry panel.

Fig. 2. A confined masonry building damaged along the out-of-plane direction of walls during Chi-Chi Earthquake, 1999.

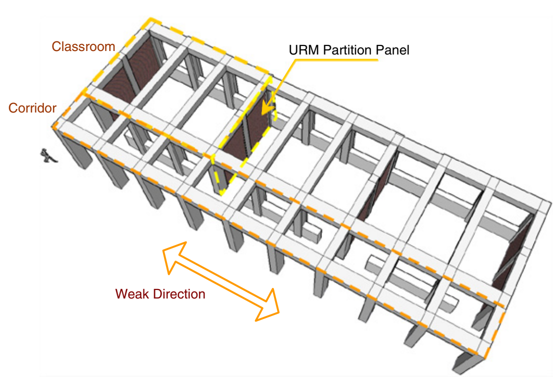

Fig. 3. Structural system of typical school buildings in Taiwan.

possibility for panel failure and the out-of-plane strength become causes for concern.

The National Center for Research on Earthquake Engineering (NCREE) has carried out several in-situ tests. The tests were used for studies on the failing behavior of school buildings and the effects of different retrofit measures [11], and provided verification for analytical methods [12]. The strong-beam-weak-column behavior was found in all the specimens; therefore the failures of the specimens were governed by base floor columns. In preceding research [13], the authors confirmed that the CM panels with notable out-of-plane deflection and damaged boundary columns can still remain stable in the frames, as shown in Fig. 4.

Fig. 4. Final stage of a specimen from in-situ tests on school buildings.

URM panels subjected to out-of-plane loads usually fail by flexure owing to their slenderness (i.e., height-to-thickness ratio (h/t)). And because mortar has little tensile strength, critical cracks form along bed joints, where the maximum flexural stress occurs. Cracked bed joints act like hinges that allow rigid rocking of panel segments. It was found by past researches [14–16] that if the panels are confined well by the top boundary, an arching action would develop between the compressive zones and provide lateral resistance. However, the dynamic behavior of confined masonry panels subjected to out-of-plane acceleration has not been sufficiently studied. Therefore, in the present study, a series of shaking table tests was performed to understand the influence of the inertial force stemming from the self-weight of the panels. The effects of boundary condition and panel thickness on out-of-plane deformation and force capacities of the panels are the main subjects. The behaviors of confined and infill masonry panels were compared. An analytical model for estimating the out-of-plane capacity is presented and its predictions are compared with experimental results. This research is expected to be useful for seismic evaluation of existing school buildings and other buildings with a similar structural system.

2. Specimens and test setup

Four full-scale specimens were built and tested in the laboratory of NCREE. The main variables were panel thickness and construction type (confined masonry/pre-laid panels or infill/post-laid panels). More details are presented as follows.

2.1. Specimens

Table 1 provides a brief summary of the specimens used in this study. In order to simulate realistic boundary conditions, each specimen was designed to include two twin RC frames with URM panels, connected by a rigid RC slab. The RC frames in all specimens were identical, and one specimen without panels was included in the study as a control. Fig. 5 shows plan and elevation views of one of the specimens. Each URM panel had a net height of 2800 mm and net width of 2700 mm, and consisted of clay bricks of size 195 mm × 95 mm × 50 mm. Thus, the double wythe and single wythe panels were 195 mm and 95 mm thick, respectively. Fig. 6 shows the differences between the two types of panels. As shown in Fig. 6(a), the confined masonry panels had toothed shear-keys inserted into boundary columns and the top edge embedded in the boundary beams. Infill-type panels were built after the RC boundary frames were completed. Therefore, as shown in Fig. 6(b), a gap of about 10–20 mm was left between the panel and top beam. The gaps were filled with as much mortar as possible, but this still left the possibility for some vacancy to remain inside.