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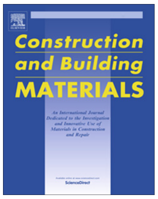

Definition of interaction curves for the in-plane and out-of-plane capacity in brick masonry walls

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HIGHLIGHTS

- Numerical investigations indicate strong in-plane/out-of-plane capacity interaction.
- Wall aspect ratio and the material properties in tension have the most influence on the level of the interaction.
- An analytical method for in-plane/out-of-plane capacity interaction in brick walls is proposed.
- The analytical method provides results that are accurate and on the safe side.

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ABSTRACT

During an earthquake a wall is subjected to a three dimensional acceleration field and undergoes simultaneous in-plane and out-of-plane loading. The action of one type of loading on the wall affects the strength of the wall against another type of loading. In this paper, a numerical investigation, supported by experiments, is conducted aimed at deriving appropriate relations for the in-plane/out-of-plane capacity interaction in unreinforced brick walls. Through a comprehensive parametric study, the main affecting parameters are recognised and their influences on the capacity interaction are established. The parametric study indicates that the aspect ratio of the wall and the elastic and inelastic material properties in tension have the most influence on the level of the in-plane and out-of-plane capacity interaction in masonry walls. Based on the results of these investigations, representing empirical relations for evaluating the interaction are derived and their accuracy is verified.

1. Introduction

During earthquake ground motion, a brick wall is simultaneously subjected to in-plane and out-of-plane loads. The former result from the storey shear force and the latter are either due to the out-of-plane inertia force of the wall itself or the out-of-plane action of the floor on the wall. Considerable experimental, analytical and numerical studies have been reported on the behaviour of brick walls under earthquake loading, but most of it concentrates on the response and capacity of the wall under in-plane shear loading. Notable experimental works carried out on the in-plane response of unconfined brick walls include those reported by Sinha and Hendry [1], Abrams [2] and Tomazevic [3]. The in-plane shear capacity of confined brick walls was also investigated experimentally by Tomasevic and Klemenc [4], Pourazin and Eshghi [5] and Riahi et al. [6]. Factors affecting the in-plane brick wall capacity, including the brick mortar bond strength and the effects of mortar joints have also been investigated experimentally by El-Sakhawy et al. [7], Abdou et al. [8] and Maheri et al. [9–11].

A number of experimental work is also reported for the strength and response of brick walls under out-of-plane loads, highlighting the orthotropic nature of brick wall response [11], the influence of pre-compression and slenderness ratio [12,13] and the effects of brick–mortar bond [11] under such loading. A comprehensive review of the above works is given by the authors in [14].

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. One of the early works on numerical modelling of unreinforced masonry walls was carried out by Page [15]. He developed a simple micro-model for unreinforced masonry subjected to in-plane loads. He applied combined Mohr–Coulomb and Maximum Tensile Strength failure surfaces to model the failure in the mortar joints. In Page's model, the masonry unit behaviour was considered elastic brittle and the nonlinear response of

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the wall was assumed to be solely due to mortar joints behaviour. Later, Ali and Page [16] presented a finite element micro-model to simulate the behaviour of masonry under large compressive point loads. They used the Von Mises criterion with tension cut off failure criteria in their model. Their approach could also model smeared cracks in the walls. Lotfi and Shing [17] also developed a simple micro-modelling approach for in-plane shear analysis of masonry walls. They used Mohr–Coulomb material model together with maximum tensile strength failure surfaces to model bond slip and tension failure in joints. The smeared crack model was also utilised to obtain cracking in masonry units. Another micro-model capable of modelling different in-plane failures in unreinforced brick walls was developed by Lourenço and Rots [18]. They presented two interface models; one was to model failure in bricks and the other was to simulate failure in mortar joints. They applied Mohr–Coulomb failure criteria with combination of a tension cut off and cap model [18]. Chaimoon and Attard [19] also adopted a micro-modelling approach similar to that developed by Lourenço and Rots. Mojsilovic and Marti [20] developed a numerical sandwich model for masonry walls. They also used Mohr–Coulomb failure criteria for modelling the bed joints and neglected shear capacity of the mortar head joints. They assumed that the mortar head joints work only in compression. Sutcliffe et al. [21] applied the lower bound limit analysis method to analyse masonry shear walls subjected to in-plane loads. They used a simple micro-model in their analyses and considered plane strain behaviour for the walls. They also adopted the Mohr–Coulomb failure criteria with a cap.

Parallel to the development of micro-modelling approaches, several macro-models have also been developed by different researchers. Lourenço et al. [22] presented an orthotropic composite failure surface for macro-modelling of unreinforced masonry subjected to in-plane loads. The failure surface is composed of a Rankine type failure surface in tension and a Hill type failure surface in compression. The model was applied to the out of plane behaviour of masonry walls investigated in another work conducted by Lourenço [23]. Other failure surfaces are also developed for masonry such as the failure surface presented by Andreaus [24]. Many investigations have also been carried out on developing homogenisation techniques in masonry walls, bridging the gap between micro- and macro-models, including those reported by Lourenço et al. [25], Mistler et al. [26] and Milani [27].

Numerical and analytical approaches for the analysis of masonry walls under out-of-plane loads have also been addressed. Sinha et al. [28] presented a failure criteria and an analytical method for masonry panels subjected to two-way bending. The limit analysis approach together with homogenisation techniques are often applied for the analysis of masonry walls subjected to out-of-plane loads, e.g. Cecchi et al. [29], Milani [30] and Casolo and Milani [31].

Despite the large volume of experimental, numerical and analytical works carried out on the response of masonry walls to separate effects of in-plane and out-of-plane loads, very little is reported on the response of masonry subjected to combined effects of in-plane and out-of-plane actions. The few reported works combining the in-plane and out-of-plane actions on the wall seem to be related to the masonry infills. Shapiro et al. [32] carried out a series of tests to investigate the effects of in-plane cracks on the out-of-plane strength of brick infills in concrete frames. Their test results showed that the in-plane cracks may reduce the out-of-plane strength of infills by up to 100%. A similar experimental study was carried out by Falangan et al. [33] on brick infills in steel frames. Also, Hashemi and Mosalam [34] conducted an in-plane shaking table test on a reinforced concrete infilled frame, subsequently used to calibrate a numerical model that was developed to include out-of-plane loading.

Recently, an experimental investigation aimed at determining the in-plane and out-of-plane capacity interaction of masonry walls was presented [14]. In that work, the results of a series of tests on small brick walls undergoing different levels of simultaneous in-plane and out-of-plane actions were presented. The test results indicated noticeable interaction between the in-plane shear and out-of-plane bending strengths of brick walls. Test results were also used to validate representing numerical models of wall panels. The combined in-plane/out-of-plane capacity interaction in full-scale walls having three different aspect ratios was then numerically investigated; results of which showed that the wall aspect ratio highly influences the level of interaction [14].

In the following, representing numerical models are developed and their accuracy is verified against experimental data. A comprehensive parametric study is undertaken to recognise the main affecting parameters and to establish their influence on the capacity interaction curves. Based on the results of these investigations, representing relations for evaluating the in-plane and out-of-plane interaction in brick walls are derived and their validity is verified.

2. Validation of the numerical approach

In this section, the numerical model used for the parametric study is presented and its accuracy in predicting the in-plane/out-of-plane interaction is verified against existing experimental data. Because of the complex nature of in-plane and out-of-plane actions on the wall, a suitable continuum macro-model based on anisotropic plasticity is adopted [35] for the three dimensional analysis of brick walls. This material model is implemented in software Diana V9.4 [36] via a user supplied subroutine.

2.1. Anisotropic continuum model

The composite yield criterion used in this model, is based on the plane stress anisotropic yield criterion of Lourenço [22], in the typical five stress component space, with two normal stresses σ_x and σ_y and three shear stresses τ_{xy}, τ_{yz} and τ_{xz}. The composite yield criterion shown in Fig. 1, includes a Hill type criterion for compression and a Rankine type criterion for tension. For an orthotropic material with different tensile strengths along the x and y directions the Rankine type yield surface is given by:

$$f_1 = \frac{(\sigma_x - \overline{\sigma_{tx}}(\kappa_t)) + (\sigma_y - \overline{\sigma_{ty}}(\kappa_t))}{2} + \sqrt{\frac{(\sigma_x - \overline{\sigma_{tx}}(\kappa_t)) - (\sigma_y - \overline{\sigma_{ty}}(\kappa_t))}{2} + \alpha\tau_{xy}^2} \quad (1)$$

where $\overline{\sigma_{tx}}$ and $\overline{\sigma_{ty}}$ are the yield values along x (parallel to bed joints) and y (normal to bed joints) directions. The scalar (k_t) denotes the

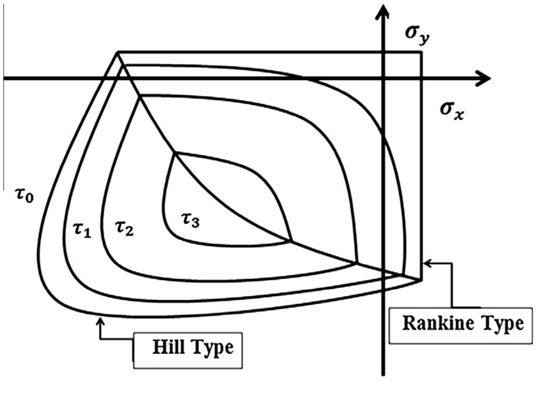

Fig. 1. The plane stress anisotropic yield criterion [22].