Construction and Building Materials 141 (2017) 353–365

Contents lists available at ScienceDirect

Construction and Building Materials

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

Parameter estimation for nonlinear analysis of multi-perforated concrete masonry walls

José F. Lizárraga [a], J.J. Pérez-Gavilán [b],*

[a] Instituto de Ingeniería de la UNAM, Av. Universidad 3000, CU, CP 04510, México D.F, Mexico
[b] Structural Engineering Department, Instituto de Ingeniería de la UNAM, Av. Universidad 3000, CU, CP 04510, México D.F, Mexico

HIGHLIGHTS

- Parameters for nonlinear analysis of masonry structures were investigated.
- The experimental program included tests in tension, shear and compression.
- Mode I and mode II fracture energies are estimated.
- Mode II fracture energy decreased linearly with the confining stress.
- A linear yield surface can be used to represent the compression cap failure surface.

ARTICLE INFO

Article history:
Received 19 September 2016
Received in revised form 8 February 2017
Accepted 1 March 2017

Keywords:
Masonry
Properties
Strength
Fracture energy
Nonlinear analysis

ABSTRACT

The mechanical properties of masonry and bed joints were investigated. The masonry was constructed using multi-perforated concrete units, and the bed joints consisted of two types of mortar, in situ elaborated (type M) and industrialized pre-mixed mortar. An experimental program was conducted that included tests of tension, shear and compression. For the masonry, the results included elastic modulus and compressive strength. For the bed joints the results included: strength in tension, tangent and normal stiffness, mode I and mode II fracture energies, dilatancy angle and the shear Mohr-Coulomb parameters, cohesion and the initial and residual friction coefficients. Details of the tests and comments on the results are provided.

1. Introduction

The seismic behavior of masonry walls is determined by the constitutive laws that characterize the materials. In the literature, there are several finite element models that predict the behavior of walls subjected to lateral loads [1–7]. Nevertheless, there are few experimental studies that have investigated the post peak regime, which is necessary to complete the numerical models. To overcome, in part, this lack of information, this study focused on determining the necessary parameters required by the models proposed by Lourenço and van Zijl [3,8] that are implemented in the finite element program DIANA [9]. This model represents the bricks as continuous elastic elements and the joints as nonlinear interface elements that include tensile, shear and compressive failure modes. The elastic properties necessary to model the bricks, considering them to be of an isotropic material, are the modulus of elasticity E_u and the shear modulus G_u.

1.1. Tensile tests

There are different test setups to obtain the parameters for modeling the tensile failure of joints. In some cases, only the tensile strength between the bricks and the mortar was studied [10–12]. Crossed brick couplet tensile tests have been used (Fig. 1a) [10,11] where the top unit is supported in the vertical direction while a vertical load is applied to the unit in the bottom causing tension in the joint.

Khalaf [12] used a Z-shaped configuration (Fig. 1b) to determine the flexural bond strength between masonry units and mortar. He was interested in the design of masonry walls subjected to out of plane forces. Four types of units, two solid and two perforated units, were used in combination with three types of mortar. The flexural bond strength, considering a parabolic stress distribution,

---

* Corresponding author.
E-mail addresses: joflizarraga@gmail.com (J.F. Lizárraga), jperezgavilane@iingen.unam.mx (J.J. Pérez-Gavilán).

http://dx.doi.org/10.1016/j.conbuildmat.2017.03.008

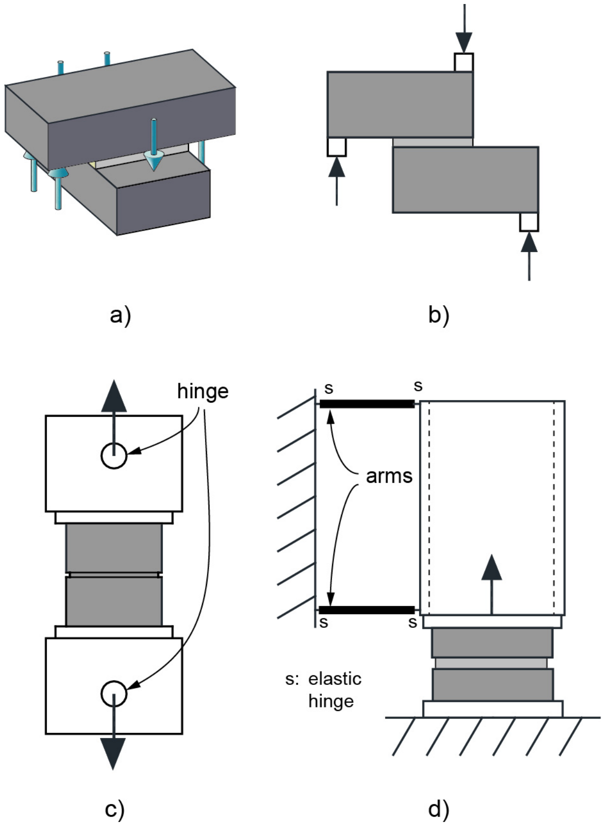

Fig. 1. Different tension tests; (a) Crossed brick couplet test [10], (b) Z-shaped specimen [12], (c) Direct tensile test with hinges [13], (d) Direct tensile test with fixed platens [14,15].

varied from 0.1 to 0.43 N/mm^2. Results of the tests showed that the flexural bond strength is reduced when perforated units are used compared to the bond strength of solid wire cut bricks.

Controlled deformation in direct tensile testing [13–17] is more convenient because it is the only way to determine the Mode I fracture energy G_f^I. Van Mier [13] studied the effect of rotating versus fixed boundaries in uniaxial tensile tests of concrete and sandstone units. Fixed end platens produces a higher tension strength and a higher Mode I fracture energy than rotating platens. Van Mier concludes that using rotating platens (Fig. 1c) is more suitable because a lower bound of the fracture energy is found.

Van der Pluijm [14,15] used two different tensile testing setups, both with full restraints against rotation of the specimen. One device was the one used by Hordijk [16], which consisted of a guiding system, and the other device consisted in a steel member with a rectangular hollow section and two hinged arms to prevent rotation (Fig. 1d). Van der Pluijm [14] studied three tensile test setups with the finite element method, direct tensile device with hinges, direct tensile device with fixed platens and the cross couplet setup. The numerically obtained bond strength was compared to the input strength. The results showed that the bond strength with the device with fixed platens had the lowest difference with respect to the input strength, only 3–5% lower, while the strength obtained with the device with hinges was 23–27% less than the input strength. The bond strength obtained with the cross couplet device was the less reliable, being 42–52% lower than the input strength. Different units in combination with different types of mortars were also investigated [15]. The tensile average strength range was [0.13, 0.5 N/mm^2] for general-purpose mortars (gpm) while the range of the mode I fracture energy average was [0.0042, 0.0115 N/mm], again for gpm.

Almeida et al. [17] tested three types of units in tension, one solid brick and two hollow bricks, and with the solid brick they evaluated four different types of mortar. Only in very few of the tests with solid bricks and mortar the mode I fracture energy could be evaluated. The average strength in tension and the mode I fracture energy were in the order of 2 N/mm^2 and 0.008 N/mm respectively.

1.2. Shear tests

As for tension, different setups have been proposed to measure the mechanical properties of masonry mortar joints in shear. In different countries with standard shear tests [18,19], as in different investigations [20–23], the tests were limited to determining the strength parameters. In Table 1 experimental results from various shear tests, are shown. In Europe, a standard test method using a triplet test has been implemented [18].

Meli [20,21] performed triplet tests to investigate the cohesion and friction coefficient of the joints with different levels of pre-compression (Fig. 2a). He found a linear variation of strength with the confining stress, defining a friction coefficient that was almost independent of the type of mortar. The bond strength was highly variable depending on the type of mortar and unit type. Lourenço et al. [22] reported the cohesion and friction coefficients for stack bonded masonry (Table 1) using the triplet test (Fig. 2b). Citto et al. [23] used a digital imaging technique to monitor the deformations of the brick-mortar assembly during an in-place shear test. The equipment consisted of a digital camera connected to a computer for image acquisition. A software program was used with a correlation algorithm that analyzed the images and estimated displacements and strains. The cohesion and friction coefficients were reported. A high level of nonuniformity of stresses was reported during the test.

Other authors [24] conducted triplet tests on masonry specimens using different types of mortar with a test setup configuration similar to Fig. 2a. They derived the cohesion and the internal friction angles from a linear regression of the test results. Additionally, they found that the shear strength increases with increasing confining pressure in a rather nonlinear fashion for different mortar strengths. However, they managed to represent the responses of bed joints in shear with simple equations that use the Young's modulus of the bricks and mortar, the mortar thickness and the normal compressive stress acting on the interface.

Different investigations [25,26] had demonstrated, with finite element models, that the direct shear apparatus produces a more uniform shear stress distribution along the mortar joints when compared with a triplet test. In a direct shear test, forces are applied to a stack assemblage of bricks joined with mortar in such a way that a pure shear stress is applied at the center of the joint (Fig. 2e–g). Knowledge on the deformation parameters such as shear stiffness, Mode II fracture energy (G_f^{II}) and dilatant behavior is necessary to implement in a numerical model. Atkinson et al. [27] tested horizontal bed joints using a servo-controlled direct shear apparatus to determine the load-displacement behavior of unreinforced brick masonry during static and cyclic loading (Fig. 2e). A model that utilizes a hyperbolic curve in the pre-peak response was used. They found that the shear stiffness varied with the shear displacement and the confining stress level and that the residual shear strengths remained constant even when shear cycles were applied. Dilatancy was observed in all of their tests.

Van der Pluijm [28] used a direct shear test apparatus (Fig. 2f) to test bed joints using three types of solid units in combination with two types of mortar. Tests showed that shear strength can be represented with the Mohr-Coulomb failure criterion and that using stronger mortars result in a higher cohesion. During the test,