



Contents lists available at ScienceDirect

Computers and Structures

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

A 3D detailed micro-model for the in-plane and out-of-plane numerical analysis of masonry panels

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ARTICLE INFO

Article history:

Received 30 January 2018

Accepted 11 June 2018

Available online xxxxx

Keywords:

Masonry

Cohesive interfaces

Micro-modelling

Plastic-damage model

Cracking

Crushing

ABSTRACT

In this paper, a novel 3D detailed micro-model to analyse the mechanical response of masonry panels under in-plane and out-of-plane loading conditions is proposed. The modelling approach is characterized by textured units, consisting of one brick and few mortar layers, represented by 3D solid finite elements obeying to plastic-damage constitutive laws. Textured units are assembled, accounting for any actual 3D through-thickness arrangement of masonry, by means of zero-thickness rigid-cohesive-frictional interfaces, based on the contact penalty method and governed by a Mohr-Coulomb failure surface with tension cut-off. This novel approach can be fully characterized by the properties obtained on small-scale experimental tests on brick and mortar and on small masonry assemblages. The interface behaviour appears consistent with small-scale tests outcomes on masonry specimens. Experimental-numerical comparisons are provided for the in-plane and out-of-plane behaviour of masonry panels. The accuracy, the potentialities and the efficiency of the modelling approach are shown and discussed.

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1. Introduction

Masonry is one of the oldest building materials. It is composed of masonry units (i.e. brick, blocks, etc.) usually bonded with mortar. Due to its heterogeneous and composite nature, its mechanical behaviour is extremely complex. The near-collapse mechanical behaviour of masonry structures is generally deeply influenced by the failure of brick-mortar bonds, which act as planes of weakness [1]. Indeed, the brick-masonry interface represent a discontinuity between two distinct and different materials and its strength, which depends from a huge number of factors (e.g. brick pores dimensions, units moisture content, nature of micro-layer of ettringite, compaction of the mortar, etc. [1]) and, therefore, is extremely variable, is generally considerably smaller than the mortar and unit one [2]. Under extreme loading conditions (e.g. earthquakes), masonry structures can show cracking and/or crushing of the units too.

Due to these features, as well as the difficulties in characterizing the masonry mechanical properties of existing structures (especially if they are historic [3]), the evaluation of the vulnerability of masonry buildings by means of deterministic numerical models is still challenging [4]. Indeed, although significant advances have been carried out in the last decades, the definition of numerical

strategies for a suitable description of the mechanical behaviour of masonry is still nontrivial and an on-going process in the scientific research [5].

Generally, computational strategies for masonry structures are classified in micro-modelling and macro-modelling [6]. In addition, homogenization and upscaling procedures represent a link between the two approaches [7–12]. The macro-modelling approaches account for the masonry mechanical nonlinearity by means of a macroscopic continuum description of its behaviour, employing different formulations (e.g. phenomenological plasticity [13], damage mechanics [14] and nonlocal damage-plasticity [15]). Isotropic continuum nonlinear constitutive laws with softening have been successfully used for the analysis of large-scale historic structures [16], where, due to the chaotic and random texture of historic masonry, the hypothesis of isotropic material generally appears suitable. Nonetheless, when dealing with masonries characterized by well-organized and periodic masonry textures, the hypothesis of isotropic material is no longer suitable. To overcome this issue, few masonry macro-modelling approaches have been extended to orthotropic continua [17,18]. Furthermore, phenomenological continuum models accounting for the micro-structure of masonry have been recently developed (the so-called continuous micro-models, see for example [19]).

However, an account of the inelastic response over discontinuity surfaces at the brick-mortar bonds appears to be crucial in the analysis of masonry structures. Indeed, the behaviour of masonry

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walls is largely affected by the displacement discontinuities which are generated at the brick-mortar interfaces, as experimentally evidenced in [20].

Although their larger computational demand, micro-models with interface elements can capture the complex patterns of discontinuities which characterize the damage evolution in masonry with a higher degree of accuracy, and reproduce the main features of their response, such as, for example, the relative sliding of units. For these reasons interface elements found broad application in the numerical analysis of masonry structures [21–30] and they are still currently object of investigation [31,32]. Discrete element models (DEM) represent a further numerical strategy, utilized to analyse the mechanical behaviour of systems made of particles, blocks or multiple bodies, which appears suitable for masonry structures [33–39].

Nevertheless, these micro-modelling approaches present some criticalities. One the one hand, DEM approaches do not generally account for masonry crushing, making this modelling strategy more suitable for analysing dry-joint masonry or low bond strength masonry, where failure occurs in the mortar or in the brick-mortar interface rather than in the units [40]. On the other hand, most of the existing micro-models in the literature concern linear elastic units and joints which can simulate the sliding, cracking and crushing of masonry (e.g. all the models based on the multisurface interface model proposed in [21]). Particularly, the crushing is usually accounted for by means of a cap in the joint failure surface, i.e. through a phenomenological representation of the crushing. However, the characterization of the compressive nonlinear behaviour of masonry is not an easy task. Indeed, it depends on the texture of masonry, on the direction of the compressive load (e.g. perpendicular to the bed joints, parallel to the bed joints, etc.), on the relative dimensions between bricks and mortar joints [11], etc. Moreover, a reliable characterization of the compressive behaviour of masonry should be based on tests on relatively large specimens. Conversely, the characterization of the single materials (mortar and brick) in compression appear easier and dependent on less variables.

In this context, the development of a novel model whose mechanical setting could be exclusively based on small-scale specimen tests of masonry components (i.e. mortar and brick) and small masonry assemblages, without using spread mechanical properties, such as the masonry compressive strength, was considered. Furthermore, the idea of developing a 3D solid model able to account for, at the same time, the in-plane and out-of-plane response of masonry elements (since, in practice, they can be coupled) was also contemplated.

To pursue this goal, a novel numerical approach to model masonry is conceived. In particular, a 3D detailed micro-model for the in-plane and out-of-plane numerical analysis of masonry structures is proposed in this paper. In this modelling approach, textured units consisting of one brick and few mortar layers are explicitly modelled using 3D solid Finite Elements (FEs) obeying to plastic-damage constitutive laws conceived in the framework of nonassociated plasticity. Particularly, two plastic-damage models with distinct parameters are assumed for brick and for mortar, both in tension and compression regimes. This permits to represent the brick and mortar behaviour when cracking and/or crushing occur.

Textured Units are assembled, accounting for any actual 3D through-thickness arrangement of masonry, by means of zero-thickness cohesive-frictional interfaces based on the contact penalty method. In the pre-failure interfacial behaviour, all the significant linear elastic deformability of the system is addressed to the 3D brick and mortar FEs, being negligible the interfacial deformations. The interfaces are characterized by a Mohr-Coulomb failure surface with tension cut-off. The post-failure interfacial

behaviour is defined by an exponential coupled cohesive behaviour in tension and a cohesive-frictional behaviour in shear, accounting for the brick-mortar bond failure both in tension and shear.

To the author knowledge, the coupling of contact-based rigid-cohesive interfaces with 3D nonlinear-damaging textured units (which explicitly account for the mortar layers) to model masonry is a novelty in the scientific literature. This novel modelling approach can, in fact, be fully characterized by the properties obtained on small-scale specimen tests on brick and mortar (stiffness, compressive and tensile responses) and on small masonry assemblages (tensile and shear responses of the mortar-brick bond).

To reach this goal, this paper introduces an interface model. The interface behaviour is governed by an ad-hoc modification of the standard surface-based contact behaviour implemented in Abaqus [41], a general-purpose FE software. Contextually, an automatic subroutine ad-hoc written by the authors is implemented to reproduce a Mohr-Coulomb failure surface with tension cut-off.

The interfacial behaviour appears consistent with experimental outcomes on small-scale masonry specimens. Experimental-numerical comparisons are provided for the in-plane and out-of-plane behaviour of masonry panels. The direct characterization of all the model mechanical properties from small-scale tests on brick, mortar and brick-mortar bond and their clear mechanical meaning constitute an appealing quality of the model proposed.

The paper is organized as follows. Section 2 illustrates the main features of the modelling approach proposed. Section 3 describes the brick-mortar interface nonlinear behaviour. Section 4 describes the plastic-damage model utilized for brick and mortar. Section 5 collects experimental-numerical comparisons and their discussion for the in-plane and out-of-plane behaviour of masonry panels. Finally, Section 6 highlights the conclusions of this research work.

2. Modelling approach

As already mentioned, several modelling strategies can be followed to analyse masonry structures, see Fig. 1. An accurate model for simulating the mechanical behaviour of masonry should account for the main masonry failure mechanisms [21]. At a small scale, masonry failures are depicted in Fig. 2. In particular, brick-mortar interface tensile failure (Fig. 2a) and shear sliding (Fig. 2b) are characterized by the failure of the bond between brick and mortar. Masonry crushing (Fig. 2d), cracking (Fig. 2e) and diagonal cracking (Fig. 2c) are, instead, combined mechanisms involving bricks and mortar (Fig. 2d–e) and bricks, mortar and brick-mortar interface (Fig. 2c).

In the modelling approach herein proposed, the brick-mortar bond failures (Fig. 2a and b) are accounted for by brick-mortar nonlinear cohesive interfaces, whereas the combined mechanisms involving also brick and mortar (Fig. 2c–e) are accounted for by the nonlinear behaviour of brick and mortar FEs, see Fig. 1b. Therefore, brick and mortar crushing and cracking, although characterized by a complex evolution of micro-cracks, are represented by the inelastic behaviour of brick and mortar FEs.

Textured units composed of 3D solid FEs (Fig. 3) with brick properties (red elements in Fig. 3) and mortar properties (grey elements in Fig. 3) are conceived and they are assembled by means of zero-thickness interfaces (green surfaces in Fig. 3). For single leaf masonry panels, the textured unit concerns one brick as well as one head joint and one bed joint (Fig. 3). Brick and mortar FEs are characterized by distinct nonlinear plastic-damaging behaviour, both in tension and compression regimes.

Each mortar layer is continuously linked to a brick and separated by an interface from other bricks. This reduces considerably the number of interfaces (instead of considering all the two

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