Engineering Structures 127 (2016) 676–685

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Dynamic testing of as-built clay brick unreinforced masonry parapets

Marta Giaretton [a,*], Dmytro Dizhur [b], Jason M. Ingham [b]

[a] Department of Civil, Environmental & Architectural Engineering, University of Padova, via Marzolo 9, 35131 Padova, Italy

[b] Department of Civil & Environmental Engineering, University of Auckland, Private Bag 92019, Auckland 1010, New Zealand

ARTICLE INFO

Article history:
Received 6 April 2016
Revised 1 August 2016
Accepted 12 September 2016
Available online 17 September 2016

Keywords:
URM parapet
Parapet failure
Rocking response
Dynamic behaviour
Out-of-plane
Shake table testing

ABSTRACT

Unreinforced masonry (URM) parapets are free-standing components located above the perimeter walls of URM buildings and pose a significant falling hazard that has resulted in numerous injuries and costly repairs in recent earthquakes around the world. When subjected to earthquake-induced loads, as-built URM parapets are prone to horizontal cracking at the roof level followed by the initiation of rocking, which leads to cantilever-type out-of-plane failure. In response to these observations, the earthquake performance of 13 full-scale solid clay brick URM parapets when subjected to out-of-plane dynamic loading was experimentally investigated using a shake-table. To mimic in-situ conditions for the most commonly encountered configurations, recycled solid clay bricks and a variety of mortar mixes were used for the tested parapets. Two-leaf-thick (230 mm) and 1200 mm wide parapets with height ranging between 720 mm and 1605 mm were tested. Valuable experimental data was attained to assess the dynamic response of as-built URM parapets, and the results were compared with the assessment procedures available in the literature and current guidelines for practice.

1. Introduction

Unreinforced masonry (URM) parapets are a common feature of vintage commercial and residential URM buildings. A parapet is a non-structural free-standing URM component located above the masonry perimeter walls with the function of preventing the spread of fire in dense urban areas, providing guard rails on roof terraces, and contributing to the decorative and ornamental features of façades. URM parapets subjected to earthquake-induced shaking often fail at the roofline and may fall inwards, penetrating the roof, or outwards onto the sidewalk (see Fig. 1a) and hence represent a significant seismic hazard for pedestrians and occupants attempting to escape a building and [1–3]. The high seismic vulnerability of such free-standing elements was also shown in fragility curves developed by [3,4], who focused on unreinforced masonry construction in New Zealand and the West coast of the United States. While some communities have adopted ordinances that require URM parapets to be braced or anchored (such as in Australia [5] and in the United States [6,7]), many jurisdictions have no such mandatory provisions. For example, Eurocode 8 - Part 1 [8] and the Italian code [9] include only general rules for assessing and securing non-structural elements that may cause risks to people, affect the main structure, or disrupt services of critical facilities. Recent guidelines in New Zealand [10] suggest methods for parapet assessment as vertical cantilevered elements, without providing details on suggested retrofit techniques.

1.1. Previous studies

Several past studies have addressed the out-of-plane response of URM walls using experimental and force-based/displacement-based numerical approaches [11]. In this section the work on the out-of-plane response of parapets and cantilever walls is summarised because of their direct relevance to the experimental study presented and the formulations adopted herein.

Lam et al. [12] studied the free-rocking behaviour of full-scale single-leaf clay brick URM parapets using shake-table testing. The dimensions of the parapet samples were 1400L × 1000H × 110 W mm with a mortar mix of 1:1:6 (cement:lime:sand) by volume. The walls were subjected to free-rocking vibration by applying a short impulse, with natural frequencies obtained by measuring the time interval between peaks and the damping ratio determined by measuring the rate of amplitude decay in the response envelope. Prior to cracking of the parapet, the natural elastic frequency was recorded in a range of 5–10 Hz depending on the amplitude of vibration; after cracking, the rocking frequency was approximately 1 Hz when the displacement amplitude exceeded 20 mm.

Derakhshan et al. [13] conducted a study that followed earlier work by Griffith et al. [14] and proposed a procedure to evaluate

* Corresponding author.
E-mail addresses: marta.giaretton@dicea.unipd.it (M. Giaretton), ddiz001@aucklanduni.ac.nz (D. Dizhur), j.ingham@auckland.ac.nz (J.M. Ingham).

http://dx.doi.org/10.1016/j.engstruct.2016.09.016
0141-0296/

(a) Typical damage to URM parapets (b) Schematic of test component

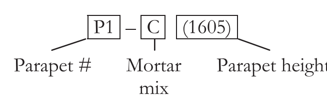
Fig. 1. Out-of-plane earthquake response of URM parapets.

the dynamic out-of-plane stability of cracked URM walls and parapets located in multi-storey URM buildings using equations derived from first principles and representative single-degree-of-freedom (SDOF) models. Based on Griffith et al.'s [14] findings, New Zealand guidelines [15] introduced instability displacement (Δ_i) as the rocking displacement corresponding to a null lateral force and subsequent collapse. Using a tri-linear model representative of the real F-Δ relationship for a vertically spanning wall supported at the top and bottom, the maximum usable displacement (Δ_{max}) corresponding to the transition point between rocking behaviour and collapse was established as 60% of the instability displacement. Derakhshan et al. [13] later modified this relationship for the assessment of parapets and suggested that the rocking period of the parapet is based on secant stiffness at 25% of instability displacement. Consequently, the equation proposed in recently updated guidelines [16] was modified with a conservative value of Δ_{max} = 30% Δ_i.

Aleman et al. [17] performed shake-table tests of two full-scale one-storey clay-brick masonry walls (1830L × 2870H × 305 W mm) with URM parapets above (1370H mm) and flexible diaphragms. The mortar compressive strength was 2.14 MPa, and the masonry compressive strength was 9.3 MPa. One of the wall and parapet assemblages was tested in the as-built condition while in the second test, the parapet was retrofitted using steel braces and anchors in accordance with [7]. The peak ground acceleration (PGA) recorded at failure was equal to 0.36 g (2011 Christchurch earthquake motion), which corresponds to acceleration at the base of the parapet of approximately 0.65 g at cracking and 0.80 g at collapse of the as-built parapet. Although previous studies have provided insight into the out-of-plane response of URM parapets, there is a lack of experimental results that consider the variation of parameters such as parapet height and mortar strength and investigate dynamic behaviour after cracking. Information acquired during a previous pilot study [3] was adopted to select the most common construction details and material properties with the aim to simulate a central portion of the façade of a common single or multi-storey URM building (see Fig. 1b). URM parapets were subjected to dynamic loading by means of a shake-table. Results from the as-built parapet tests and free-rocking behaviour are presented herein. An experimental programme on retrofitted URM parapets will be the subject of a follow-on study.

2. Experimental programme

13 full-scale solid clay brick masonry parapets were tested in an as-built condition to evaluate their earthquake performance and to serve as a control to quantify the level of performance improvement of the selected retrofitted solutions that will be the subject of the follow-on study. The tested parapets ranged between 720 mm and 1605 mm in height and were constructed using different mortar mixes to investigate the influence of mortar conditions on the seismic capacity of parapets. Based on a previous study [3], the thickness of each parapet was selected as 230 mm (two-leaf-thick). The adopted width of 1200 mm was related to the maximum dimensions that could be accommodated on the shake-table. Table 1 shows the summary test matrix for the as-built parapets, with each parapet denoted with the following notations:



The experimental programme was performed in two phases. Phase 1 was undertaken using a 300 kN-capacity single-axis shake-table with dimensions of 3600 × 2400 mm capable of reproducing earthquake motions and involved three parapets, being P4-B(1180), P6-B(1180), and P7-C(1180). The availability of this shake-table was limited so the research team also used a purpose-built shake-table capable of applying unidirectional harmonic excitations to test multiple parapets with different parameters within a reasonable timeframe (Phase 2), see Table 1. The results collected during Phase 2 were then validated against the results attained during Phase 1.

3. Parapet construction

Recycled clay bricks obtained from a demolished vintage URM building constructed in the 1930s were arranged in a common bond pattern with mortar-joint thickness of approximately 10–15 mm. Brick dimensions were of standard size (230L × 110 W × 75H mm) for heritage masonry construction. Three different mortar mixes were used, being 1:2:9 (referred to as mix 'A', with the highest compressive strength), 1:3:12 (noted as mix 'B'), and 0:1:3 (referred to as mix 'C', with the lowest compressive strength) (cement:lime:sand) by volume, to simulate the common field conditions of vintage mortar with variable strength ranging from moderately strong (A) to severely deteriorated due to weathering (C). Material characterisation tests, including compressive tests of mortar cubes [18], half bricks [19], and masonry prisms [20], were conducted prior to the shake-table tests. The results are presented in Table 2.