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Capacity interaction in brick masonry under simultaneous in-plane and out-of-plane loads

M.A. Najafgholipour [a], Mahmoud R. Maheri [a,*], P.B. Lourenço [b]

[a] Department of Civil Engineering, Shiraz University, Shiraz, Iran
[b] ISISE, Department of Civil Engineering, University of Minho, Portugal

HIGHLIGHTS

- ▶ In-plane/out-of-plane capacity interaction in brick walls is investigated.
- ▶ Experimental and numerical investigations indicate strong capacity interaction.
- ▶ A tentative conservative formula is proposed on the in-plane/out-of-plane load/capacity interaction in brick walls.

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ABSTRACT

A considerable number of numerical and experimental studies, carried out to-date to investigate the behaviour of masonry walls under seismic loading, have considered the in-plane or the out-of-plane response of the wall separately without due consideration for any possible interaction between the two responses. In this paper, the results of a series of tests with different levels of simultaneous in-plane shear and out-of-plane bending actions on small brick walls are presented. The tests results indicate noticeable interaction between the in-plane shear and out-of-plane bending strengths of brick walls. Test results are also used to validate representing numerical models of wall panels. The combined in-plane/out-of-plane capacity interaction in full-scale walls having different aspect ratios is then investigated using these numerical models. It is found that the wall aspect ratio highly influences the interaction level, which must be considered in masonry design.

1. Introduction

A brick wall undergoing an earthquake global acceleration field is subjected to both in-plane and out-of-plane loads. The former results from the storey shear force under horizontal loading and the latter is either due to the out-of-plane inertia force caused by the considerable mass of the brick wall or the out-of-plane action of a flexible floor on the wall. The presence of one type of loading on a structural element affects the strength of that element against another type of loading. Considerable experimental, numerical and analytical studies have been carried out on the behaviour of masonry buildings, particularly under earthquake loading and mostly on the behaviour of brick walls.

As one of the earliest experimental works, Johnson and Thompson [1] investigated the tensile strength of brickwork as the main parameter for brick wall in-plane failure and its relation to the angle between the load and the direction of the bed joints. Another early work was done by Sinha and Hendry [2], with a series of racking tests on brick walls with openings. They derived relations for the in-plane shear capacity of brick walls based on Mohr–Coulomb and maximum tensile strength criteria. More recently, Abrams [3] reported a series of pushover and cyclic tests on unreinforced brick walls and suggested relations for calculating the in-plane shear and bending strengths of these elements. Tomazevic [4] also investigated diagonal shear strength of brick walls and compared the results with those obtained through relations suggested by Eurocode 6 [5], showing some discrepancies in the results. The in-plane shear behaviour of confined brick walls has also been investigated experimentally by Tomasevic and Klemenc [6], Pourazin and Eshghi [7] and Riahi et al. [8] and simple load displacement models are suggested for these elements. In some of the studies, the effects of the confining concrete ring beam on the strength and behaviour of brick wall was also investigated. Other investigators have concentrated on the brick–mortar bond strength and response under in-plane direct shear force, such as Atkinson et al. [9], El-sakhawy et al. [10], Abdou et al. [11] and Maheri et al. [12,13]. The effect of mortar joints on the in-plane shear strength of brick walls was also

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* Corresponding author. Tel.: +98 917 7167274; fax: +98 711 6286619.
E-mail address: maheri@shirazu.ac.ir (M.R. Maheri).

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investigated by Maheri et al. [14]; showing the considerable influence of the head joints on the response.

Experimental and numerical investigations on masonry are often aimed at deriving simplified analytical models for the response or capacity. Although analytical methods have limitations, they are popular due to simplicity and relevance for design purposes. Most analytical methods have been presented for the in-plane shear response of masonry walls. Calderini et al. [15] reported a series of existing analytical methods for calculating the in-plane strength of unreinforced masonry walls. Bosiljkov et al. [16] also reviewed the existing analytical methods for evaluating the in-plane strength of masonry walls and presented an approach for calculating the performance limits of masonry buildings. Roca [17] proposed simple equilibrium equations to calculate the ultimate strength of solid brick walls and walls with openings under concentrated or distributed gravity and lateral loads. Giordano et al. [18] presented a simple formula for predicting the in-plane strength of masonry portals based on limit analysis approach. Benedetti and Steli [19] derived the lateral load–displacement curve for unreinforced and FRP reinforced masonry walls through analytical methods, assuming an elastic-perfectly plastic behaviour for the masonry material.

Considerable experimental work is also reported for the strength and response of brick walls under out-of-plane loads. Kanit and Atimtay [20] carried out a cyclic test on an unreinforced brick wall and presented its failure mode and hysteretic curve. Griffith et al. [21] conducted a series of cyclic tests on full scale brick walls with different pre-compression levels and aspect ratios, with and without openings. Their results showed considerable post peak strength and displacement capacity in the walls resulting from the pre-compression. Derakhshan et al. [22] carried out static one-way, out-of-plane bending tests on three brick walls with different height to thickness ratios and various pre-compression loads. They obtained a tri-linear force–displacement model for walls in one-way bending and concluded that pre-compression and slenderness are important parameters in the out-of-plane response. Meisle et al. [23] carried out a series of out-of-plane shaking table tests on unreinforced brick walls subjected to three types of ground motions. The results showed that the type of ground motion did not have significant effects on the out-of-plane strength of walls. In a recent experimental study Maheri et al. [14] highlighted the orthotropic nature of the out-of-plane response of brick walls. The failure mechanism of the orthotropic wall panels undergoing bi-directional bending initiated with a vertical crack as the stiffness of the wall in bending parallel to the bed joints far exceeds the stiffness of the wall in bending perpendicular to the bed joints. Following the softening of the wall parallel to the bed joint, caused by the vertical crack, the wall exhibited a relatively isotropic behaviour [14].

Several researchers performed out-of-plane tests on masonry prisms. Grimm and Tucker [24] derived a relation between the out-of-plane strength of brick walls and flexural strength of masonry prisms. Rao et al. [25] and Pavia and Hanley [26], in similar experimental studies, investigated parameters such as mortar type and moisture content of masonry units affecting the flexural strength of prisms. They concluded that these parameters have significant effects on the flexural strength. Khalaf [27] proposed a new test set up with lower scatter in results for obtaining the flexural brick–mortar strength.

In addition to the above experimental works, numerous numerical investigations have also been carried out in recent years to further study the response of brick walls to in-plane and out-of-plane loading. A review of these studies is beyond the scope of this article and the reader is directed to [28–32] for a review.

Very few studies were carried out on the numerical response under simultaneous in-plane and out-of-plane loading. Shapiro et al. [33] studied the interaction of the in-plane and out-of-plane responses of brick infills in concrete frames. They carried out a series of tests to investigate the effects of in-plane cracks on the out-of-plane strength. Their test results showed that the in-plane cracks may reduce the out-of-plane strength of infills up to 100%. A similar experimental study was carried out by Flanagan et al. [34] on brick infills in steel frames. Recently, Hashemi and Mosalam [35] conducted an in-plane shake table test on a concrete infilled frame, subsequently used to calibrate a numerical model that was further developed to include out-of-plane loading. Also, Milani carried out a 3D heterogeneous upper bound limit analysis of multi-leaf brick masonry walls subjected to simultaneous in-plane and out-of plane loading [36]. In that study, under the assumption of associated plasticity for the constituent materials, mortar joints were reduced to interfaces with a Mohr–Coulomb failure criterion with tension cut-off and cap in compression, whereas for bricks a Mohr–Coulomb failure criterion was adopted.

The absence of experimental investigations directly addressing the in-plane shear/out-of-plane bending capacity interaction in brick masonry in the literature is the main reason for the present study, which complements the experimental campaign with the numerical simulation of the results and a parametric study on the influence of the aspect ratio of the panels.

2. Experimental program

A series of tests are conducted here on wallets to study the in-plane and out-of-plane capacity interaction and to determine the interaction curve for brick walls. Next, a discussion on the adopted test specimens, set up, procedure and results is given.

2.1. Test specimens

In total, 27, single-layer square brick wall panels were constructed for the experiments. All panels were of the same size and materials using constant workmanship and post-construction treatment, aiming at obtaining a moderate scatter in the results. The wall panels were 60 cm by 60 cm and 10 cm thick. To ensure that the pure in-plane shear failure of the wall panels develops indeed in the form of a diagonal line crack running through both the mortar and brick units, it was decided to use stronger mortar and slightly weaker brick units. Therefore, in constructing the panels, compressed vertically perforated clay brick units were used with dimensions 22 cm (length), 10 cm (width) and 5.0 cm (height). These are the best type of engineered bricks available locally with low variation in quality and strength. The mortar was made of ordinary Portland cement and fine aggregate (passing sieve # 20) with a weight ratio of 1:3, providing a high strength mortar. The wall panels were also cured under polythene sheet for 28 days against loss of moisture and for uniformity of treatment. Such treatment was shown previously by Maheri et al. [13,14] to result in increased brick–mortar bond strength and low variation in the results. A number of samples were also made for the material and prism tests, including: compressive and tensile tests on mortar; compressive and flexural tests on brick units; shear, compression and bending capacity tests of brickwork; and determination of modulus of elasticity of mortar, brick units and brickwork. The obtained properties are listed in Tables 1 and 2, together with the standards followed and the numbers of specimens used for each test.

2.2. Test set-up

Based on the observations made on the behaviour of walls during earthquakes and supported by experimental research reported in the literature, a most relevant in-plane shear failure mode in unreinforced brick walls is diagonal shear cracking. This failure mode is characterised by a diagonal crack perpendicular to the maximum tensile stress in the wall panel. There are a number of in-plane shear test set-ups (also known as diagonal tension or compression tests), see Vilet [37] and the ASTM-E519-10 [38] was utilised here, regarding the size and preparation of the specimens, as well as the test set-up and procedure. In this test, the brick wall panel is subjected to a static diagonal compressive force until failure. A number of researchers, including Calderini et al. [39], Gabor et al. [40], Brignola et al. [41] and Borri et al. [42], have recently used this particular test to determine the in-plane shear strength of brick walls.

For the present study, a minor modification was needed in the test set-up so that simultaneous application of in-plane and out-of-plane loads to the wall panels could be carried out. For this purpose, a reaction frame was designed and constructed in such a way that it did not confine the brick panel and also did not reduce the effective dimensions of the panel. A square steel frame having internal dimen-