A new hybrid FEM-DEM approach for more realistic evaluation of masonry structures

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RESUME The present work proposes a new hybrid FEM-DEM strategy, which combines the advantages of the classical finite and discrete element methods. The present paper illustrates the capabilities of the hybrid model in reproducing the behavior of masonry during experimental tests. In this hybrid approach, deformable blocks, managed by a damage model, interact each other through contact joints governed by frictional cohesive behaviors. The main aspect of the numerical results concerns the ability of this approach in providing realistic prediction of failure mechanisms.

Mots-clefs Masonry, Anisotropic damage mechanics, Non-smooth contact dynamics, Cohesive zone model, Hybrid FEM-DEM model

I. INTRODUCTION

The analysis of the dynamic nonlinear behavior of masonry structures is a complex task. Since masonry is a composite material, made of brick units and mortar joints, a large number of parameters (mechanical properties of its components, stereotomy of blocks and joints, etc.) leads to a laborious evaluation of the whole structure. Moreover, the evolution of the Finite Element Method (FEM) and Discrete Element Method (DEM) allows refined analyses. Those numerical implementations are principally dedicated to developing either reliable contact or joints models, considering frictional sliding and mortar joints damage, or incorporating fracture mechanics and plasticity theory notions on the masonry materials.

The research work presented in this paper concerns the proposal of a new hybrid FEM-DEM method, which aims to combine and optimize the advantages of the FEM and DEM techniques. A comparative work is developed with a focus on the advantages and disadvantages of the hybrid model with respect to usual micro- and macro-modeling. It requires the robust calibration of several material parameters defining the linear and nonlinear behavior of the bulk and interface behavior; this is a fundamental step to guarantee the model accuracy and applicability.

II. HYBRID FEM-DEM MODEL

The originality of the present work is to propose a new hybrid FEM-DEM strategy that consider anisotropic damageable deformable blocks which interact to each other through frictional cohesive contacts.

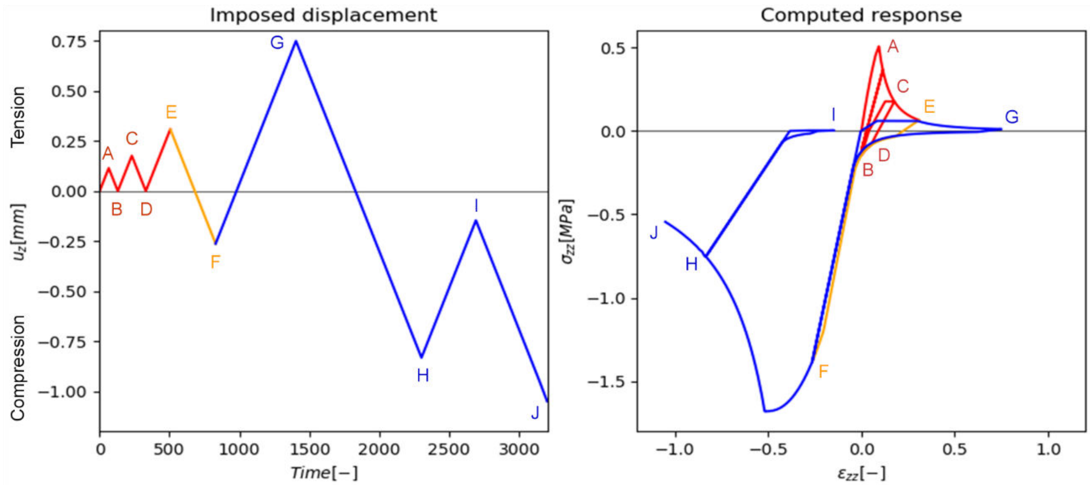

FIGURE 1. **Response of the model for a uniaxial cyclic test on a cubic finite element**

Firstly, the behavior of the blocks are governed by a phenomenological law (Sellier et al., 2022), which arises from (Sellier et al., 2013) and was already applied to homogenized masonry calculus (Parent et al., 2016). The response behavior obtained on a uniaxial cyclic test is reported in Fig. 1. In this model, seven plastic criteria are implemented and they manage the evolution of the relative inelastic strain in the 3 dimensions and, so on, to the induced damages: 1) the tensile cracking is governed by three anisotropic Rankine criteria in principal positive stresses which lead to plastic strains, localized opening of cracking and damages (softening phase after tensile strength reaching, as from point A to E in Fig. 1); 2) the localized re-closure cracking is controlled by three other Rankine criteria in principal negative stresses. It allows to find back the rigidity in compression after a tensile crack opening, as from point E to F in Fig. 1; 3) the shear-compression cracking are driven by the Drucker-Prager criteria (Drucker and Prager, 1952) with non-associated flow. The plastic strain calculated lead to an isotropic induced damage, as from point F to J in Fig. 1. Furthermore, pre peak damages and plastic strains are computed in tension or compression to reproduce the nonlinear behavior of the materials in that phase. Thus, the total stress σ_{ij} depends on the different damage conditions which are integrated in the present model (Eq. 1):

$$\sigma_{ij} = \underbrace{\underbrace{\left(1-D_0^{c,s}\right)}_{Pre\ peak}}_{Drucker\ Prager} \Big[\underbrace{\underbrace{\underbrace{\left(1-D_0^{t}\right)}_{Pre\ peak} \underbrace{\left(1-D^{t}\right)_{kl}}_{Post\ Peak}}_{Rankine} \tilde{\sigma}^{+}_{ijkl}}_{Tensile\ Damages} + \underbrace{\underbrace{\underbrace{\left(1-D^{c,s}\right)_{kl}}_{Post\ Peak}}_{Drucker\ Prager} \underbrace{\left(1-D^{c,t}\right)_{kl}}_{Rods\ Bucling} \underbrace{R_{ijkl}}_{Reclosure} \tilde{\sigma}^{-}_{ijkl}}_{Compressive\ damages} \Big] \quad (1)$$

Consequently, the basic-elasticity parameters in the damage model are the Young modulus, Poisson ratio and density. The mechanical parameters related to the plasticity are the tensile and compressive strength, strains at tension and compression peak, Drucker-Prager confinement coefficient, dilatancy for non-associated Drucker-Prager plastic flow, reclosure stress. In addition, the material parameters for the damage associated to plasticity are the characteristic plastic strain for Drucker-Prager associated damage, fracture energy in tension, and tensile crack reclosure energy. Finally, another main aspect of the proposed model concerns its ability to set the ratio between plasticity and damage pre peak in compression.

Secondly, the behavior of the brick-mortar interface is determined by the contacts which involve frictional and damage response according to the Cohesive Zone Model (CZM) (Venzal et al., 2020), used within the Non-Smooth Contact Dynamics method (NSCD) (Jean, 1999; Moreau, 1988). The law is dedicated to the progressive damage due to quasi-brittle behavior of materials. Thus, under combined traction and shear loadings, a mixed mode response based on pure Mode I and Mode II cohesive behaviors is proposed. Under combined compression and shear loadings, a coupling between Mode II cohesive behavior and frictional behavior based on the damage level is considered. The DEM framework permits large strains, rotations, and complete detachments of the blocks (Ferrante et al., 2021), which are neglected with joint FEM models (Pegon and Anthoine, 1994). The combined hybrid FEM-DEM approach allows to deal efficiently with the numerical assessment of complex masonry structures. The numerical implementation has been made in the open-source LMGC90 code (Dubois et al., 2018).

III. APPLICATIONS

To illustrate the efficiency of our modeling strategy we present some results of our answer to the blind prediction competition of a cross vault (SERA project, 2021).

Experimental set-up: To calibrate the models several experimental tests results were provided: 1) for the hardened mortar, tripoint bending test (EN 1015-11:2019) and compressive test (EN 1015-11:2019); 2) for the prismatic brick and masonry triplet, the compressive test (EN 772-1) and triplet test (EN 1052-3:2002); 3) the parameters of a masonry wallet can be deduced from the axial compression test (EN 1052-1:1998) and diagonal compression test (ASTM E519/E519M).

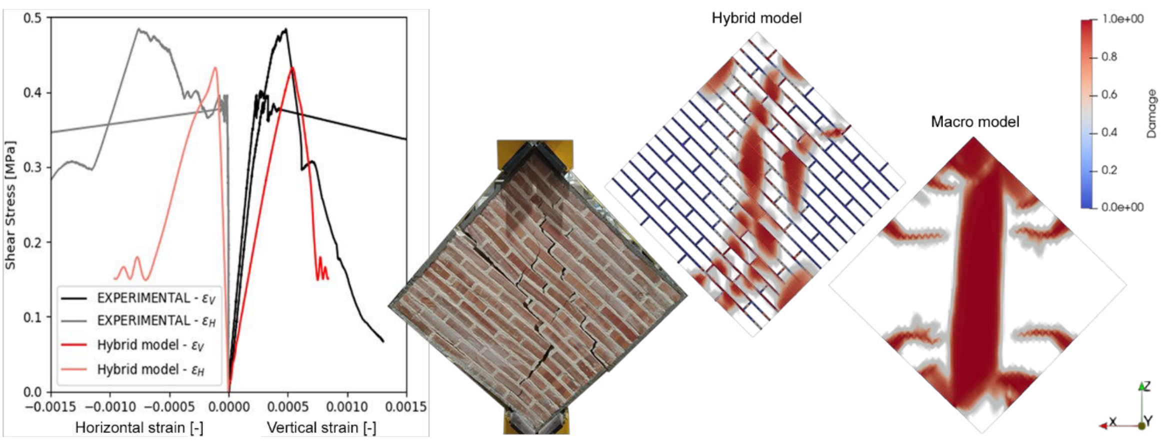

FIGURE 2. Comparison of numerical and experimental results: shear stress-strain curves and cracking pattern of the diagonal compression test

Results and critical discussion: For brevity of the paper, we focus on the diagonal compression test. The three different numerical modeling consider the real boundary and loading conditions. The numerical results for the hybrid and macro models are analyzed and compared by the experimental findings, as reported in Fig.2. The outcomes in Fig. 2 remark the capability of the hybrid method to provide a realistic prediction of failure mechanisms, pointing out the failures of bricks and mortar joints. The damage of the macro model in Fig. 2 shows a vertical failure that does not appropriately consider the stereotomy of the masonry panel. Thus, the main difference with respect to the results of the macro and micro models (not presented here) concerns the ability of the discrete approach in reproducing the real cracking pattern following the real stereotomy of the masonry and considering large deformations which could be an entry data of a real structure diagnosis.

IV. CONCLUSIONS

The new hybrid FEM-DEM method allows understanding the behavior of masonry and the numerical results provide a realistic prediction of failure mechanisms. The global dynamics of a cross vault in a blind prediction competition (SERA project, 2021) and the thermal damage using are crucial targets for future development works.

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