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XIX ANIDIS Conference, Seismic Engineering in Italy

# Seismic assessment of masonry vaults by means of an advanced hybrid FEM-DEM modeling strategy

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## Abstract

The current work presents a hybrid Finite Element Method and Discrete Element Method (FEM-DEM) strategy, which combines classical finite and discrete element methods in a common tool, and illustrates its capabilities in reproducing the real behavior of masonry during experimental quasi-static tests and seismic actions. The numerical implementation is available in the open-source LMGC90 code. In this hybrid approach, anisotropic damageable deformable blocks interact each other through contact joints governed by frictional cohesive behaviors. The DEM framework permits large displacements, rotations, and complete detachments of the blocks, which is usually neglected with FEM models. A comparative work is developed with a focus on the advantages and disadvantages of the hybrid model with respect to FEM micro- and macro-modeling (aka block based description or continuous homogeneous description), and DEM using rigid blocks. In this regard, validations through experimental benchmarks are achieved and the results of a diagonal compression test are discussed. Then, the main application performed in this work concerns the seismic assessment of a masonry cross vault. The key aspect of the numerical results concerns the ability of this approach in providing realistic prediction of failure mechanisms, which are relevant for retrofitting works, according to the real cracking pattern, considering the real stereotomy of the masonry and large deformations.

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*Keywords:* Masonry; Anisotropic damage mechanics; Non-smooth contact dynamics; Cohesive zone model; Hybrid FEM-DEM model.

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## 1. Introduction

The analysis of the dynamic nonlinear behavior of masonry vaults and buildings is a complex task. The importance of intensifying the knowledge of the behavior of these structures is essential for the preservation of the cultural heritage, considering the massive presence of peculiar existing buildings in the European area with high seismic hazard, and for the evaluation of new structures against strong actions. In this context, masonry vaults represent relevant elements in the ancient buildings that have been investigated in literature using several approaches (D'Ayala and Tomasoni, 2011; Gaetani et al., 2016) and experimental tests (Rossi et al., 2016).

In this framework, the relevance of the present work is to propose a new hybrid FEM-DEM strategy, which combines classical finite and discrete element methods in a common tool. The capabilities of the hybrid model to reproduce the real complex behavior of masonry during experimental tests and seismic actions are illustrated in this paper. The numerical implementation is available in the open-source LMGC90 code (Dubois et al., 2018). In this hybrid approach, anisotropic damageable deformable blocks interact each other through contact joints governed by frictional cohesive behaviors. The Discrete Element Method (DEM) framework permits large displacements, rotations, and complete detachments of the blocks (Ferrante et al., 2021a, 2021b), which is usually neglected in Finite Element Method (FEM) models (Pegon and Anthoine, 1994). The combined hybrid FEM-DEM approach allows dealing efficiently with the numerical assessment of masonry vaults and complex structures. Thus, a comparative work is performed with a focus on the advantages and disadvantages of the hybrid model with respect to usual micro- and macro-modeling (aka block based model or continuous homogeneous model). The calibration process of the mechanical material characteristics was based on the experimental tests on masonry specimens (triplet test, axial, and diagonal compression tests), which were numerically simulated with each modeling technique. Therefore, the validations through experimental benchmarks are achieved and, for the brevity of the paper, only the results of the diagonal compression test are here discussed. Finally, the main application performed comparing the new proposed model and the existing approaches concerns the seismic assessment of a masonry cross vault.

## 2. Hybrid FEM-DEM model

Hybrid FEM-DEM model is a sophisticated technique, which aims to accurately describe masonry behavior. Such advanced model reproduces the basic and relevant failure mechanisms of masonry (Lourenço and Rots, 1997), taking into account damages in the joints and in the bricks, i.e., joint tensile and sliding cracking, unit direct and diagonal tensile cracking, and crushing. Some damage effects are governed by a bulk model (endo3D – (Sellier et al., 2022)) and others by a cohesive zone model (Venzal et al., 2020).

### 2.1. Endo3D model for the bulk

Firstly, the behavior of the bulk (blocks or joints) may be governed by a phenomenological law (Sellier et al., 2022), which arises from (Sellier et al., 2013). In this model, seven plastic criteria are implemented and they manage the evolution of the relative inelastic strain in the three 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); 2) the localized reclosure 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 reclosure; 3) the shear-compression cracking is driven by the Drucker-Prager criterion (Drucker and Prager, 1952) with non-associated plastic flow. The plastic strain calculated lead to an isotropic induced damage. Furthermore, pre-peak damages and plastic strains may be introduced in tension or compression to mimic the actual nonlinear behavior of the materials. Thus, the total stress  $\sigma_{ij}$  depends on different damage variables which are managed by the present model. The Hillerborg energy based regularization technique (Hillerborg et al., 1976; Pijaudier-Cabot and Bazant, 1987) is used with the damage model to guarantee its localization. Finally, another main aspect of the proposed model concerns its ability to set the ratio between plasticity and pre-peak damage in compression.

## 2.2. Cohesive zone model for the interfaces

Mortar joints and block/mortar interfaces are lumped into contact interaction. The behavior of the brick-mortar interface is determined by interactions which involve frictional contact and damage response (CZM) according to a decreasing exponential evolution dedicated to the progressive damage due to quasi-brittle behavior of materials (Venzal et al., 2020). The Non-Smooth Contact Dynamics method (NSCD) (Jean, 1999; Moreau, 1988) helps to manage non regularized frictional contacts. In this framework, the cohesive stresses decrease (after an elastic response) according to the rising of a damage variable that reflects the level of the mechanical degradation of the interface due to the development of crack surface. 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. Elastic springs may be added to the cohesive law to reproduce the mortar joints behavior.

## 3. Calibration process and experimental validation

For the calibration and validation of the proposed phenomenological approach, different types of real behavior observed in experimental tests have been reproduced: compression and traction on brick or joints, axial compression on wall, confined shear on triplet and diagonal compression on wall. These tests are related to the blind prediction competition (SERA project, 2021) concerning the shaking table tests of a full-scale masonry cross vault. Such tests illustrate the efficiency of the proposed modeling strategy to predict the behavior of masonry structures.

### 3.1. Overview on the calibration process

In brief, the experimental surveys concern the masonry material and its components (clay brick and mortar) through appropriate tests according to international standards. For the hardened mortar, three-point bending test and compressive test were performed. For the prismatic brick and masonry triplet, the compressive test and triplet test were conducted, respectively. The parameters obtained from these procedures are required to define the behavior of mortar and bricks in the damage model. Moreover, the homogenized parameters of a masonry wallet can be deduced from the axial compression test and diagonal compression test.

### 3.2. Diagonal compression results

Thus, in order to achieve the main goal of the blind competition and to obtain a good prediction of the seismic response of the cross vault, the experimental fitting was achieved from all the tests available. The results of the diagonal compression test is here summarized.

The hybrid model is compared with the meso-, macro- and detailed micro-modeling approaches in the present work. A methodology for the calibration of the mechanical parameters in the damage model for each type of modeling is demanded due to the lack of information in international/national standards and literature and the heterogeneity of the existing masonry. Indeed, the hybrid model requires the bricks, mortar, and masonry parameters for a detailed definition of the extended blocks and contact joints. The other approaches respectively involve the mortar and mortar/brick interface information for the meso-, the homogenized masonry characteristics for the macro-, and the brick and mortar materials for the detailed micro-modeling.

For brevity of the paper, the results of the diagonal compression test using the hybrid FEM-DEM and micro approaches are reported in Fig. 1. The two different numerical strategies consider the real boundary and loading conditions. The numerical results for the hybrid model and the micro-modeling are analyzed and compared by the experimental findings, as reported in Fig. 1.

The outcomes in Fig. 1 highlight the capability of the hybrid FEM-DEM method to provide a realistic prediction of failure mechanisms, pointing out the failures of bricks and mortar joints. The detailed micro-modeling exhibits close to reality response. The main difference with respect to the results of the micro-model concerns the ability of the hybrid approach in reproducing the real cracking pattern following the real stereotomy of the masonry. Considering the Shear stress-Strain curves in Fig. 1, the hybrid model shows two peaks that correspond to failures in

joints and bricks of the wall which are similarly exhibited in the experimental curves for one wallet. Nevertheless, the different behavior of the two experimental walls (black and grey lines) do not allow to conclude definitely on the faithfulness of the model on that subject.

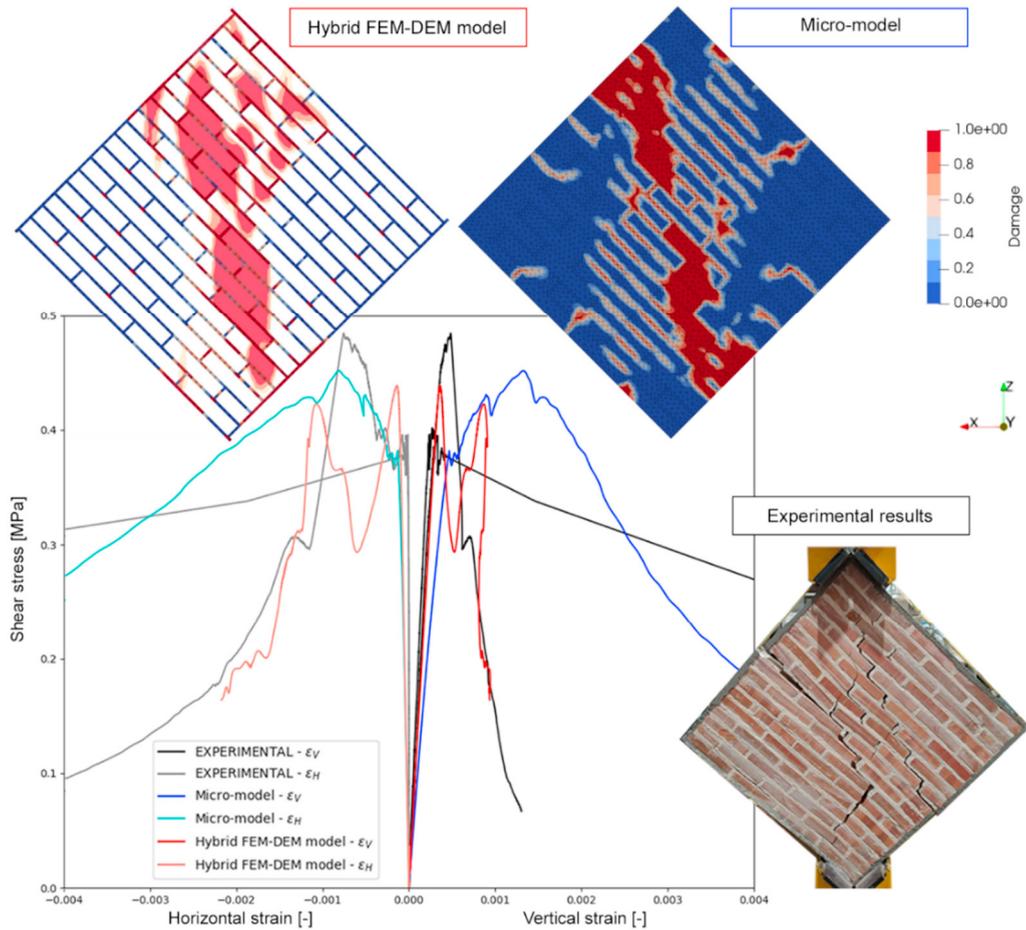


Fig. 1. Comparison of numerical and experimental results: shear stress-strain curves and cracking pattern of the diagonal compression test.

## 4. Cross vault seismic assessment

### 4.1. Experimental setup and numerical model

The geometry of the cross vault is built in a 3D model according to the drawings and details of the mock-up provided on the blind prediction website (SERA project, 2021). The geometry of the numerical discrete and continuum models are plotted in Fig. 2 a) and b), respectively. The stereotomy of the discrete model consists of an arrangement of discrete extended blocks and zero-thickness joints managed by punctual contacts, which are reported in detail in Fig. 2 a) and c), respectively. The arrangement corresponds to the so called orthogonal weaving, which directly transmits the thrusts to the supports and thus concentrates the loads into the four corners of the vault. Thus, the extended blocks consider the brick units ( $0.045 \times 0.12 \times 0.23 \text{ m}^3$ ) and the thickness of the mortar (0.01 m) and have dimensions of  $0.046 \times 0.12 \times 0.24 \text{ m}^3$ , which allow to keep the entire geometry unchanged with respect to the real one. Then, a similar 3D model is built as a continuum of solid finite elements.

The infill, supports, masses and piers are modeled using simplified geometries of equivalent global shapes, thus not considering the arrangement of the bricks for the masonry parts or other details (see Fig. 2 d)). The steel profiles,

frame, connectors, wheels, and bars are not modeled using 3D elements. All these elements are considered in the numerical model through equivalent relation and boundary conditions in order to simulate similar behaviors. An exception arises with respect to the discrete model for the steel bars, which are modeled in this approach using 3D equivalent elements, as shown in Fig. 2 b).

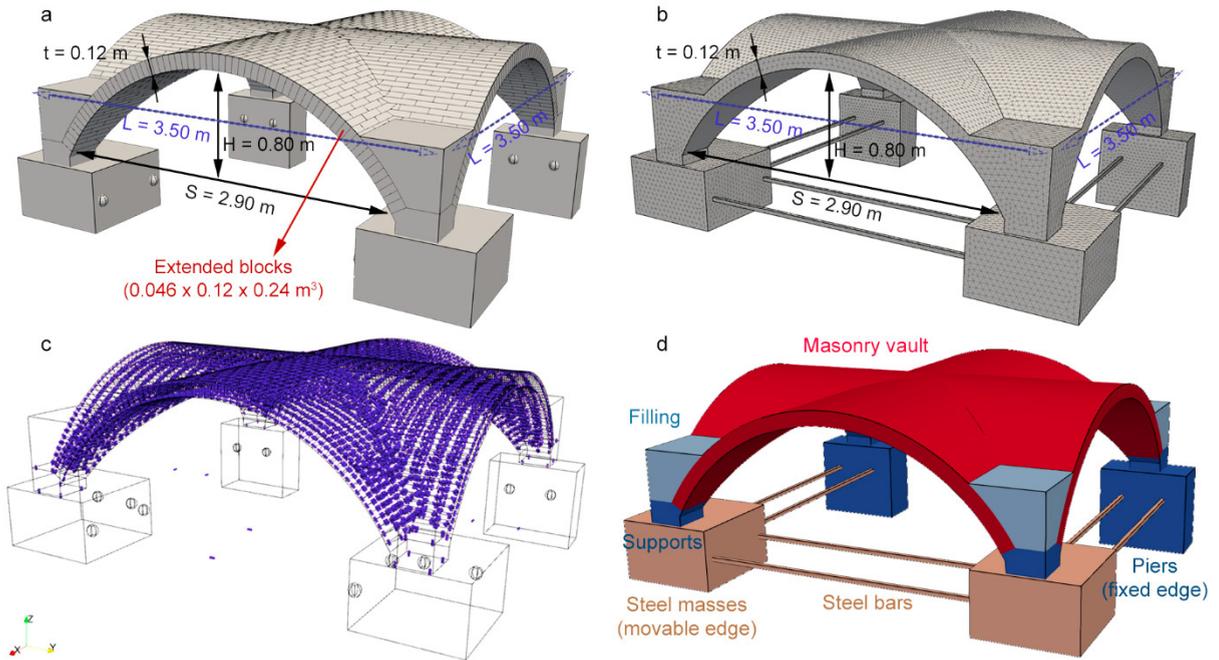


Fig. 2. Geometry of the numerical a) discrete and b) continuum models. Detailed views of c) the contacts in the discrete approach and d) a scheme of the materials adopted in both modeling strategies.

Moreover, 1242 blocks and 14532 punctual contacts compose the entire discrete model of the mock-up. Its dimensions in plan are equal to  $3.55 \times 4.04 \text{ m}^2$ . The masonry cross vault is made of 1230 blocks. The size of the vault model is about  $3.5 \times 3.5 \text{ m}^2$  in plan and the thickness is equal to a constant value of 0.12 m. The remaining 12 blocks recreate respectively: the filling (4), the supports (4), the piers (2), the masses (2).

The finite element model is composed of tetrahedral meshes of an average size equal to 0.05 m. The detailed numerical model involves a number of nodes equal to 35454 and 143390 degrees of freedom.

The boundary conditions reproduce the experimental set-up. The masses are free to slide in two directions on the plan  $xy$  by means of wheels and the piers are well connected to the shake table. Therefore, the masses and piers are fixed in  $z$ -direction and  $x$ - and  $z$ -directions, respectively. The supports are perfectly connected with the piers, masses, and filling. The steel bars are considered in order to link the masses to each other and to the piers and avoid rotations of the supports.

A scheme of the materials adopted in both modeling strategies is reported in Fig. 2 d). The discrete model of the masonry vault is used for the analyses performed in the classical DEM framework, applying rigid blocks, and in the hybrid approach, assigning the masonry material parameters for the damageable deformable blocks of the vault. Thus, the blocks of the vault are defined by a density equal to  $2255.2 \text{ kg/m}^3$ , which is the unique bulk parameter for the rigid model. In addition, for the damageable model, the masonry material of the vault is characterized by a Young modulus equal to 2667.6 MPa, Poisson ratio of 0.1, tensile and compression strength of 0.31 MPa and 9.1 MPa, fracture energy in tension of  $3.6 \text{ J/m}^2$ . Moreover, in both strategies the contacts are governed by the cohesive law. The mechanical parameters for contacts obtained from the experimental tests and their adopted values are the friction coefficient equal to 0.785, the initial normal and shear stiffness  $85\text{e}9 \text{ N/m}^3$  and  $39\text{e}9 \text{ N/m}^3$ . Similarly, the

macro-model of the vault is defined by the masonry material parameters of endo3D model. The other components of the mock-up are modeled as perfectly rigid and elastic in the discrete and continuum approaches, respectively.

The 3D meshes are generated by the open-source GMSH tool and the numerical models are built using the open-source LMGC90 code for both modeling strategies.

#### 4.2. Results

Nonlinear dynamic analyses are performed in the NSCD framework in order to evaluate the seismic response of the vault. The method uses an implicit time integrator and the Non Linear Gauss Seidel contact solver. The seismic input adopted in the shaking table test of the full-scale masonry cross vault (SERA project, 2021) is applied at the piers of the models in the y-direction. The total duration of the dynamic action is equal to 25 s and the peak ground velocity (PGV) is  $-0.182$  m/s corresponding to the record of the L'Aquila earthquake of 6<sup>th</sup> April 2009 scaled with 75% of amplitude.

Unfortunately, the simulations using the hybrid model are still in progress and the results are not reported in the present paper. However, the cohesive zone model for the interfaces and the endo3D model for the bulk are applied to the meso (with rigid blocks) and macro modeling, respectively. Accordingly, an overview on the proposed models is achieved and the results are analyzed in this section. These interesting outcomes propose a perspective view on the next hybrid FEM-DEM application. A brief comparison of the numerical damages of the meso- and macro-model at the end of the dynamic action applied from the top view are figured out in Fig. 3. The results highlight a good match of the failure mechanisms for the vault in both models. The approaches adopted well reproduce the shear failure of the vault, pointing out a high damage presence along the diagonal sections of the vault.

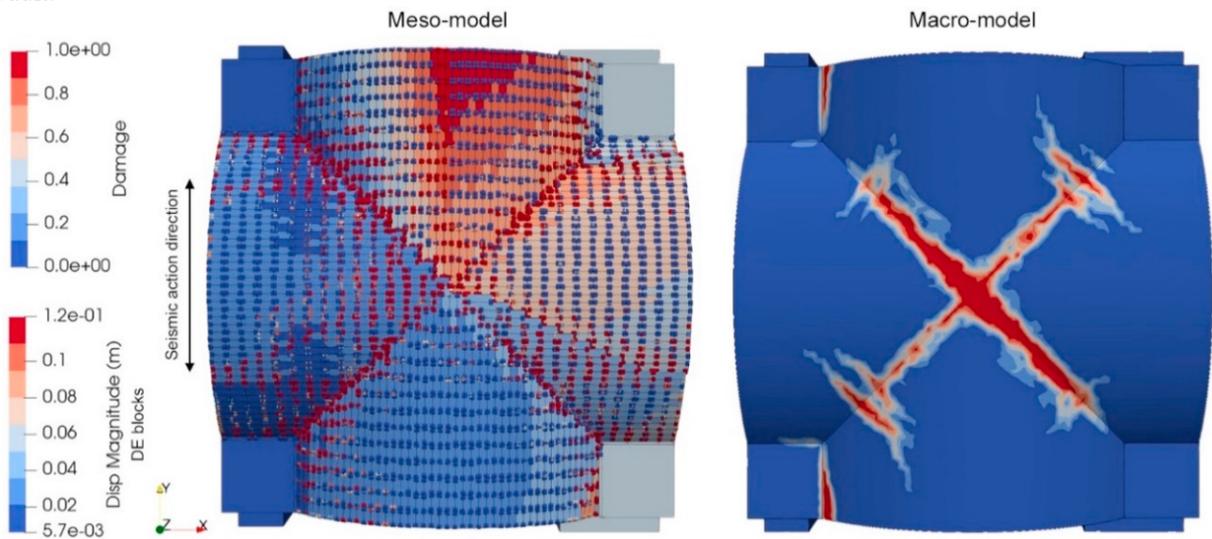


Fig. 3. Comparison of the cross vault numerical damages of the meso- and macro-model at the end of the seismic input applied in the nonlinear dynamic analyses performed (top view).

As the seismic assessment of the masonry vault here investigated belongs to a blind prediction competition in progress, a validation of the proposed model by comparing the experimental results is not available in the present paper. However, the numerical results obtained from the dynamic analyses are representative of the seismic response of the vault expected in the shake table test and they are comparable with the typical behavior investigated in the literature (Bianchini et al., 2019; Gaetani et al., 2016).

The North views in Fig. 4 show the cross vault numerical hinges of the meso- and macro-model. The meso-model allows an easier check of the activated hinges and their evolution over time, which manage the collapse of the structure. The macro-model approximately mimics the location of the hinges observed in the meso-model.

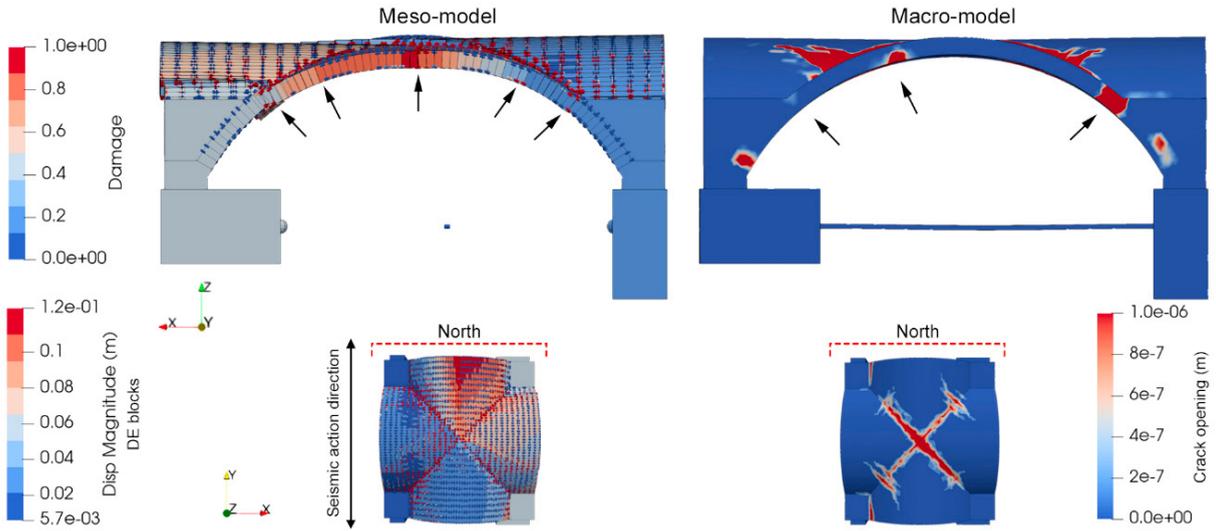


Fig. 4. Comparison of the cross vault numerical damages of the meso- and macro-model from the North view.

Furthermore, the reclosure of the crack openings for the macro approach managed by the endo3D model is plotted in Fig. 5. It is seen that at 3.4 s of the seismic input applied (Fig. 5 a) the diagonal cracks reach the maximum opening. At 3.7 s (Fig. 5 b) and 3.8 s (Fig. 5 c) the cracks are reclosing and then opening again in the other diagonal section. The behaviors in Fig. 5 a, c) correspond to the PGV in positive and then negative directions.

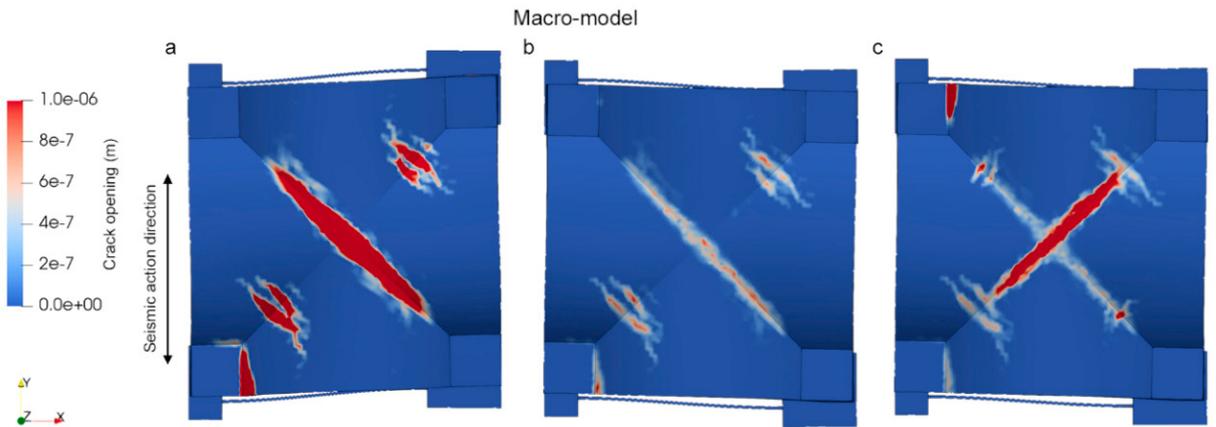


Fig. 5. Reclosure of the crack opening for the macro-model at a) 3.4 s, b) 3.7 s and c) 3.8 s of the seismic input applied in the nonlinear dynamic analyses performed (top view).

### 5. Conclusions

The originality of the present work is to propose a new hybrid FEM-DEM method, which aims to combine and optimize the advantages of the FEM and DEM techniques. Its validation through experimental benchmarks are achieved and the results of a diagonal compression test are examined. The main aspect of the new hybrid FEM-DEM approach highlighted from the numerical results concerns the ability of this strategy in providing realistic prediction of masonry failure mechanisms according to the real cracking pattern. Thus, a detailed assessment of masonry is feasible representing the damages that follow the masonry stereotomy and considering large deformations, which are relevant aspects for retrofitting works.

The global dynamics of a cross vault is still underwork. However, encouraging findings on the groin vault are achieved from the cohesive zone model in DEM and endo3D model in FEM simulations. Both advanced models proved to be efficient for the seismic assessment of vaults and in reproducing failure mechanisms of this structural elements.

The optimization of the approach, the thermal damage using and applications on the damaged masonry vaults of the Notre Dame de Paris cathedral in the DEMMEFI project are crucial targets for future development works.

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