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A detailed micro-model for brick masonry structures based on a diffuse cohesive-frictional interface fracture approach

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Abstract

In the past decades, the mechanical behavior of brick masonry material has been largely investigated using different modeling strategies, ranging from purely microscopic to purely macroscopic ones. The so-called simplified micro-modeling approaches, in which the behavior of mortar joints and brick/mortar interfaces is lumped in discontinuous elements, are commonly judged as very effective for accurately representing the interaction between the masonry constituents with an acceptable computational burden. However, they completely disregard the competition between brick/mortar decohesion and mortar cracking, whose role is not negligible, especially in presence of sufficiently thick joints and/or high-strength mortars. In this work, a detailed micro-modeling approach is proposed for the nonlinear analysis of brickworks subjected to in-plane loads. Such an approach allows failure to occur at the brick/mortar interface level and/or inside the mortar layer, while keeping the discrete nature of fracture phenomena. For this purpose, a novel diffuse cohesive-frictional interface approach for joints is presented, able to simulate multiple micro-crack onset and propagation along a-priori unknown paths. Suitable comparisons with a simplified micro-model are provided to validate the proposed approach. Moreover, a good agreement with the experimental outcomes is found, thereby assessing the reliability of the present fracture-based detailed micro-model in the numerical prediction of masonry strength under complex loading conditions.

Keywords: Brick masonry; Detailed micro-modeling; Diffuse cohesive interface elements; Mixed-mode crack propagation; Failure analysis.

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Nomenclature

c	interfacial cohesion
$\mathbf{C}_b, \mathbf{C}_m$	fourth-order elasticity tensors of brick and mortar
d	scalar damage function
DIM	diffuse interface model
E	Young's modulus of the bulk
f_t	interfacial tensile strength
G	tangential modulus of the bulk
G_{Ic}, G_{IIc}	mode-I and mode-II fracture energies
$\mathbf{K}_0$	second-order elastic constitutive tensor of the interface
K_n^0, K_s^0	normal and tangential elastic stiffness parameters of the interface
L_{mesh}	mesh size
SIM	single interface model
$\mathbf{t}_{\text{int}}$	interface traction vector
$\mathbf{t}_{\text{coh}}$	cohesive traction vector
$\mathbf{t}_{\text{fric}}$	frictional traction vector
t_{fric}	frictional tangential stress
t_s^{coh}	tangential component of the cohesive traction vector
$[[\mathbf{u}]]$	displacement jump at interfaces
α	dimensionless softening shape parameter
Γ_{int}	cohesive interfaces
Γ_{int}^{bm}	brick/mortar interfaces
Γ_{int}^{mm}	mortar/mortar interfaces
δ_n, δ_s	normal and tangential components of the displacement jump
δ_s^0	tangential displacement jump at damage onset in pure mode II
δ_s^f	tangential displacement jump at total decohesion in pure mode II
Δ_s	shear displacement measured for the couplet test by Van der Pluijm
κ	dimensionless interfacial normal stiffness
μ_0	initial friction coefficient
μ_r	residual friction coefficient
ν	Poisson's ratio of the bulk
σ	applied precompression stress for the couplet test by Van der Pluijm
τ	applied average shear stress for the couplet test by Van der Pluijm
φ_0	initial friction angle
φ_f	residual friction angle

1. Introduction

At a conventionally defined microscopic scale, masonry can be considered as a two-phase heterogeneous material made of units (bricks, blocks, stones) and joints. The units are bonded together along the joints with or without mortar. The first case is not only that of modern regular masonry, but also typical of irregular historic masonry, in which mortar possesses the role of filling and sealing the gaps between the units. Instead, the latter case is typical of regular historic masonries, whose units are separated by dry joints, characterized by a dominant frictional behavior. In both situations, the extremely complex mechanical behavior of masonry structures is related to the multiple interactions between different nonlinear phenomena (such as damage inside units, fracture along joints, contact with friction between crack faces) occurring at various length scales and induced by the geometrical arrangement of units.

With special attention devoted to periodic brick masonries subjected to in-plane loading conditions, various models have been proposed for the nonlinear analysis of small-scale to large-scale structures. For an exhaustive literature survey about existing modeling strategies for the computational analysis of unreinforced masonry structures, the reader is referred to D'Altri et al. (2019), as well as to the references therein. In particular, most of the existing models in the literature may be grouped into three distinct classes, i.e. micro-models, macro-models and multiscale models (see, for instance, Addessi et al. (2014)).

Micro-models explicitly consider all the microstructural details of the given masonry structure, thus providing very accurate results. However, they require a huge computational effort to solve the associated nonlinear mechanical problems. Macro-models are based on homogeneous continua, in which units, mortar joints and material interfaces are smeared out. These models are equipped with suitably defined phenomenological constitutive laws, able to capture the main nonlinear features of masonry. However, they usually have a limited predictive capability in presence of competing failure mechanisms in the different phases, since they do not distinguish between units and joints behavior. Finally, multiscale models combine the advantages of micro- and macro-models, leading to a high level of accuracy at a reduced computational cost; this is made possible by virtue of micromechanical concepts and/or homogenization methods, able to derive the macroscopic behavior of masonry directly from the microscopic behavior of its constituents as well as from their mutual interactions at the microscopic scale (see, for instance, Masiani et al. (1995), Anthoine (1995), Luciano and Sacco (1997), de Buhan and de Felice (1997), Cecchi and Sab (2002), Massart et al. (2007), Sacco (2009), Bacigalupo and Gambarotta (2011), De Bellis and Addessi (2011), Giambanco et al. (2014), Greco et al. (2016), Greco et al. (2017), Leonetti et al. (2018), Reccia et al. (2018), Leonetti et al. (2019)).

In the framework of micro-models for masonry, two alternative approaches are usually adopted in the literature:

- detailed micro-modeling approaches, in which bricks and mortar joints are represented by continuum elements whereas the brick/mortar interfaces are represented by discontinuous elements;
- simplified micro-modeling approaches, in which expanded bricks are described as continuum elements and the behavior of the mortar joints and the brick/mortar interfaces is lumped into (discontinuous) brick/brick interface elements (see, for instance, Gambarotta and Lagomarsino (1997), Bisoffi-Sauve et al. (2019)).

On the one hand, the main advantage of detailed micro-models, here referred to as continuous/discontinuous detailed micro-models, consists of their ability to capture the interaction between brick/mortar decohesion and damage within mortar layers. However, such approaches inevitably lose the discrete nature of fracture phenomena in the mortar phase. On the other hand, simplified micro-modeling possess, as their main advantage, a greater computational efficiency compared to detailed micro-modeling. However, their main disadvantage consists in the impossibility to capture the complex brick/mortar interactions, due to the fact that Poisson effect of joints is totally neglected in both elastic and inelastic regimes.

In this work, a novel detailed micro-model, referred to as discontinuous detailed micro-model, is proposed for the nonlinear analysis of brick masonries, able to overcome the limitations of the above-mentioned detailed and simplified micro-models. According to this approach, the inelastic behavior of both mortar layers and brick/mortar interfaces is represented by means of discontinuous elements, thus keeping the discrete nature of cracking also within mortar layers.

This model relies on the Diffuse Interface Model (DIM), based on an inter-element fracture approach within a cohesive/volumetric finite element setting and proposed by some of the authors in De Maio et al. (2019a) and successfully extended to general concrete-like structures in De Maio et al. (2019b) and De Maio et al. (2019c). Accordingly, the bulk finite elements for both brick and mortar materials possess a linearly elastic response, whereas the inelastic mechanical behavior of the composite system is governed by (physical) brick/mortar interfaces and (mathematical) mortar/mortar interface elements equipped with suitably calibrated mixed-mode traction-separation laws. The main aspect of novelty of the adopted interface formulation is the incorporation of a frictional behavior coupled with the cohesive one, needed to investigate the inelastic response of mortar joints in the combined compressive/shear stress regime.

The proposed discontinuous detailed micro-model is hereafter validated by performing comparisons between the related numerical results and those obtained from the experimental tests by Van der Pluijm, with reference to a direct shear test on a brick couplet. Moreover, the numerical results of the present model are further compared with those obtained with a simplified micro-model, here considered as a reference one, being a well-established model, and the differences between these two models are discussed. Finally, additional numerical results are shown, devoted to the investigation of mesh dependency issues, to further demonstrate the reliability of the proposed approach.

2. Theoretical formulation and numerical implementation of the detailed micro-model

2.1. Cohesive/volumetric finite element formulation

Generally speaking, detailed microscopic modeling approaches for masonry structures assume that the underlying material can be considered as a two-phase composite, made of units (e.g. bricks, blocks or stones) and mortar joints. It is useful to point out that such approaches are not applicable to masonry with dry joints, whose nonlinear behavior is dominated by contact and friction phenomena, which may be naturally described at the interface level between adjacent units.

In the special case of regular brick masonry structures, the underlying microstructure is generated by the periodic repetition of a unit cell made of rectangular units (bricks) connected by only (horizontal) bed joints and (vertical) head joints according to a uniform arrangement. In this case, the thicknesses of both bed and head mortar joints are assumed to be constant, although different from each other.

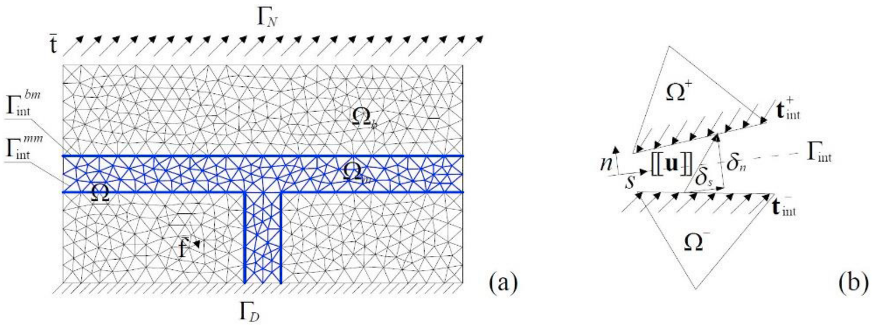


Fig. 1. (a) Detailed micro-model for 2D masonry structures based on the cohesive/volumetric finite element approach (cohesive interface elements are depicted in blue); (b) representation of the cohesive interfaces and related notations.

Since the out-of-plane mechanical behavior of masonry is not investigated in this work, a 2D model reduction is considered, based on the assumption of plane strain conditions. Such a reduction is able to represent more accurately than the plane stress state the condition of the mortar joints, with particular reference to mortar layers next to the interfaces, which are constrained from spreading out of the plane of the masonry by the presence of adjacent stiffer bricks. Clearly, this simplified state is more realistic for very thin mortar joints and large elastic mismatches between the bricks and the mortar, but in general it can be applied to masonries whose overall behavior is strongly influenced by the failure of the mortar, for which the plane stress state is inaccurate, as already pointed out by Anthoine (1997).

In the present work, only the joints are susceptible to damage under the action of in-plane loads, due to the supposed relative weakness of the mortar compared to the bricks, so that the latter are made of a linearly elastic material. The resulting nonlinear structural behavior associated with multiple micro-crack nucleation and propagation is taken into account by inserting special cohesive interface elements inside mortar joints, as well as along the brick/mortar interfaces. According to the previous considerations, a two-dimensional masonry composite structure, occupying the region Ω, is schematized as a collection of mortar joints and bricks, indicated with Ω_m and Ω_b, respectively, both regarded as continuous phases (see Fig. 1a). The embedded (physical) brick/mortar and (mathematical) mortar/mortar interfaces are denotes as Γ_{int}^{bm} and Γ_{int}^{mm}, respectively. Under the action of body forces $\overline{\mathbf{f}}$ on Ω and surface forces $\overline{\mathbf{t}}$ on Γ_N, in presence of constraints on Γ_D, while considering quasi-static loading conditions and small deformations, the following cohesive/volumetric variational formulation is valid: Find $\mathbf{u} \in U$ such that

$$\int_{\Omega_b} \mathbf{C}_b \boldsymbol{\varepsilon} \cdot \delta\boldsymbol{\varepsilon} \, d\Omega + \int_{\Omega_m \setminus \Gamma_{\text{int}}^{mm}} \mathbf{C}_m \boldsymbol{\varepsilon} \cdot \delta\boldsymbol{\varepsilon} \, d\Omega + \int_{\Gamma_{\text{int}}} \mathbf{t}_{\text{int}}([\![\mathbf{u}]\!]) \cdot \delta[\![\mathbf{u}]\!] \, d\Gamma = \int_{\Omega \setminus \Gamma_{\text{int}}} \overline{\mathbf{f}} \cdot \delta\mathbf{u} \, d\Omega + \int_{\Gamma_N} \overline{\mathbf{t}} \cdot \delta\mathbf{u} \, d\Gamma \quad \forall \delta\mathbf{u} \in U, \tag{1}$$

where the third term of the left-hand side represents the virtual work of the tractions $\mathbf{t}_{\text{int}}$ acting on the brick/mortar and mortar/mortar interfaces, collectively referred to as Γ_{int}. Moreover, $\mathbf{C}_b$ and $\mathbf{C}_m$ are, respectively, the elasticity tensors of brick and mortar continuous phases (both assumed as linearly elastic), $\boldsymbol{\varepsilon}$ is the usual infinitesimal strain tensor, the double brackets denote the jump of the enclosed quantity across the interfaces Γ_{int}, δ denotes the usual variation operator, and U is the set of kinematically admissible displacement fields compatible with homogeneous Dirichlet boundary conditions on Γ_D.

2.2. Mixed-mode cohesive-frictional traction-separation law

Both brick/mortar and mortar/mortar interfaces are equipped with an enhanced version of the intrinsic traction-separation law with linear-exponential softening adopted in De Maio et al. (2019b), here proposed to take into account a coupled cohesive-frictional response. In this work, a simple although powerful modeling approach is adopted to incorporate the coupling between Coulomb friction and decohesion within a purely damage-based interface law. According to this approach, friction forces act during decohesion in pure mode II in addition to cohesive forces, so that the total interface tractions $\mathbf{t}_{\text{int}}$ can be expressed as the sum of two contributions:

$$\mathbf{t}_{\text{int}} = \underbrace{(1-d)\mathbf{K}_0[[\mathbf{u}]]}_{\mathbf{t}_{\text{coh}}} + \mathbf{t}_{\text{fric}} \tag{2}$$

where $\mathbf{t}_{\text{coh}}$ denotes the cohesive traction vector, d being the damage variable defined in a complete manner in De Maio et al. (2019b) and $\mathbf{K}_0 = K_n^0 \mathbf{n}\otimes\mathbf{n} + K_s^0(\mathbf{I}-\mathbf{n}\otimes\mathbf{n})$ being the elastic constitutive tensor of the interface, expressed in terms of normal and tangential stiffness parameters K_n^0 and K_s^0 (with $\mathbf{n}$ the unit normal vector to Γ_{int}, as shown in Fig. 1b). The second term $\mathbf{t}_{\text{fric}} = t_{\text{fric}}\mathbf{s}$ represents the frictional traction vector, $\mathbf{s}$ being the unit tangent vector to Γ_{int} and:

$$t_{\text{fric}} = \begin{cases} 0 & \delta_n > 0 \\ -\text{sgn}(\delta_s)\,\mu(|\delta_s|)\,K_n^0\delta_n & \delta_n \le 0 \end{cases} \tag{3}$$

being the Coulomb friction traction, assumed to be proportional to the compressive normal stress $\sigma_n = -K_n^0\delta_n$ acting along Γ_{int}. Moreover, $\delta_n = [[\mathbf{u}]]\cdot\mathbf{n}$ and $\delta_s = [[\mathbf{u}]]\cdot\mathbf{s}$ are the normal and tangential components of the displacement jump, and $\mu(|\delta_s|)$ is the (variable) friction coefficient, defined as:

$$\mu(|\delta_s|) = \begin{cases} \mu_0 \dfrac{|\delta_s|}{\delta_s^0} & 0 \le |\delta_s| < \delta_s^0 \\ \mu_f + (\mu_0 - \mu_f)\dfrac{t_s^{\text{coh}}}{c} & \delta_s^0 \le |\delta_s| < \delta_s^f \\ \mu_f & |\delta_s| \ge \delta_s^f \end{cases} \tag{4}$$

where the initial friction coefficient $\mu_0 = \tan\varphi_0$ (with φ_0 initial friction angle) is attained at the shear displacement jump δ_s^0 corresponding to the damage onset, whereas the final (or residual) friction coefficient $\mu_f = \tan\varphi_f$ (with φ_f final friction angle) is attained for shear displacement jump values equal or greater than δ_s^f, corresponding to the total decohesion. In the range between damage onset and total decohesion, the friction coefficient assumes intermediate values, depending on the ratio between the current value of the shear component t_s^{coh} of the cohesive traction vector, computed according to the first term of the right-hand side of Eq. (2), and the cohesion value c.

It is worth noting that such a friction approach, similarly to other simplified approaches as the one proposed in Bilbie et al. (2008), does not allow for permanent shear displacement jump at the interface during unloading/reloading branches. The choice of adopting a total displacement formulation for friction is motivated by the need of keeping simple its computational implementation, unlike for more sophisticated combined interface damage and friction formulations (see, for instance, Alfano and Sacco (2006)).

2.3. Numerical implementation of the detailed micro-model

In this section, the proposed micro-model for the nonlinear analysis of masonry structures is described, together with some implementation details. Such a model, developed and implemented within the commercial finite element software COMSOL Multiphysics (COMSOL AB (2019)), incorporates two distinct submodels: (a) a Diffuse Interface Model (DIM) for simulating multiple crack initiation and propagation within the mortar phase, and (b) a Single Interface Model (SIM) for describing brick/mortar debonding.

It is worth noting that the SIM interfaces represent physical interfaces between distinct phases (i.e. bricks and mortar joints), whereas the DIM interfaces are mathematical interfaces lying within a single phase, inserted with the aim of capturing in a discrete manner the diffuse damage phenomena occurring inside mortar layers.

The synergistic application of these two submodels, both based on the inter-element fracture approach described in Section 2.1, allows several damage mechanisms in masonry structures subjected to in-plane loading to be predicted in a unified manner, including brick/mortar mixed-mode decohesion, tensile and shear cracking of mortar joints, as well as their interactions.

The numerical implementation of the proposed discontinuous detailed micro-model requires the construction of the enriched finite element mesh in a dedicated preprocessing stage, consisting of three different steps:

- Generation of the initial 2D volumetric mesh, made of three-node triangular elements arranged in an unstructured mesh of the Delaunay type, in order to avoid preferential potential crack paths after the insertion of inter-element cohesive interfaces.
- Separation of the volumetric finite elements performed via duplication of common nodes sheared by each pair of adjacent triangles.
- Interconnection of adjacent volumetric elements via insertion of four-node zero-thickness cohesive interface elements between them.

The main computational advantage of the adopted inter-element fracture approach is that no mesh updates are required to account for crack initiation and propagation, unlike for many classical discrete fracture approaches.

It is worth recalling that the above-described enrichment is performed only inside mortar joints, in which the DIM approach is applied, whereas the remaining mesh portion inside bricks is not teared off, since bricks are assumed to be undamageable in the present work.

Finally, both brick/mortar and mortar/mortar interface elements are equipped with the intrinsic traction-separation law described in Section 2.2. To account for its irreversible damage behavior, two additional weak contributions are defined, involving two auxiliary state variables, storing the maximum value attained by the effective displacement jump δ_m at current and previous simulation steps, as discussed in De Maio et al. (2019c).

The number of parameters involved in the proposed discontinuous detailed micro-model is eighteen, i.e. nine for each interface type (brick/mortar or mortar/mortar interface). Among them, seven parameters with physical meaning could be directly measured from experiments or calibrated via inverse identification techniques. Such parameters are: tensile strength f_t and cohesion c; mode-I and mode-II fracture energies, denoted as G_{Ic} and G_{IIc}, respectively; softening shape parameter α, influencing the rate of damage evolution of the cohesive interface; initial and final friction coefficients μ_0 and μ_f. The two remaining parameters are the initial normal and tangential stiffness constants K_n^0 and K_s^0, which do not have a physical meaning, playing the role of penalty parameters. These parameters have been computed using the following calibration relations, proposed in De Maio et al. (2019b):

$$K_n^0 = \kappa \frac{E_m}{L_{\text{mesh}}}, \quad K_s^0 = \frac{1-\nu_m}{1+3\nu_m} K_n^0 \tag{5}$$

where E_m, ν_m are Young's modulus and Poisson's ratio of the mortar, L_{mesh} is the mesh size adopted within the mortar joints, and κ is the dimensionless interfacial normal stiffness, here chosen equal to 200, such that the resulting Young's modulus reduction (which is inevitable for the DIM approach) is of about 1%, according to the numerical procedure proposed in De Maio et al. (2019b). It follows that the number of input parameters to be inserted into the proposed detailed micro-model is reduced to fourteen.

Nevertheless, it is useful to highlight that the available parameters for masonries, estimated by means of common characterization tests, refer to a specific material model, i.e. the well-established simplified micro-model, based on a Single Interface Model (SIM) for describing the failure of mortar joints (in pure fracture mode I or mode II) without distinguishing between brick/mortar decohesion and damage inside mortar, and thus requiring a fewer number of parameters to be calibrated. As a matter of fact, it is almost impossible to obtain from single experiments all the parameters required by the present model, the related numerically predicted failure pattern being characterized by a strong interaction between competing microscopic fracture events involving both brick/mortar and mortar/mortar interfaces locally subjected to different mixed-mode loadings.

Therefore, in this work a different approach is pursued aimed at calibrating the above-mentioned parameters. The brick/mortar parameters are directly obtained from experimental data involving tensile or shear tests on simple masonry specimens (as for the simplified micro-models), whereas the mortar/mortar parameters, (which are supposed to play a minor role to determine the global response of masonry joints) are not assigned with precise values identified from experimental tests, but rather grossly approximated with values consistent with available data for mortar.

3. Numerical simulation of the couplet shear test by Van der Pluijm: results and discussion

In this section, the results of the numerical simulations performed to assess the efficacy of the present discontinuous detailed micro-model are presented, with reference to the prediction of the shear behavior of brick masonry.

In the current literature, three different setups are available to analyze the structural response of masonry under shear loadings:

- the couplet shear test setup proposed by Van der Pluijm (1999);
- the couplet shear test setup proposed by Lourenço and Ramos (2004), which is similar to the classical shear box used in geomechanics;
- the triplet shear test setup, which has been adopted as the standard setup in Europe (CEN - EN 1052-3 (2002)).

For the numerical validation of the proposed model, the couplet shear test by Van der Pluijm is here chosen (see Fig. 2), being the most detailed and reliable setup, to the best knowledge of the authors, especially in terms of the quantity of available input and output experimental data (see Van der Pluijm (1999)).

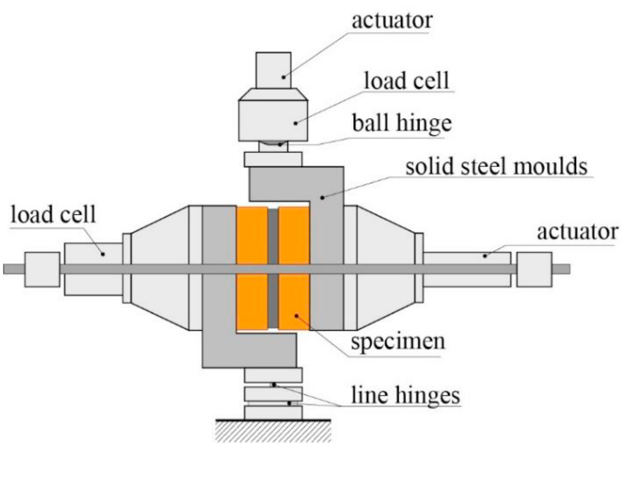


Fig. 2. Schematic representation of the couplet shear test by Van der Pluijm (1999).

The considered specimen, composed of two units with dimensions $200 \times 100 \times 50$ mm bonded together along the mortar joint with thickness of 15 mm, is glued between the left and right plates of the testing machine. Such an arrangement allows to move the above two plates independently of each other, and more precisely: the right plate in the shear direction, whereas the left plate in the direction perpendicular to the bed joint. The tests are carried out with a constant value of normal precompression stress and an increasing value of shear deformation. In particular, two LVDTs on the specimen are used to control the shear displacement.

3.1. Comparison between numerical and experimental results

In this section, the results of the numerically simulated couplet shear test are shown, referring to plain strain conditions, for three different values of the precompression stress level, i.e. 1.00, 0.50 and 0.10 MPa. The adopted elastic bulk parameters and inelastic interface parameters are reported in Tables 1 and 2, respectively. Such parameters are directly taken from Van der Pluijm (1999), except for the cohesion values of the brick/mortar interface (see Table 2), here modified via the heuristically found multiplicative factor 1.15 in order to compensate the softening effect induced by the unconstrained rotation of the steel plates, explicitly modeled in the present numerical simulations to facilitate the application of external boundary conditions.

The elastic parameters of the interfaces are calibrated according to Eq. (5), assuming $L_{\text{mesh}} = 2$ mm, whereas the dimensionless softening shape parameter α is set as 5 (suitable values for concrete-like materials).

Table 1. Elastic parameters for brick and mortar phases.

Bulk phase	σ [MPa]	E [MPa]	ν [-]	G [MPa]
Brick	-	16,700	0.15	-
	-1.00			1,830
Mortar	-0.50	-	0.20	1,909
	-0.10			2,029

Table 2. Inelastic parameters for brick/mortar and mortar/mortar interfaces.

Interface	σ [MPa]	Tension		Shear		Friction	
		f_t [MPa]	G_{Ic} [N/m]	c [MPa]	G_{IIc} [N/m]	$\mu_0 = \tan \varphi_0$ [-]	$\mu_f = \tan \varphi_f$ [-]
	-1.00			1.242	206.4	0.798	0.77
Brick/mortar	-0.50	0.30	11.5	1.139	116.5	0.80	0.80
	-0.10			1.012	66.90	1.0	0.92
Mortar/mortar	-	0.90	10.0	$1.4 f_t$	$10 G_{Ic}$	1.0	1.0

The predicted loading curves are in good agreement with the ones obtained by the experimental tests, especially for the case $\sigma = -1.00$ MPa, the related numerical curve being almost completely inside the experimental envelope, as clearly shown in Fig. 3.

The related failure mechanisms are depicted in Fig. 4, with reference to both peak and residual stages. At peak (see the top side of Fig. 4), they are characterized by the nucleation of shear cracks inside the mortar joint (induced by local mode-I conditions). At the end of simulation, the complete failure of the masonry couplet is characterized by a combination of mortar separation and mode-II brick/mortar decohesion, resulting in a global brick/mortar failure divided between two faces, for all the three precompression stress levels (see the bottom side of Fig. 4).

A deeper analysis of the numerical results reported in Figs. 3 and 4 suggests that the peak strength is greatly influenced by the local fracture properties of mortar. Therefore, by suitably tuning strength and/or toughness of mortar, it could be possible to anticipate or postpone the appearance of shear cracks within the joint thickness, thus making possible to reproduce the dispersion of experimentally measured peak loads.

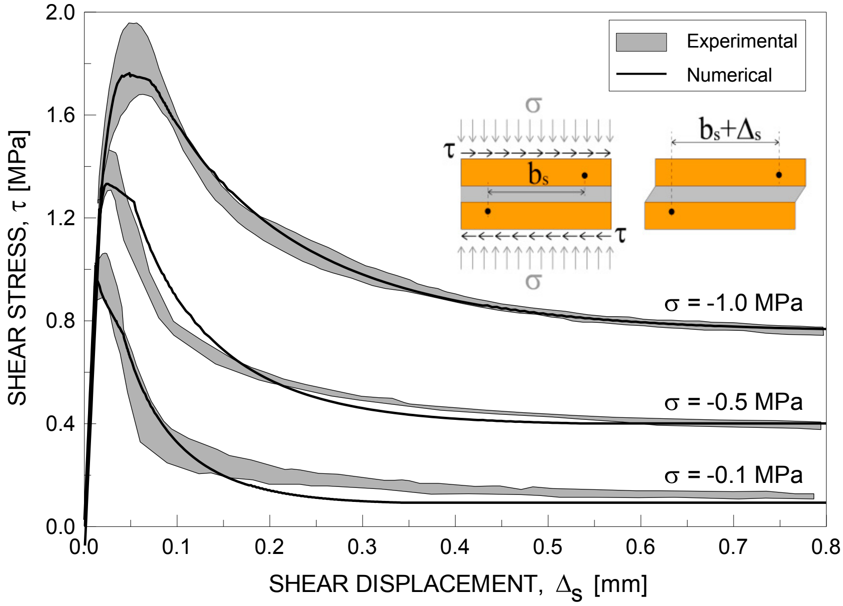


Fig. 3. Comparison between the present numerical simulations and the experiments by Van der Pluijm in terms of shear stress-displacement curves for three different precompression stress levels.

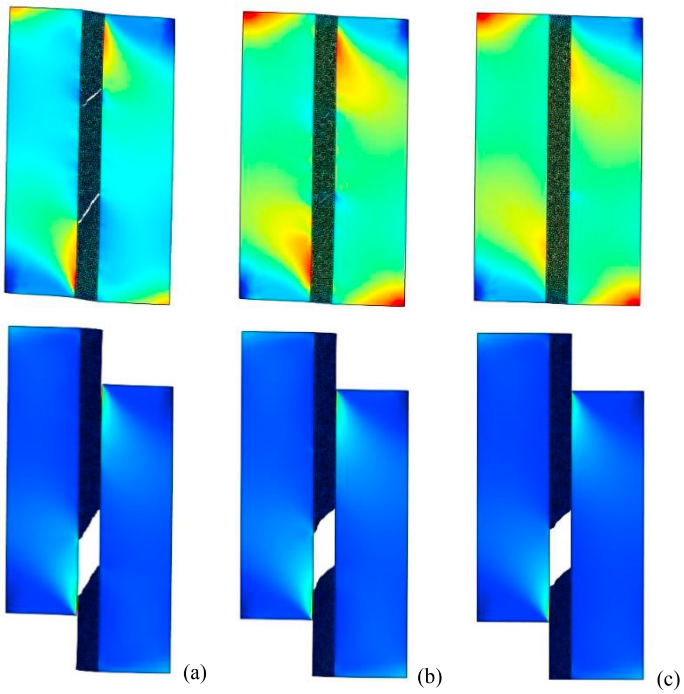


Fig. 4. Deformed configuration and failure pattern at peak load (top) and at complete mortar joint failure (bottom) for three different precompression levels: (a) 1.00 MPa; (b) 0.50 MPa; (c) 0.10 MPa.

3.2. Comparison with a simplified micro-modeling approach

In order to better investigate the peculiar features of the proposed discontinuous micro-modeling approach, suitable comparisons with a simplified one are reported, with reference to the couplet shear test presented in Section 3.1. The comparison simplified micro-model is based on a Single Interface Model (SIM) by which the mortar joint is lumped into a brick/brick interface equipped with the same inelastic properties as the brick/mortar interfaces of the detailed micro-model. Instead, the initial stiffness parameters of this interface are chosen to take into account the elastic properties of both brick and mortar phases, according to the relations adopted in Lourenço (1996):

$$K_n^0 = \frac{E_b E_m}{H_m\left(E_b - E_m\right)}, \qquad K_s^0 = \frac{G_b G_m}{H_m\left(G_b - G_m\right)} \tag{6}$$

where E_b, E_m are the Young's moduli, G_b, G_m are the shear moduli for brick and mortar, respectively, and H_m is the mortar joint thickness.

The shear stress-displacement diagram depicted in Fig. 5 clearly shows that both models are able to predict in a reliable manner the peak and post-peak response of the masonry specimen, being the two related curves for each confinement pressure almost superposed in a large range of shear displacements. However, the slightly different peak stresses predicted by the two models suggest that the proposed detailed micro-model possesses a greater capability to capture the usually experienced scatter in the peak strength, which may be numerically reproduced by suitably varying the mortar inelastic properties within a well-defined physical range.

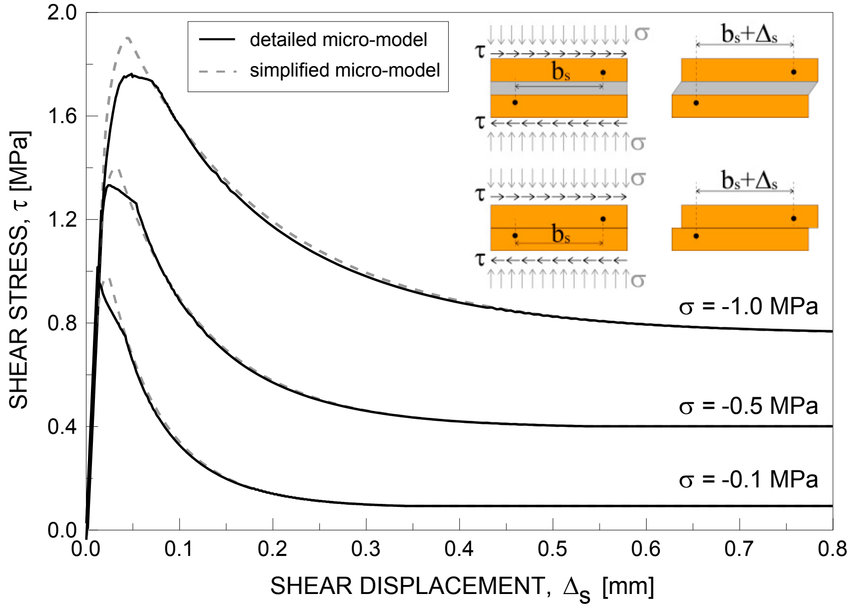


Fig. 5. Comparison between the present detailed and a simplified micro-model in terms of stress-displacement response for the couplet shear test.

3.3. Investigation of mesh dependency issues

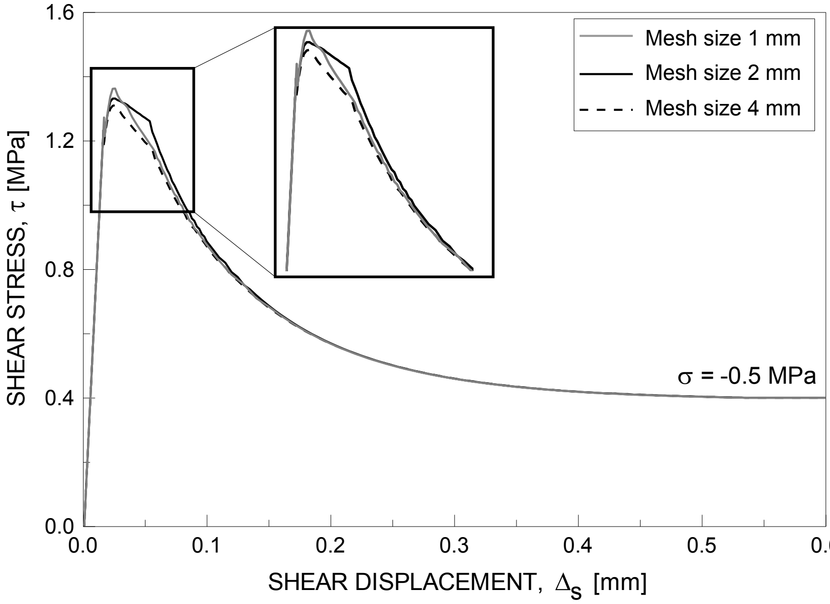
Finally, an investigation of mesh dependency is provided, since it represents an intrinsic feature of the proposed detailed micro-modeling approach for masonry structures, relying on the Diffuse Interface Model (DIM). To this end, three different meshes have been considered for the same numerical test (referring to the intermediate confinement level, i.e. $\sigma = -0.5$ MPa), by varying the maximum interface element length within the mortar joint from 1 to 4 mm.

These values have been chosen by halving and doubling a reference mesh size, i.e. 2 mm, which has been already considered for deriving the numerical results reported in Section 3.1.

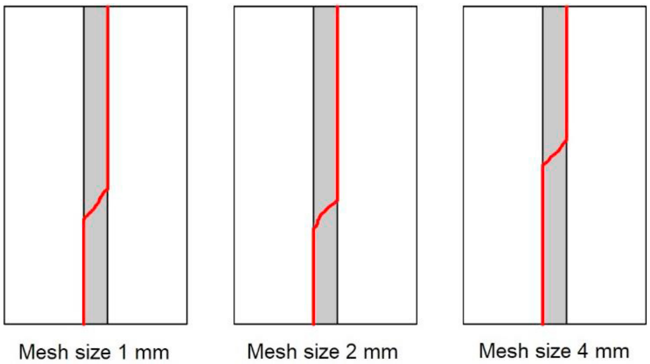
The related numerical results in terms of shear stress-sliding curves are shown in Fig. 6a. It can be noted that all the curves are almost superposed to each other, thus confirming that the numerically predicted structural response by the present detailed micro-model is almost insensitive to the mesh size. Moreover, a slight deviation is reported for the peak strength (see the zoomed-in detail of Fig. 6a), indicating a greater mesh sensitivity in the competition between brick/mortar decohesion and mortar damage initiation, also confirmed by the different position of the localized damage within the mortar layer (see Fig. 6b).

Ultimately, the lack of convergence for the numerically predicted crack pattern is essentially due to the tortuosity induced by the irregularly distributed cohesive interface elements within the mortar layer. As the mesh is refined, the observed crack propagation path inside the mortar becomes more jagged, being forced to pass through a greater number of randomly placed mesh elements.

Nevertheless, the relative errors with respect to the reference mesh size are equal to 1.53% and 2.35% for mesh sizes of 1 and 4 mm, respectively, and therefore fully acceptable from an engineering point of view. Moreover, the above result is particularly appealing, since it suggests the possibility to perform future numerical simulations with coarser meshes, associated with considerably smaller computational costs.



(a)



(b)

Fig. 6. Global structural response predicted by the detailed micro-model for different mesh sizes within the mortar joint (a) shear stress-displacement curve; (b) localized failure pattern.

4. Final remarks

In this work, a novel detailed micro-model for the failure analysis of masonry structures is proposed, based on a diffuse cohesive interface fracture approach. This model possesses some advantages over most of the existing detailed micro-modeling approaches (usually based on smeared crack or continuous damage models), since it preserves the discrete nature of cracking phenomena within mortar joints. Moreover, the proposed model is able to capture the various competing failure mechanisms inside the mortar joint (mainly brick/mortar decohesion and shear cracking across the mortar layer), thus resulting superior also to common simplified micro-models, in which the mortar joint failure appears as a brick/brick mixed-mode debonding, i.e. a single discrete crack, at the mesoscopic scale (intended as an intermediate scale between the scale of micro-constituents and the scale of the entire structure).

By virtue of its peculiar feature, the present discontinuous detailed micro-model could be suitable for simulating complex damage phenomena in brickworks dominated by a strong interaction between brick/mortar decohesion and mortar cracking, e.g. in masonries with very thick joints and/or joints made of fiber-reinforced mortar, characterized by bridging-induced toughening mechanisms (see, for instance, Greco et al. (2017), Benaimeche et al. (2018)).

The proposed model adopts a novel cohesive/frictional behavior for both brick/mortar and mortar/mortar interfaces, which is an enhanced version of that encountered in De Maio et al. (2019b). A Coulomb-type friction is incorporated into the constitutive response of the cohesive interfaces, according to a total-displacement approach, accounting for variable pressure-dependent friction forces acting in parallel with cohesive forces. Such an enhancement has been required to properly predict the load-carrying capacity of masonry structures under combined compression/shear stress states, thus correcting the global dissipated energy value with the additional frictional contribution.

Subsequently, the proposed micro-model has been validated, by presenting some numerical results obtained with reference to different simulated failure tests on a small-scale masonry sample. These are three direct shear tests on a brick couplet subjected to different levels of precompression stress, chosen to assess the reliability and the numerical accuracy of the adopted frictional/cohesive model. Suitable comparisons with the available experimental outcomes have confirmed the strong predictive capabilities of the present micro-model for damaging masonries, especially in terms of global structural response at both peak and post-peak regimes.

Furthermore, with reference to the same simulated test, suitable comparisons with a simplified micro-modeling approach (based on a single interface placed between the two bricks) have demonstrated that the present discontinuous detailed micro-model possess a greater ability to capture the commonly measured dispersion in the peak strength, by only varying the inelastic properties of the mortar/mortar interfaces.

Finally, the attention has been focused on the investigation of mesh dependency issues intrinsically related to the adopted diffuse interface approach. The numerical results have shown that, although the well-known lack of crack path convergence is experienced, almost mesh-independent global structural responses are obtained, thus confirming the reliability of the proposed nonlinear microscopic model for masonry.

As future perspectives of the present work, the following issues could be addressed:

- Development of a moving mesh strategy aimed at avoiding the typical mesh dependency of diffuse cohesive interface methodologies, similar to those already employed by some of the authors in previous works (see, for instance, Feo et al. (2015) and Greco et al. (2018)).
- Identification of the most influential parameters of the presented detailed micro-model of masonry by using a rigorous screening analysis approach, as recently done by one of the authors for the failure analysis of arch bridges (see Lonetti et al. (2019), Lonetti and Pascuzzo (2019), Greco et al. (2019a)).
- Incorporation of the proposed micro-model within a more efficient and versatile multiscale approach of the concurrent type (eventually equipped with adaptive capabilities), similar to those proposed in Greco et al. (2014) and Greco et al. (2019b) for various fiber- and platelet-reinforced composite structures.

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