Computers and Structures 167 (2016) 1–14

Contents lists available at ScienceDirect

Computers and Structures

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

Analyzing the effect of workmanship quality on performance of unreinforced masonry walls through numerical methods

Maryam Tabbakhha *, Arezou Modaressi-Farahmand-Razavi

Laboratoire MSS-Mat, Ecole Centrale Paris, Grande Voie des Vignes, 92290 Chatenay-Malabry, France

ARTICLE INFO

Article history:
Received 27 April 2015
Accepted 26 January 2016
Available online 22 February 2016

Keywords:
Unreinforced masonry wall
Workmanship quality
In-plane loads
Out-of-plane loads
Combined loads

ABSTRACT

The considerable effect of workmanship quality on the performance of masonry structures is well-known. In this study, a 3D nonlinear FE model was used to investigate the effect of workmanship quality on masonry wall strength under in-plane and out-of-plane loads. Mortar joint cohesion was utilized as a random variable to represent variation in workmanship quality. In-plane and out-of-plane displacements were applied to the wall, separately and simultaneously. Results indicate that mortar cohesion has a considerable effect on wall strength under in-plane loads. However, under combined loads, the influence of workmanship quality on wall strength decreases/increases for the in-plane/out-of-plane direction.

1. Introduction

Masonry structures serve as homes to a large proportion of the worlds population, especially in developing countries. The failure of these structures under earthquakes and wind loads frequently results in fatal catastrophes [1–4]. Moreover, there are numerous masonry-based historical landmarks throughout the world, many of which are poorly maintained and deteriorating. Therefore, the design, maintenance, and reinforcement of masonry structures against different loading conditions has been the subject of several research studies [5–8]. Since masonry is a composite material made of units (e.g., brick, concrete, stone) and mortar with different material properties, its performance under different types of load is difficult to model and predict. Moreover, workmanship quality and weather conditions have a significant influence on the performance of these complex structures [9–11]. Variations in mortar thickness, incorrect proportions when mixing the mortar, and poor protection of bricks from weather are some examples of workmanship defects that can affect the capacity of masonry walls considerably [12]. Experiments by Francis et al. [13] and Hendry [14] demonstrated that increasing bed joint thickness from 10 to 24 mm reduces wall strength by approximately 30–40%. In addition, experimental studies at the Building Development Laboratories in Australia [15] have shown that the misalignment of a masonry wall from its vertical line can result in 13–20% strength reduction, depending on the amount of deviation.

In order to gain comprehensive insight into the effects of workmanship quality on the performance of masonry walls, a large number of laboratory tests involving various conditions are required. However, the high costs of conducting such experiments, along with the dependence of the obtained data on the precise experimental conditions, make numerical methods a competitive alternative. Numerical methods also suffer from drawbacks though, such as insufficient information about the input parameters of numerical models. Several researchers have dealt with this problem by utilizing stochastic analyses [16–21]. For instance, Milani and Benasciutti [16] proposed a response surface approximation based on Latin Hypercube sampling to accurately estimate the collapse loads of in-plane-loaded structures. Additionally, Milani and Lourenco [17] have investigated the influence of the geometrical statistical variability of block dimensions on out-of-plane strength of wall using a kinematic rigid plastic homogenization model. They showed that the model can reliably predict the load bearing capacity of large scale masonry structures with a limited computational effort. Despite the harmful effect of poor workmanship quality on the strength and reliability of masonry structures, only a few research studies have implemented computational methods to study such effects [12,22,23]. Moreover, these studies mainly focused on the effect of mortar joint thickness and units flexural bond strength on the performance of unreinforced masonry walls. Using computational methods, Fyfe et al. [12] showed that excessive mortar joint thickness decreases the lateral strength of a wall more than misalignment of the wall. Baker and

* Corresponding author at: Civil and Environmental Engineering Department, University of California at Berkeley, Berkeley, USA. Tel.: +1 213 610 6300.

E-mail address: tabbakhha@berkeley.edu (M. Tabbakhha).

http://dx.doi.org/10.1016/j.compstruc.2016.01.013
0045-7949/

Franken [22] stressed the important effect of random variations in unit flexural bond strength on the overall strength of brick work. Lawrence developed the Baker and Franken idea and assumed statistical independence between the flexural bond strength of units in the model [24]. In doing so, his model exhibited greater consistency between computational and experimental results for a masonry wall under one-way bending.

One of the important parameters that affect a walls lateral strength is mortar joint cohesion. Studies have shown that the water/cement ratio and the aggregates are among several variables that significantly influence the mechanical behavior of mortar joints [25]. For example, reducing the water/cement ratio from 0.96 to 0.91 increases mortar cohesion 66% [26]. Therefore, small variations in the water/cement ratio due to different workmanship quality may increase or decrease mortar cohesion considerably. Hence, mortar joint cohesion was included as a random variable in the present study, serving as a representation of workmanship quality. Using a validated 3D Finite Element (FE) model and applying Monte Carlo stochastic analysis, the effect of mortar cohesion on the lateral strength of unreinforced masonry walls was investigated under in-plane and out-of-plane loads. The rest of this paper is organized as follows: Section 2 describes the methodology to model the masonry wall and workmanship quality; Section 3 presents, analyzes, and compares the performance of walls with different workmanship quality under single and combined lateral loads; and Section 4 presents the final conclusions.

2. Research methodology

This section begins by presenting a validated 3D FE numerical model used to simulate the behavior of unreinforced masonry walls. Then, the methodology for modeling varying workmanship quality is described in detail.

2.1. Numerical model

In this study, a micro-modeling strategy is used to capture the failure mechanism of the masonry wall under different types of loads. In this strategy, bricks and mortar joints are modeled separately; bricks are modeled using solid elements, whereas the properties of mortar and the interface between bricks and mortar are lumped into the interface elements [27,28]. The *GEFDyn* FE numerical tool is used to simulate the behavior of an unreinforced masonry wall [29] in this study. Bricks are supposed to remain elastic while the nonlinear behavior of masonry is concentrated in the mortar joints. Moreover, an interface element is placed in the middle of each brick to capture their tension failure.

The nonlinear properties of the mortar joints are presented by a multi-surface yield function and isotropic softening, as well as associated and non-associated flow rules. The composite yield function is composed of three parts: tension cut-off for the tension failure, Mohr–Coulomb failure criterion for the shear failure, and a linear compression cap for compressive failure of mortar joints. Lourenco [30] was the first to add a compression cap to the yield surface of the interface elements in modeling masonry walls through a micro-modeling strategy. Softening behavior is assumed for the cohesion, tensile strength, and compressive strength of mortar joints. An associated flow rule is considered for tensile strength, while non-associated flow rules are assumed for shear strength and the compression cap. Previous studies describe the model in more detail [31,32].

- Tension cut-off:

$$f_1 = \sigma_n - f_t \exp(-f_t/G_I. < [u_n^p]^+ >) \quad (1)$$

- Mohr–Coulomb shear failure criterion:

$$f_2 = \sqrt{(\sigma_s)^2 + (\sigma_t)^2} + \sigma_n.\tan\phi - c\exp(c|\gamma^p|/G_{II}) \quad (2)$$

$$\gamma^p = \sqrt{[u_s^p]^2 + [u_t^p]^2} \quad (3)$$

- Compression cap

$$f_3 = \sqrt{(\sigma_s)^2 + (\sigma_t)^2} - \sigma_n.\tan\theta - f_c\exp(f_c/G_{III} < [u_n^p]^- >).\tan\theta \quad (4)$$

where σ_n, f_t, G_I, and u_n^p are: normal stress, tensile strength, fracture energy of mode I, and normal plastic displacement in the interface element, respectively; $\sigma_s, \sigma_t, c, \phi, \psi, G_{II}, u_s^p$, and u_t^p are: shear stresses in $\vec{t}$ and $\vec{s}$ directions, cohesion of mortar joints, friction angle, dilatancy angel, fracture energy of mode II, and plastic shear displacements in the interface elements, respectively; and f_c, G_{III}, θ, and β are compressive strength of masonry, fracture energy of mode III, slope of the compression cap, and the direction of normal plastic deformations, respectively. The model has been validated against experimental data in the literature, and a good agreement has been observed between experimental and numerical results. For further information about the model, refer to Tabbakha [31].

2.2. Workmanship quality

A building consists of different walls that can have the same or different dimensions. This study investigated the effect of workmanship quality on the lateral strength of walls with the same dimensions, under single and combined loads. Therefore, all the mortar joints are modeled with the same material property throughout the wall. However, mortar joint cohesion is treated as a random variable, and thus the tensile strength of mortar joints is also treated as a random variable due to the relationship between these two parameters, $c = 1.4f_t$ [30]. The effects of other parameters like ϕ and f_c on wall performance are beyond the scope of this study and should be considered in future research.

The random variables were generated using the truncated normal probability distribution function. Hefler et al. [10] the flexural bond strength of wall units. The present study assumes the same distribution for mortar joint cohesion. Three coefficients of variation (COV) representing good (0.1), fair (0.3), and poor (0.5) workmanship quality were selected to represent different groups of walls, as observed in [10,33]. The generated values, according to the truncated normal distribution, were assigned to all the mortar joints throughout the walls.

3. Analyses, results, and discussions

This section summarizes the performance of masonry walls with different workmanship quality under in-plane, out-of-plane, and simultaneous in-plane and out-of-plane displacements. The boundary conditions and the level of pre-compression were identical across simulations, and the tops of the walls were subjected to the same amount of displacement. The pushover curves, failure mechanisms, and wall strength statistics are presented for each case.

In order to better appreciate and understand the effects of workmanship quality on unreinforced masonry wall performance, it is important to first describe the deformed shape and pushover curve from a validated model with specific material properties. In this study, the unreinforced masonry wall tested by Raijmakers and