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Cyclic behavior of Peruvian confined masonry walls and calibration of numerical model using genetic algorithms

Luis G. Quiroz [a,*], Yoshihisa Maruyama [a], Carlos Zavala [b]

[a] Department of Urban Environment Systems, Chiba University, 1-33 Yayoi-cho, Inage-ku, Chiba 263-8522, Japan
[b] Japan-Peru Center for Earthquake Engineering Research and Disaster Mitigation, National University of Engineering, Tupac Amaru Avenue 1150, Lima 25, Peru

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ABSTRACT

The experimental results of four full-scale confined masonry (CM) walls subjected to cycling loading are presented. These structural elements are widely used in low- and mid-rise buildings in Peru to take the vertical and lateral loads. The objective of these experiments was to evaluate the cyclic behavior of CM walls constructed with handmade bricks and lime mortar. The brick units used in the walls were made of clay, and they were considered to be solid components. In the experiment, the dimensions of all the walls were kept constant in all specimens, but the reinforcement ratios of the confining elements (bond beam and tie-columns) were changed. The structural behaviors were examined in terms of the strength, lateral stiffness, dissipated energy, and equivalent viscous damping. Finally, an equivalent macro-model based on an equivalent strut approach with a smooth hysteretic model was calibrated and validated in order to reproduce the behaviors of the CM walls. For this purpose, we used a genetic algorithm (GA) that considered the experimental results of a CM wall. The parameters were applied to the results of the other CM walls to evaluate their applicability. The results of numerical simulations showed good agreement with the experimental results.

1. Introduction

Masonry is one of the most widely used materials for the walls of dwellings in Peru, especially in Lima. However, the inherent weakness of masonry in tension has been repeatedly observed during seismic events around the world. The need to overcome the seismic deficiency of unreinforced masonry (URM) walls has led to the development of structural walls with different reinforcement patterns. From the structural and seismic points of view, masonry can generally be used in two ways for dwellings: confined or reinforced masonry and reinforced-concrete (RC) frames with masonry infill. Confined masonry (CM) walls consist of URM walls confined with RC tie-columns and bond beams. Walls of this type are used in both urban and rural areas for low- and mid-rise dwellings because they can be constructed with a low cost compared with other structural systems (e.g., RC frames and RC walls). With the increased popularity and availability of RC and different types of masonry units, this construction is common in many countries, including Peru, Chile, Argentina, Mexico, Iran, Slovenia, according to the World Housing Encyclopedia [1]. CM walls are often used as structural elements to provide resistance to gravitational and seismic lateral loads. This type of construction seems to have more strength, ductility, and stiffness than URM walls, and it showed better seismic performance during recent earthquakes.

Lima City has not been hit by a big earthquake since 1974. The last big earthquake that occurred in Peru was the Pisco, Peru earthquake of August 15, 2007 (Mw = 8.0), which caused severe damage to masonry constructions. Under these circumstances, it is expected that masonry constructions that are properly built according to the requirements of the design standard for masonry structures [2] will show better seismic performances. In Peru, the first regulations for masonry seismic design appeared in 1977. Then, in 1982, the first masonry design standard (E.070) was issued. Because of the small amount of experimental data available, the design of the walls was performed in an elastic range considering allowable stresses. Research programs have been developed by both the Japan–Peru Center for Earthquake Engineering Research and Disaster Mitigation (CISMID) of the National University of Engineering (UNI) and the Pontifical Catholic University of Peru (PUCP) to bring about a better understanding of the behavior of masonry walls. For many years, researchers studied the materials (brick units, mortar), effects of the reinforcement of confining elements and walls, effects of vertical loads, types of connections between panels and tie-columns, effects of slenderness, and various other aspects. Some of the results of these studies

* Corresponding author. Tel.: +81 43 292 3528; fax: +81 43 292 3558.
E-mail address: lgquiroz@uni.edu.pe (L.G. Quiroz).

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can be found in the literature [3]. Based on recent studies and the lessons learned from past earthquakes in Peru and other countries, a new masonry design standard was proposed in 2001. This new masonry design standard (E.070) [2] was issued in 2006, and it defines the performance criteria.

Several other studies have been carried out around the world on structural elements or entire structures to increase the understanding of the behavior of masonry walls or to improve standards. These studies have considered variations in the characteristics or configurations of the components (e.g., the characteristics of bricks, confining elements, etc.). Several of these studies are reviewed below. Decanini et al. [4] tested eight CM panels subjected to the effects of horizontal loads simulating seismic motion in the laboratory of the National University of Cordoba, Argentina. Four of these masonry panels were made of solid clay bricks, and the others were made of hollow clay bricks. They found that the walls made of hollow clay bricks showed 20% more strength against ultimate cracking than against initial cracking. In 1999, Alcocer and Zepeda [5] analyzed the test results of four isolated large-scale multi-perforated clay brick walls under constant vertical axial loads and cyclic lateral loads in order to evaluate their behaviors and develop analysis, design, and construction guidelines. Irimies [6] studied the influence of both the confining of un-reinforced masonry walls and the vertical reinforcement ratio in tie-columns on the seismic behavior of the masonry walls in three half-scale two-story specimens. One of these was an un-reinforced masonry wall, and the others were CM walls. The wall models were tested under lateral cyclic loading in the presence of a constant vertical force. It was found that increasing the amount of vertical reinforcement in the tie-columns by 1.8 times enhanced the lateral strength by approximately 20%. Meli [7] presented test results for CM walls and assessed the responses in terms of strength, ductility, and energy absorption. Yoshimura et al. [8] studied CM walls and their nonlinear characteristics when lateral reinforcement is employed for the mortar joints at the corner part of the wall. Marinilli and Castilla [9] evaluated the effects of the number of vertical confining elements on the seismic behavior of CM walls by using four specimens. The walls were tested under cyclic lateral loads and a constant vertical load. The results showed how the number of confining-columns affected the stiffness degradation, energy dissipation capacity, ductility, cracking pattern, and strength of the walls. An important aspect of the wall performance is the openings, which were studied by Yañez et al. [10]. They found that walls with an opening ratio of around 11% of the total area of the wall presented similar stiffness as walls without openings. In 2007, Gouveia and Lourenco [11] studied the effects of confinement, horizontal reinforcement, and different kinds of brick units on the response of CM walls. Tena-Colunga et al. [12] presented a complete experimental protocol for combined and CM walls. They found that combined and CM walls jointed with non-engineered mortar did not satisfy all the criteria to be qualified as earthquake resistant walls. In contrast, the combined and CM walls jointed with engineered mortar showed a performance (cracking patterns, initial stiffness, cracking drift angle, drift angle for design, etc.) equivalent to the experimental results for similar CM walls made with solid clay bricks. Wijaya et al. [13] studied the influence of the type of connection between the wall panel and RC elements (e.g., grooves at interface of masonry and tie column, continuous anchorage embedded in mortar joint and RC elements). They investigated a reinforced concrete frame with masonry infill. Recently, Torrisi et al. [14] found that a structural separation occurs between a masonry panel and the confining elements at the initial stages of loading for both CM and infill walls. They also observed the formation of a compression stress field in a masonry panel using experimental data and numerical simulations. Recently, research on the seismic performance of CM walls with hollow and tubular brick units and improvement of their structural performance has been carried out in Peru [15,16].

In spite of the masonry experimental research programs conducted in many countries [4–14], the behavior of CM walls is still not well known [10], and the results tend to be for the characteristics of structural systems related to regional situations (e.g., construction process, quality of labor, material properties). As noted above, the available information on CM walls in the case of Peru is limited. Hence, continuing with the experimental study of CM walls in countries where they are widely used like in Peru is important. In the present study, the results of experiments carried out in Lima, Peru, at CISMID in 2003 [17] will be investigated using their structural characteristics and a numerical simulation. Later, based on the experimental results, an equivalent strut approach with a smooth hysteretic model is calibrated, and validation of the numerical simulation is discussed. The walls employed in this study were the typical type of walls used in low- and mid-rise Peruvian dwellings.

2. Description of full-scale experiment

A series of tests were carried out on CM walls in 2003 with different reinforcement ratios in the tie-columns and bond beams. The walls were cast at full scale with the same geometrical properties. An important parameter that governs the damage pattern and failure mode is the aspect ratio (height-to-length ratio). The h_w/l_w ratio was set to 0.906. Squat CM walls with an aspect ratio of around 1 are commonly used in practice [18]. These walls were subjected to slow cyclic horizontal loading. The responses of four walls were studied in terms of the elastic stiffness and maximum strength [17].

2.1. Description of specimens

Four walls were constructed and tested under cyclic lateral loading. The walls were divided into two groups, with each group containing two specimens. The first group was called A1, and the specimens were named A1-1 and A1-2. Similar denominations were used for the second group. The difference between the two specimens of the first group was the reinforcement ratio used in the bond beams. In the case of the second group, the difference was the reinforcement ratio of the tie-columns. In both groups, the transversal reinforcement of the confining elements was kept constant.

The geometry of the walls is schematically shown in Fig. 1(a). The general dimensions of the walls and their confinement elements were set to be as close as possible to the dimensions of a CM wall used in low- and mid-rise dwellings.

The nominal dimensions of all the specimens were a total height of 2400 mm, total length of 2650 mm, and thickness of 205 mm. The specimens were monolithically connected to a foundation, which was used to fix the wall to the floor in order to consider a fully fixed footing. The nominal dimensions of this foundation were a width of 800 mm and a height of 300 mm. The characteristics of the confining elements are as follows. The tie-column elements were 300×230 mm in size, with the reinforcement presented in Table 1. The bond beam elements were 300×200 mm in size, with different reinforcements, which are also specified in Table 1. Fig. 1(b) depicts the arrangement of the reinforcements in the confining elements for specimen A1-1. The distributions of the reinforcements in the other specimens were similar. Additionally, Fig. 1(b) shows the transversal reinforcement of the confining elements.

The compressive strength of the concrete used for the confining tie-columns and bond beams was $f'_c = 20.6$ MPa, according to the