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Micro-scale continuous and discrete numerical models for nonlinear analysis of masonry shear walls

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HIGHLIGHTS

- A novel damage continuous micro-model for masonry shear walls is presented.
- A novel bi-dissipative damage model able to represent dilatancy of mortar joints.
- The proposed micro-model is validated and compared to others available in literature.
- Results are critically discussed and compared.

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ABSTRACT

A novel damage mechanics-based continuous micro-model for the analysis of masonry-walls is presented and compared with other two well-known discrete micro-models. The discrete micro-models discretize masonry micro-structure with nonlinear interfaces for mortar-joints, and continuum elements for units. The proposed continuous micro-model discretizes both units and mortar-joints with continuum elements, making use of a tension/compression damage model, here refined to properly reproduce the nonlinear response under shear and to control the dilatancy. The three investigated models are validated against experimental results. They all prove to be similarly effective, with the proposed model being less time-consuming, due to the efficient format of the damage model. Critical issues for these types of micro-models are analysed carefully, such as the accuracy in predicting the failure load and collapse mechanism, the computational efficiency and the level of approximation given by a 2D plane-stress assumption.

1. Introduction

Masonry is a composite material, with a micro-structure consisting of bricks and joints, with or without mortar. These micro-structural constituents, their very different elastic and inelastic properties, and their arrangement lead to very complex behaviors and different failure mechanisms. Several computational strategies were proposed to deal with the numerical analysis of such a complex material [1]. Several macro-models, also known as continuum finite element models, are available in the existing literature to study masonry structures. The most recent macro-models regard the material as a fictitious homogeneous orthotropic continuum, without making any explicit distinction between units and joints in the discrete model [2–4]. This approach presents some intrinsic difficulties mainly related to the identification of the mechanical parameters of the continuum and the definition of realistic phenomenological failure criteria. However, macro-models are still a suitable option for the numerical analysis of large and complex structures due to their limited computational cost. More sophisticated numerical strategies were proposed by several authors for detailed analysis of single structural members, where a full description of the interaction between units and mortar is necessary (Fig. 1a). Very popular approaches used nowadays to study masonry, including its heterogeneous micro-structure in the discretization, are based on micro-modeling [5–8]. Midway between macro- and micro-modeling there are the homogenization methods [9–19].

A complete and detailed description of masonry micro-structure would require the full three-dimensional discretization of bricks, mortar joints, and the interface between them. In this

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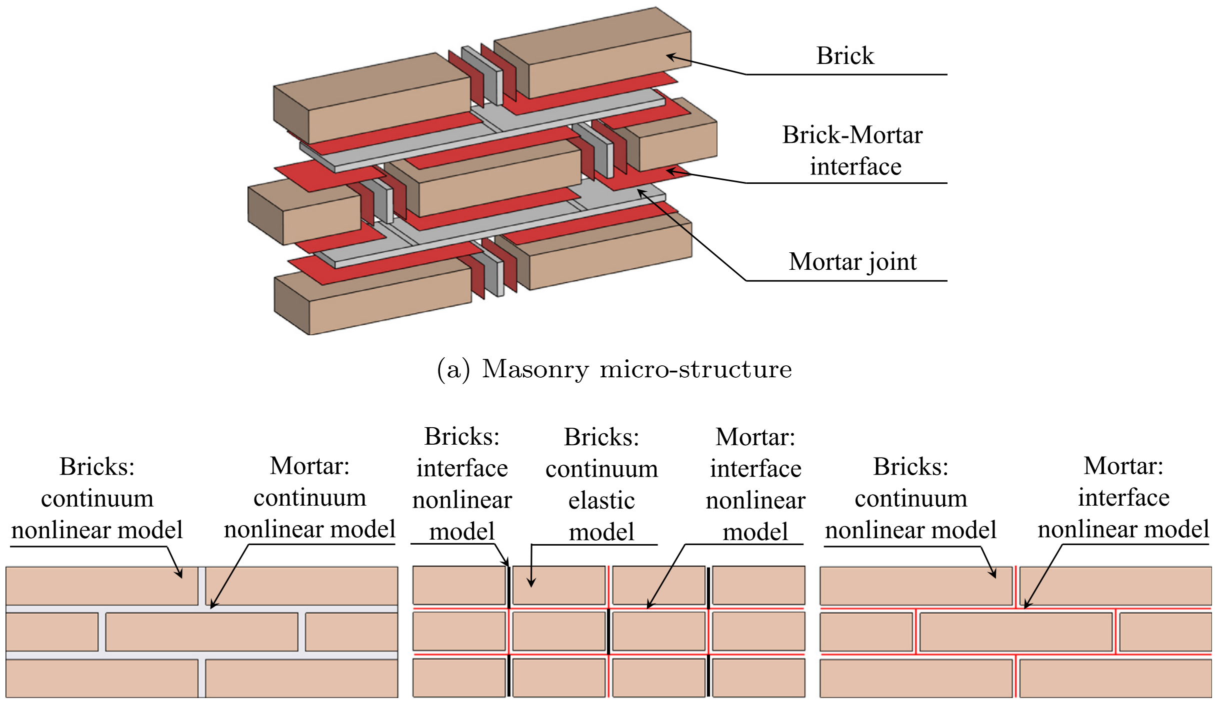

(a) Masonry micro-structure

(b) 2D-C micro-model (c) 2D-D micro-model (d) 2D-CD micro-model

Fig. 1. Masonry modeling strategies.

way all masonry constituents and their complex interaction would be explicitly accounted for. However, three-dimensional modeling requires a complex model generation and high computational costs. For the case of a wall made of one layer of bricks with a regular pattern, the 2D plane stress assumption can be made to simplify the problem. This however can lead to imprecise results when the wall is subjected to high levels of compressions, since the state of triaxial compression in the mortar joints cannot be represented with the plane-stress assumption. A more accurate solution can be the adoption of generalized plane state [20,21].

The objective of this paper is to propose a novel damage-mechanics based continuous micro-model able to represent the mechanical behaviors of masonry constituents. The proposed micro-model is based on a tension–compression continuum damage model [22–24], here refined in order to accurately reproduce the nonlinear response of masonry constituents, especially in shear. The adoption of appropriate failure criteria enables the analyst to control the dilatant behavior of the material, even though this aspect is not generally associated to continuum damage models as it is for plasticity models. The study proposes a simple solution to this issue, consisting in the appropriate definition of the failure surfaces under shear stress states together with the formulation of proper evolution laws for damage variables. For this aim, a failure criterion for quasi-brittle materials [25] is suitably enhanced under shear conditions and a novel hardening–softening law based on quadratic Bézier curves is established. The model keeps the simple and efficient format of classical damage models, where the explicit evaluation of the internal variables avoids nested iterative procedures, thus increasing computational performance and robustness.

Another purpose of this research is to carry out a critical comparison of the proposed continuous micro-model with other two well-known discrete micro-modeling strategies for the numerical simulation of shear walls made of periodic masonry. The three micro-models explicitly take into account the interaction between units and mortar joints by including their separate discretizations. The main distinction made here between continuous and discrete micro-models is referred to the different type of elements and constitutive models used for the discretization of masonry micro-structure. Discrete micro-modeling has been widely adopted by several authors in literature [5,7,26–30] using a discrete description of masonry micro-structure, mixing continuum and interface elements for bricks and mortar joints, respectively. On the contrary, the proposed continuous micro-modeling uses a continuum discretization of all components of the masonry micro-structure, without resorting to interface elements.

The investigated approaches are validated against experimental tests of masonry shear walls under different level of vertical compression [31], proving to be similarly effective and accurate in predicting the global strength of shear walls up to their collapse. All three micro-modeling techniques are able to properly reproduce the main failure mechanisms of the material, such as tensile cracking, sliding, shear and crushing. However, each one of the selected models introduces different approximations that lead to slight differences in accuracy, robustness and computational cost. The validation of the novel continuous micro-model, together with the critical review of available discrete micro-models, leads to a fruitful discussion on advanced computational strategies for the analysis of masonry structures at the level of material constituents.

2. Adopted modeling strategies

The three selected modeling strategies to represent the micro-structure of masonry material (see Fig. 1a) are:

1. **2D Continuous micro-model(2D-C)**: Both units and mortar joints are modeled using 2D plane-stress continuum elements with nonlinear behavior (see Fig. 1b)). This paper presents a novel formulation for this approach at the level of the constitutive law.