Structures 3 (2015) 187–199

Contents lists available at ScienceDirect

Structures

journal homepage: http://www.elsevier.com/locate/structures

In Situ Out-of-Plane Testing of Unreinforced Masonry Cavity Walls in as-Built and Improved Conditions

Kevin Q. Walsh [a,*], Dmytro Y. Dizhur [a], Jalil Shafaei [b], Hossein Derakhshan [c], Jason M. Ingham [a]

[a] Department of Civil and Environmental Engineering, University of Auckland, New Zealand
[b] School of Civil Engineering, College of Engineering, University of Tehran, Tehran, Iran
[c] School of Civil, Environmental, and Mining Engineering, University of Adelaide, Australia

ARTICLE INFO

Article history:
Received 9 January 2015
Received in revised form 25 April 2015
Accepted 27 April 2015
Available online 6 May 2015

Keywords:
Unreinforced masonry (URM)
Earthquakes
Out-of-plane
Infill walls
Cavity walls
Masonry anchors
Cavity wall ties

ABSTRACT

Extensive research has been performed previously on assessing the out-of-plane (OOP) seismic performance of unreinforced fired clay brick masonry (URM) walls and the retrofitting of URM load-bearing and infill walls having a solid wall thickness. However, comparatively little research has been performed pertaining to URM walls with cavities (i.e., continuous air gaps separating wythes of brick from one another), despite the prominence of cavity masonry construction in various parts of the world. Hence, research was pursued with an emphasis on efficiently retrofitting URM cavity walls to enable the formation of semi-composite to composite behaviour when such walls were subjected to simulated seismic OOP loading. The research reported herein was based on an experimental testing approach wherein walls were loaded OOP using inflatable airbags. A total of ten tests were performed on nine separate URM cavity walls located in two separate buildings.

The outcomes of the research program included determining the behaviour of URM cavity walls in one-way vertical flexure when bordered and when not bordered by rigid moment-resisting reinforced concrete frames; quantifying the improvement in drift levels of cavity walls prior to loss in strength and prior to collapse using a variety of cavity wall ties at different spacing; and establishing an equivalent solid wall thickness for cavity walls with various retrofit tie conditions for use in existing analytical models used to predict the OOP capacity of URM walls.

1. Introduction

The earthquake vulnerability of buildings constructed using conventional British architecture with unreinforced fired clay brick masonry (URM) prior to the introduction of modern earthquake loading standards is well-known in New Zealand [1–5]. Furthermore, a high proportion of such existing URM structures have not been retrofitted to resist design basis earthquake (DBE) forces, and little experimental testing has been performed within New Zealand or elsewhere on the behaviour of URM walls with cavities (i.e., continuous air gaps separating wythes of brick from one another) [6], despite the prominence of this construction type in the building population in the form of both load-bearing and infill walls [7,8]. Hence, an experimental program was undertaken in order to fill the knowledge gap that currently exists amongst structural engineering practitioners regarding the out-of-plane (OOP) seismic behaviour of URM cavity walls. URM cavity walls were physically tested in two different buildings utilising an approach wherein lateral forces were applied using a system of airbags to simulate distributed OOP seismic forces. This approach was consistent with the testing procedures recommended by ASCE [9] and previously utilised by Derakhshan et al. [10,11] and Angel et al. [12]. The URM cavity walls were tested in vertically-spanning, one-way bending (herein referred to as "vertical flexure") to facilitate comparison of the results with existing predictive models that assume vertical flexure only for estimating OOP behaviour [12,13].

* Corresponding author.
E-mail address: kq.walsh@gmail.com (K.Q. Walsh).

2. Research context

2.1. Historical observations of URM cavity wall performance

Few earthquake reconnaissance reports have remarked on the performance of URM cavity walls specifically. Following the 2009 L'Aquila earthquake, it was observed that many URM cavity walls collapsed primarily due to OOP mechanisms resulting from inadequate or absent cavity ties between the inner and outer wythes of masonry [14]. Individual wythes (especially the outer wythe) often collapsed separately from their counterparts due to the high slenderness ratios associated with their non-composite response [15] [see Fig. 1(a)–(b)]. Following the 1989 Newcastle earthquake and the 2010–2011 Canterbury earthquakes, many URM cavity walls were observed to have collapsed OOP [see Fig. 1(c)], often due to the failure of cavity ties resulting from cavity tie corrosion or bed joint shear slippage of the tied bricks [3–5] [see Fig. 1(d)]. Investigators compiling reconnaissance reports following

http://dx.doi.org/10.1016/j.istruc.2015.04.005

(a) OOP collapse of URM cavity infill walls in L'Aquila, Italy (Credit: Win Clark)

(b) OOP collapse of both the outer wythe and (to a lesser extent on the lower storey) inner wythe of URM cavity infill walls in L'Aquila, Italy (Credit: Win Clark)

(c) OOP collapse of a URM cavity wall below a reinforced concrete bond beam and evidence of damage from one-way vertical flexure between window openings in Christchurch, New Zealand

(d) OOP collapse of the outer wythe of a URM cavity wall with cavity ties still attached to the inner wythe in Christchurch, New Zealand

Fig. 1. Examples of OOP collapses of URM cavity walls in earthquakes.

the 1989 Loma Prieta [16] and the 1994 Northridge [17] earthquakes made similar observations to that of their Italian and New Zealand peers regarding the potential for outer wythes of brick (including veneers) to collapse if not properly tied to the inner wythes.

2.2. Predictive models for the OOP performance of solid URM walls

Various methods for predicting the OOP behaviour of solid URM walls have been considered previously based on applications of energy dissipation, finite elements, yield lines, failure lines, compressive struts, spring-struts, and rigid bodies [18–23]. Based on experimental testing [10,11] and previous model iterations [24,25], Derakhshan et al. [13] proposed an assessment procedure for determining the OOP response of simply-supported URM load-bearings walls in vertical flexure based largely on the consideration of a semi-rigid rocking wall mechanism developing post-cracking as follows:

$$F_0 = (W+O)\frac{b_w}{h_1} + \frac{W_2+O}{h_1 h_2} b_w h - \frac{2Oe_w}{h_2} \tag{1}$$

$$\Delta_{ins} = \frac{(W_2+O)(h+h_2)b_w + W_1 h_2 b_w - 2e_w O h_1}{2Oh + 2cW_2(h_2+h) + W_1 h_2} \tag{2}$$

where F_0 represents the predicted OOP force capacity (N) of the cracked wall assuming uniformly distributed lateral forces and rigid-body motion, and Δ_{ins} represents the displacement (m) associated with the point of "static" instability when the wall is subjected to a pushover test such as the airbag tests used in this experimental program. The variables h_i and W_i are, respectively, the height (m) and weight (N) of the wall, with index i referring to the individual wall segments below (1) and above (2), respectively, the primary horizontal crack. O and e_w are, respectively, the applied overburden (N) and its eccentricity (m). Parameter c is related to the location of the centre of mass of the top segment. Parameter b_w is the solid wall thickness (m) measured across the mortar joints, determined as follows:

$$b_w = b_{w,nom} - 2p \tag{3}$$

where $b_{w,nom}$ is the nominal solid wall thickness (m), and p is the average inset depth (m) of mortar pointing (or loss of degraded mortar material) on each side of the wall.

Buildings in Australasia with load-bearing URM walls typically have timber diaphragms [7] which have been experimentally shown to provide little to no arching action to URM walls [9,11]. For simply-supported walls with no significant overburden load or without arching action, Derakhshan et al. [25] recommended that the crack height be assumed to occur such that $h_1 = 0.67(h_1 + h_2)$, wherein the variables h_1 and h_2 represent the height (m) of the individual wall segments below and above, respectively, the primary horizontal crack. Assuming one-way vertical flexure and that the floor/roof diaphragm is sufficiently stiff to prevent higher mode effects [26], the laterally loaded wall is expected to respond to uniformly distributed lateral forces in a simply supported condition, with the drift below the crack that causes instability (θ_{ins}) being determined as follows:

$$\theta_{ins} = \frac{\Delta_{ins}}{h_1}. \tag{4}$$