Construction and Building Materials 155 (2017) 892–909

Contents lists available at ScienceDirect

Construction and Building Materials

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

Experimental and numerical assessment of in-plane monotonic response of ancient mortar brick masonry

Arash Rahgozar *, Abdollah Hosseini

School of Civil Engineering, University College of Engineering, University of Tehran, Tehran, Iran

HIGHLIGHTS

- Comprehensive experiment campaign for ancient and traditional mortars.
- Mechanical property of heritage masonry building for seismic retrofitting.
- Upgrades suggested to enhance the interface material model available in literature.
- Modeling the complex behavior of ancient materials.

ARTICLE INFO

Article history:
Received 15 May 2017
Received in revised form 30 July 2017
Accepted 15 August 2017

Keywords:
Ancient mortar
Clay brick masonry
Experimental test
Shear response
Contact behavior
FEM model
Numerical analysis

ABSTRACT

The structural assessment of extant historical buildings constructed using ancient or traditional masonry is a critical research area for seismic retrofitting. In this study, the in-plane characteristics of the brick masonry of ancient mortars including mud, lime–mud, and lime–sand are investigated experimentally and numerically. For this purpose, several brick masonry prisms are constructed using these mortars. The brick and mortar properties are selected to match those of surviving heritage masonry buildings. Moreover, brick masonry prisms composed of cement and cement–lime (“bastard”) mortars are constructed for comparison. The in-plane responses of these masonry prisms are examined through compression, shear, and tension tests. Failure of brick masonry structure occurs frequently in mortar joints owing to its nonhomogeneous in-plane behavior. The experimental shear and tension responses of masonry joints are used to develop an appropriate contact behavior that can be used for modeling ancient masonry structure in Abaqus FEM software. The experimental tests on masonry prisms are modeled in the software, and the results of the analysis have exhibited reasonable accordance with those of the actual tests.

1. Introduction

Several ancient mosques, schools, and other heritage masonry buildings that survive in the world have been constructed from ancient brick masonry using mortars of mud, lime, and plaster. In a majority of these buildings, it is mandatory to preserve their exterior and refrain from interfering with the facade. Therefore, certain reinforcement methods such as center core and post-tensioning have been proposed for the seismic retrofitting of these buildings [1]. To implement these retrofitting strategies, adequate information about the structural behavior and capacity of such buildings is required.

Historically, heritage masonry buildings used to be constructed with bricks and mortar joints, with the latter acting as a weak component in the masonry structures. It has been suggested by the authors in an earlier research study [2,3] that tension and shear failure mechanism occur in such mortar joints because of the composite behavior of such structures. Two failure modes occur in the mortar joints [2]: tension failure (mode I) is caused by the separation of bricks at the joints and shear failure (mode II) is caused by the sliding of bricks at the joints. A few experimental studies on masonry bed joint behavior were previously carried out [3–9]. Moreover, several other experimental and analytical studies were conducted to increase the available knowledge about the compressive behavior of masonry [3,10–12]. These studies were often based on commonly used cement or cement–lime mortars.

When modeling masonry structure in common FEM software such as Abaqus [13] and LS-DYNA [14], it is not possible to correctly define the masonry joint behavior. Therefore, it is necessary

* Corresponding author. Tel.: +98 9190089567.
E-mail addresses: a.rahgozar@ut.ac.ir, arash_rahgozar1990@yahoo.com (A. Rahgozar), hosseiniaby@ut.ac.ir (A. Hosseini).

http://dx.doi.org/10.1016/j.conbuildmat.2017.08.079
0950-0618/

to utilize user-defined subroutine code to model the joint behavior accurately. In this regard, several studies have been conducted in the past few decades [2,13,15–17].

In the current study, several brick masonry prisms of *ancient mortar* including mud, lime–mud, and lime–sand are investigated experimentally and numerically. The in-plane responses of these masonry prisms are studied using compression, shear, and tension tests. The experimental shear and tension responses of masonry joints have been used to develop an appropriate contact behavior (interface material model) for modeling ancient masonry structure in Abaqus FEM software.

2. Preparation of mortar specimens and brick masonry prisms

According to Persian literature [18–20], in rural areas, *mud* mortar used to be prepared from pure clay. In such mortar, 10–30% sand was used in clay for reducing shrinkage and cracks. *Lime–mud* mortar was also used in humid regions owing to its water scour-resistance and was prepared in various proportions of lime and clay by weight (1:3, 1:4, and 1:5). *Lime–sand* mortar was prepared with natural river sand, which generally contains 30% of clay by weight. The fraction of lime in *lime–sand* mortar was similar to that in *lime–mud* mortar.

For laboratory experiments, various materials were supplied by various providers. To select the materials that were most similar to heritage masonry materials, diverse tests were performed. The selected clay brick had the following features: a mean compressive strength of 10.02 MPa (in eight bricks, with variation coefficient of 0.26), water absorption of 13.7%, and dimensions $210 \times 100 \times 63$ mm [21]. Relatively pure clay (with no sand), with plasticity index of 14 and soil classification of "CL" was used [22]. Natural river sand with maximum grain size of 2 mm was selected as per the range specified by the ASTM C144-11 standard [23]. The lime was passed through sieve #100, and its weight loss in L.O.I test was approximately 20% according to ASTM C25 [24].

To prepare mortars of cement–sand 1:5 and cement–lime 1:1:6 (volume ratios), Portland cement of type 2–425 was used. In the rest of this article, these two types of mortars are referred to as *traditional cement mortars*, while mortars of mud, lime–mud, and lime–sand are referred to as *ancient mortars*.

The material proportions used for preparing the mortars have been presented in Table 1. For each mortar, a specific water ratio was maintained to achieve adequate workability and reduce scattering of the experimental test results. The lime was mixed in water uniformly before being added to other materials [19].

For each mortar, three mortar specimens of dimensions $50 \times 50 \times 50$ mm for the compression test, nine mortar specimens of dimensions $60 \times 60 \times 20$ mm for the shear test, nine brick masonry prisms of two courses each for the shear test, three brick masonry prisms of five courses each for the compression test, and three brick masonry prisms of two courses each for the direct tension test were constructed (Fig. 1). The bricks were soaked in water for a day, and their surfaces were cleaned; an hour later, after their surfaces were dried, the masonry prisms were constructed. After curing for 7 d with wet sacks and 21 d in laboratory climate, at the age of 28 d, all the specimens were tested.

3. Shear behavior of brick masonry bed joints

A number of experimental research studies [3–9] on masonry bed joint shear combined with axial loading have been previously carried out, as illustrated in Fig. 2. Based on these works, the shear strength (τ) can be estimated with the Mohr–Coulomb criterion (Eq. (1)). Therefore, shear strength is composed of two elements:

$$\tau = c + \sigma_c \tan\phi \qquad (1)$$

The two elements are cohesion of mortar (c) and friction under axial compressive stress ($\sigma_c \tan\phi$), where σ_c is the axial compressive stress and ϕ is the mortar internal friction angle.

3.1. Testing procedure

For evaluating the shear response, a large-scale direct shear device with a gravitational axial force was used (Fig. 3). A critical requirement in testing the shear response of brick masonry bed joints is to create actual conditions of axial compressive stress on the wall. During the shear test, the dilation angle of the masonry bed joint was measured with a vertical LVDT over the axial loading plate. The direct shear test setup, illustrated in Fig. 4, includes a shifting box at the bottom and a fixed box above, wherein the masonry bed joint was cut from the seam of the two boxes. To fit the masonry prism in both the $300 \times 300 \times 100$ mm boxes, a concrete frame was built, and the bottom of the masonry prism was fixed with a dental plaster. The shear force data was logged with a load cell installed along the seam of the two boxes. The bed joint slip was measured with a horizontal LVDT on the shifting box relative to the fixed box. The axial force was applied using a lever arm ratio of 20:1. The monotonic loading was performed at the speed of 2 mm/min.

For each type of mortar, nine shear tests under three axial forces of 2.73, 5.45, and 8.66 kN were conducted. These axial forces, applied to an average brick area of 210×100 mm, are equivalent to axial stresses of 0.13, 0.25, and 0.4 MPa. To minimize experimental errors, three shear tests were performed under each axial stress.

3.2. Test results, observations, and comparisons

In the direct shear tests on masonry bed joints, the failure of mud, cement–sand, and cement–lime masonry prisms were observed above and below the joint. The failure of the lime–mud and lime–sand masonry prisms occurred through the joint (Fig. 5).

It was also observed that the shear failure of cement–sand masonry prisms occurred above the joint, while it occurred below

Table 1
Mortar proportions by weight percentage (wt%).

Mortars name	Total dry (wt%)	Clay (wt%)	Sand (wt%)	Lime (wt%)	Cement (wt%)	Water (wt%)
Mud mortar	100	83.3	16.6	–	–	30
Lime-mud 1:3	100	52.5	22.5	25	–	38
Lime-mud 1:4	100	56	24	20	–	35
Lime-mud 1:5	100	58.3	25	16.7	–	30
Lime-sand 1:3	100	22.5	52.5	25	–	25
Lime-sand 1:4	100	24	56	20	–	20
Lime-sand 1:5	100	25	58.3	16.7	–	16.7
Cement-sand 1:5	100	–	86.8	–	13.2	15.8
Cement-lime 1:1:6	100	–	80.7	8.8	10.5	17.4