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Exploring the Impact of Spatial Variation of Material Properties on Seismic Behavior of URM Walls with Openings via Computational Modeling

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ABSTRACT: The mechanical properties of unreinforced masonry (URM) wall constituents (i.e., brick, mortar, and unit-mortar interface) vary considerably due to their inherent nature and manufacturing process. In this context, the present study explores the impact of material uncertainty related to the tensile bond strength, friction angle, and masonry compressive strength by considering their spatial variation. A recently proposed computational modeling approach is used throughout this study, called probabilistic discrete rigid block analysis (D-RBA). The masonry texture is represented using a system of rigid blocks interacting along their boundaries. In the proposed modeling strategy, unit-mortar interfaces are explicitly simulated, and failure mechanisms (e.g., joint openings, sliding, and crushing) are considered at the contact points defined among adjacent blocks. The adopted computational framework predicts and characterizes variations in the ultimate load and drift capacity of URM walls with openings and the associated failure mechanisms. The results indicate the advantageous feature of probabilistic D-RBA when the spatial variation of mechanical properties of the URM system is considered. D-RBA provides a more realistic representation of the existing condition of the URM walls and offers less uncertainty in the numerical predictions compared to non-spatial probabilistic analysis. The implementation of D-RBA can thus enhance the decision-making process in seismic assessment and retrofitting old masonry buildings.

1. INTRODUCTION

Providing accurate predictions regarding the seismic behavior of unreinforced masonry (URM) buildings is a challenging task and an active research topic. Significant variations of the material properties, lack of knowledge about the existing boundary conditions, uneven deterioration, and aging process of the masonry are just some of the open questions and uncertainties, among many other factors. Furthermore, the morphological features (i.e., construction technique) and the composite characteristics of masonry comprising the unit, mortar, and unit-mortar interfaces play an important role in the macro-behavior of the URM structure in terms of lateral load-carrying capacity and displacement capacity. Exploring the influence of these parameters via experiments requires a significant amount of material and economic resources, which may not be feasible for large-scale testing programs. Therefore, once validated, computational simulations can be a reliable source to further investigate the effect of material uncertainties on major structural engineering parameters such as lateral stiffness, ultimate load, and deformation capacity.

Computational modeling of masonry structures has received strong interest in the last decades. By and large, Finite Element Analysis (FEA) has been overwhelmingly adopted to explore the seismic response of URM load-bearing walls and systems assuming the masonry composite as a homogenous and isotropic or orthotropic continuous medium, also referred to as macro-modeling (Aldemir et al. 2013; Funari et al. 2021; Lourenço et al. 1998; Saloustros et al. 2018)). Alternatively, a discontinuum-based approach can be used to better represent the discrete nature of masonry following the discrete element method (DEM) or discontinuous FEA (Roca et al. 2010). Several applications of DEM and FEA on masonry structures were carried out (Hamp et al. 2022; Kesavan and Menon 2022; Kumar et al. 2022; Lemos and Campos Costa 2017; Mendes et al. 2018). Most discontinuum-based simulations follow a simplified micro-modeling approach, where the masonry units and unit-mortar interfaces are explicitly represented in the numerical model. This methodology offers a realistic representation of the existing geometrical properties of masonry (e.g., bond patterns, existing cracks, geometrical imperfections) together with the joints. Typically, mortar and unit-mortar interfaces corresponding to weak planes where the joint openings and sliding are expected to occur. Figure 1 illustrates a masonry wall texture and its idealization within the simplified micro-modeling framework.

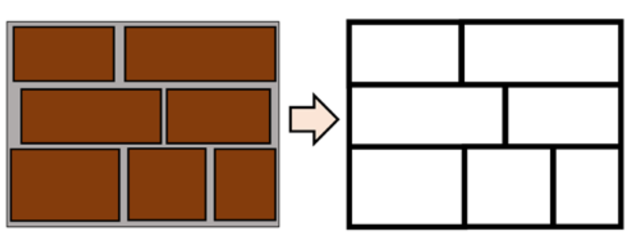


Figure 1: From a random masonry texture (left) to its representation (right) based on a simplified micro-modeling approach.

Throughout this research, the discrete element method, developed by Cundall (1971), is utilized to assess the seismic behavior of URM walls with an opening, which is denoted as Discrete Rigid Block Analysis (D-RBA). The proposed modeling approach has been applied to similar URM structures earlier, where promising results are obtained and presented (Ehresman et al. 2021; Pulatsu et al. 2022). The adopted modeling approach utilizes rigid blocks to represent each masonry unit that can mechanically interact with each other along their boundaries. As shown in Figure 2, the analyzed pier-spandrel structure is represented via a system of rigid blocks where each masonry unit is represented via two rigid blocks with a potential cracking/sliding surface at the mid-length. The action/reaction forces that develop between adjacent blocks are computed following the point contact hypothesis. To that aim, three orthogonal springs at the sub-contacts are defined along the contact surface, as shown in Figure 2.

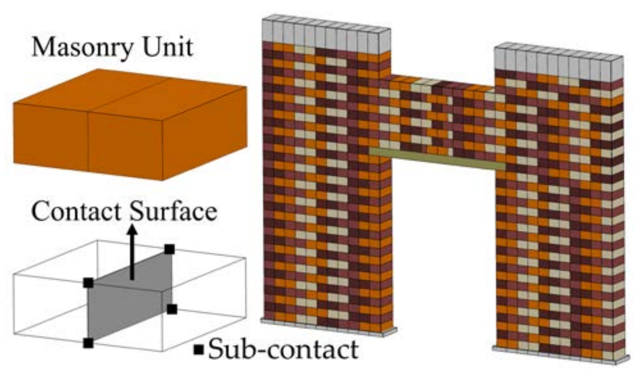


Figure 2:Discontinuum model of the analyzed pier-spandrel structure.

Once the adopted modeling strategy is validated, a probabilistic assessment of the reference pier-spandrel structure is performed, considering the spatial variation of the material properties. In the next section, the computational background of the D-RBA and the proposed probabilistic analysis framework are discussed.

2. PROBABILISTIC ASSESSMENT VIA D-RBA AND BENCHMARK STUDY

In this section, the probabilistic discontinuum-based analysis and the utilized benchmark study are presented.

2.1. D-RBA and Spatial Probabilistic Assessment

The DEM relies on the integration of equations of motion using the central difference method to predict new translational ($\dot{u}^{t+}$) and rotational (ω^{t+}) velocities for each rigid block, which has six degrees of freedom (three translations and three rotations). Note that quasi-static solutions are obtained using Cundall's local damping formulation (Cundall and Detournay 2017), as shown into Eqs. (1) and (2):

$$\dot{u}_i^{t+} = \dot{u}_i^{t-} + \frac{\Delta t}{m}\left(\Sigma F_i^t - \lambda |F_i^t| sgn(\dot{u}^{t-})\right) \quad (1)$$

$$\omega_i^{t+} = \omega_i^{t-} + \frac{\Delta t}{I}\left(\Sigma M_i^t - \lambda |M_i^t| sgn(\omega^{t-})\right) \quad (2)$$

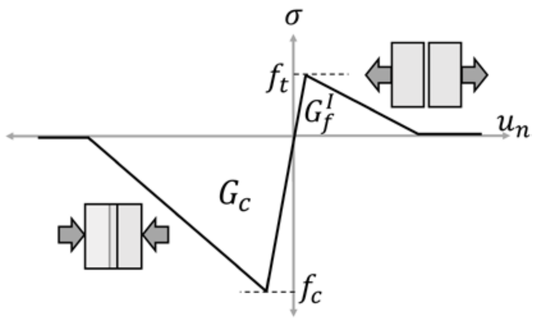
where F, M, I, m, and λ are the force vector, including the sum of contact forces and applied forces, moment vector, consisting of moments developed by contact forces and applied forces, mass moments of inertia, block mass, and dimensionless damping constant (default value is 0.8), respectively. The time step is evaluated at mid-intervals (i.e., Δt; $t^+ = t + \Delta t/2$, $t^- = t + \Delta t/2$). After calculating the new velocities, the block positions are updated, and relative contact displacements are obtained for the active contact points. In DEM, the contact forces are computed as a function of relative displacements at the sub-contact points in the normal and shear directions in an incremental fashion (Δu_n, $\Delta u_{s,i}$), which are utilized to predict normal and shear contact forces (F_n, F_s) once multiplied with the associated contact stiffnesses (k_n, k_s), as follows:

$$\Delta F_n = k_n \Delta u_n A_c \quad (3)$$

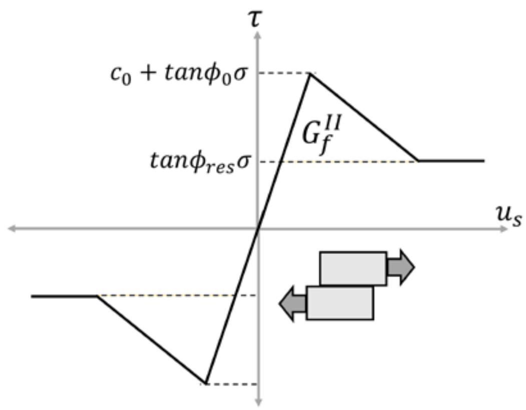
$$\Delta F_{s,i} = k_s \Delta u_{s,i} A_c \quad (4)$$

where A_c denotes the sub-contact area. The elastic force increments are added to the old ones to predict the new sub-contact forces. Finally, they are corrected (if applicable) based on the defined failure criterion and then utilized in Eqs. (1) and (2). This numerical procedure is executed until a quasi-static solution, or pre-defined convergence limit is reached. It is worth noting that nonlinear actions are lumped at the contact planes corresponding to the unit and unit-mortar interfaces. In this study, the cohesive bond breakage is simulated via elasto-softening contact constitutive law implemented in tension, shear, and compression, as shown in Figure 3, using a commercial three-dimensional discrete element code, 3DEC (Itasca Consulting Group Inc. 2013). The implemented fracture energy-based contact models require several nonlinear parameters that can be obtained from material characterization tests (Pulatsu et al. 2019, 2020). The shear behavior is modeled via Coulomb Friction Law, which requires initial cohesion (c_0), residual cohesion (c_{res}), initial friction (ϕ_0), residual friction (ϕ_{res}) and mode-II fracture energy (G_f^{II}), while the tension and compression bilinear behavior is determined by tensile strength (f_t), mode-I fracture energy (G_f^I) and compressive strength of masonry (f_c) together with the associated compressive fracture energy (G_c), respectively (see Figure 3).

As mentioned earlier, the mechanical interaction among adjacent blocks is computed at the contact surfaces, where the linear and nonlinear parameters are defined. To consider the material uncertainty, a variation in the unit and unit-mortar interface properties are determined as random and dependent parameters. Specifically, the compressive strength of masonry (f_c), joint (or bond) tensile strength ($f_{t,j}$), unit tensile strength ($f_{t,u}$) and the interface friction angle (ϕ) are considered random parameters. Experimental data (Augenti and Parisi 2010, 2011; Parisi et al. 2014)) are utilized to define the mean (μ) and coefficient of variation (CoV) of these parameters that are summarized in Table 1, including the dependent variables.



(a)



(b)

Figure 3: Contact constitutive models in (a) normal and (b) shear directions.

Table 1: Statistical parameters related to the random and dependent variable used in D-RBA.

Random Variable	*Probability Distribution*	μ	*CoV*
f_c*(MPa)*	*Normal*	*3.96*	*0.125*
$f_{t,j}$*(MPa)*	*Lognormal*	*0.15*	*0.300*
$f_{t,u}$*(MPa)*	*Lognormal*	*0.23*	*0.220*
ϕ_0*(°)*	*Normal*	*16*	*0.200*
Dependent Variable		*Relationship*	
c		$1.5f_{t,j}$	
G_f^I		$0.029f_{t,j}$	
G_C		$3.2f_m$	

The dependent parameters are defined using the recommended relationships and ductility indexes in the literature (Lourenço and Gaetani 2022). After the probability distributions are set for each random variable, the Latin Hypercube Sampling (LHS) method is used to get the sample values for Monte Carlo Simulations (Stein 1987). In total 250 simulations are run.

To generate a realistic representation of the reference URM pier-spandrel system, spatial variation of the material properties is addressed in D-RBA. A special algorithm is implemented, assigning different contact properties to the joints corresponding to the unit and unit-mortar interface, once they are grouped and identified separately. Figure 4 illustrates a spatial variation of the bond tensile strength generated through the pre-defined probability distribution. It is noted that no correlation between properties of adjacent joints was considered because it is quite difficult to quantify even experimentally (Gonen et al. 2022).

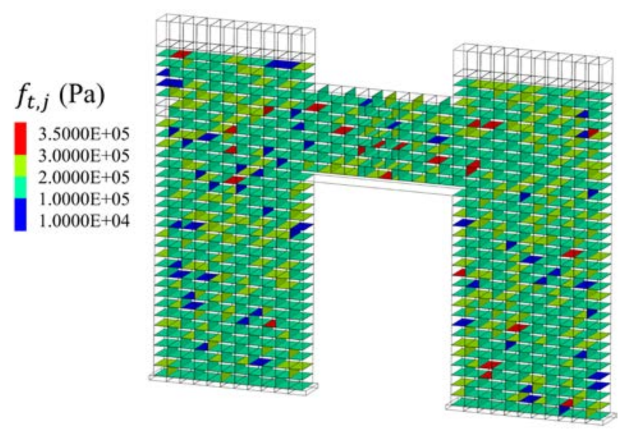
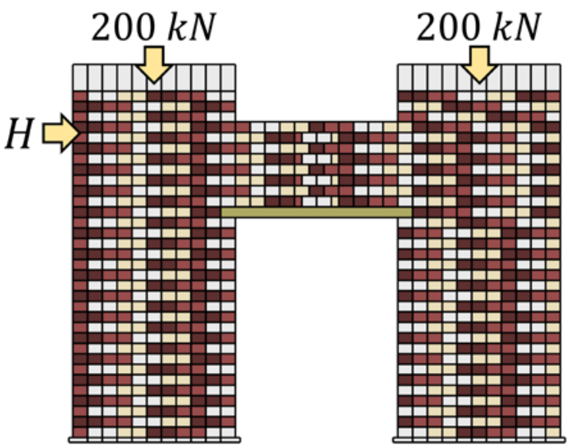


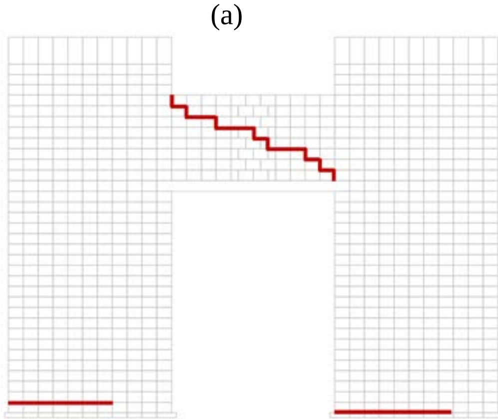
Figure 4: Illustration of the spatial variation of the bond tensile strength ($f_{t,j}$) after sampling.

2.2. Benchmark Study

A full-scale experimental study carried out by Parisi et al. (2014) on a pier-spandrel system under lateral loads is used as a benchmark study. The specimen consisted of a couple of tuff stone masonry piers connected through a spandrel with a timber lintel above a central opening. Each pier was initially subjected to a pre-compression load equal to 200 kN, which was kept constant over the entire test duration. Then, an in-plane lateral load (H) was applied approximately on top of the spandrel under monotonically increasing lateral displacement, as depicted in Figure 5a. According to the experimental results, a rocking mechanism of the piers accompanied by diagonal shear cracking of the spandrel was observed (Figure 5b). The ultimate load (H_{max}) was found to be 184.31 kN, whereas the maximum displacement reached during the test (d_{max}) was 27.17 mm. Further details regarding the test setup and material characteristics can be found in the reference study.



(a)



(b)

Figure 5: Representation of (a) loading condition and (b) crack pattern in the benchmark study.

3. PROBABILISTIC ASSESSMENT OF THE IN-PLANE BEHAVIOR OF PIER-SPANDREL SYSTEM

The adopted modeling strategy was validated first via deterministic model using the average material and contact properties with no spatial variation, presented in an early study of the authors (Pulatsu et al. 2022). The discrete element model consists of 861 rigid blocks and 28329 sub-contacts.

As shown in Figure 6, a good match is obtained when comparing the D-RBA against experimental findings, in which approximately a 10% difference was noted between computational and experimental results regarding the peak base shear force. Furthermore, an identical collapse mechanism is obtained from the discontinuum model. Nonetheless, spatial variability of material properties can play a key role into a more accurate estimation of some capacity features such as the ultimate load.

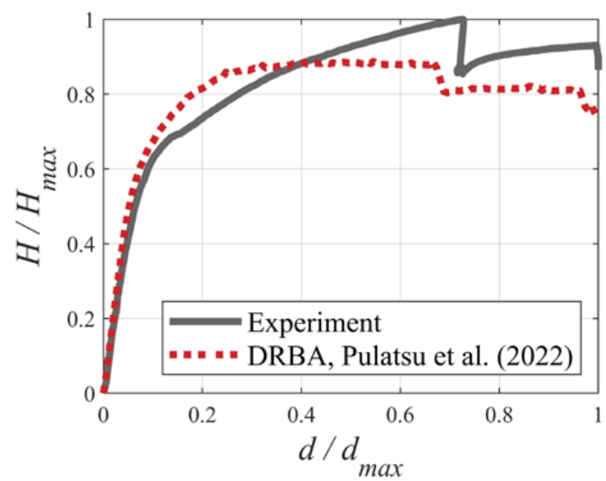


Figure 6: Comparison of the numerical pushover curve associated with D-RBA reference non-spatial deterministic model against the experimental curve.

4. RESULTS AND DISCUSSION

The overall results of DEM-based spatial probabilistic analyses are given in Figures 7, 8 and 9 compared with the non-spatial analyses. As the name suggests, the spatial variation of the material properties is not considered in the non-spatial assessment, where all the contact surfaces have the same mechanical properties that are assigned based on the pre-defined statistical distribution mentioned earlier and changed for each simulation.

It is evident that the consideration of the spatial variation in the computational model yields less uncertainty in the prediction of lateral load-carrying capacity of the analyzed URM structure as observed in Figure 7. This effect is more pronounced in Figure 8 where the histograms of the maximum lateral forces obtained in the spatial and non-spatial analyses are compared. As can be seen, the variation in the non-spatial analysis is very significant whereas the spatial analysis results are clustered mostly between the 160-170 kN interval. On the other hand, maximum lateral displacements vary a lot in both types of analysis, albeit slight grouping of the results is observed for spatial analysis. Such discrepancy in the attained maximum displacements was observed in authors' previous studies, but it should be noted that different failure modes are observed within 250 simulations, either spatial or non-spatial analysis, and the grouping of failure modes is expected to reduce the variation in the attained displacements.

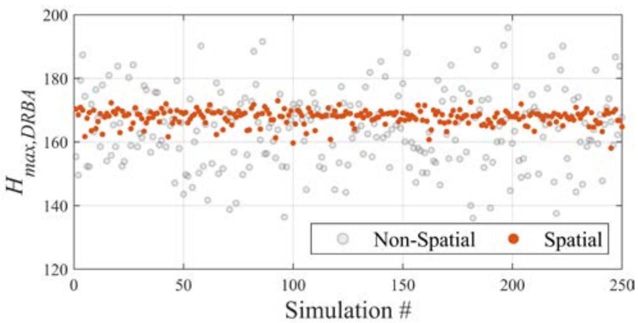


Figure 7: The scatter plot of the ultimate lateral load obtained from spatial and non-spatial DRBA.

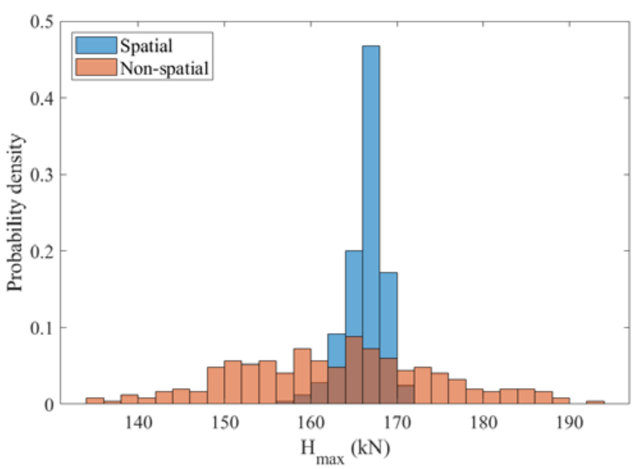


Figure 8. Histograms of ultimate lateral load obtained in stochastic non-spatial and spatial analyses.

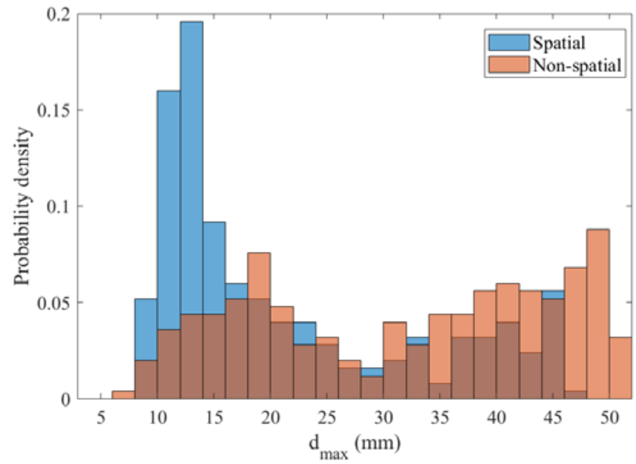


Figure 9. Histograms of maximum lateral displacements obtained in stochastic non-spatial and spatial analyses.

5. CONCLUSIONS

In this study, the influence of spatial variability of material properties on the in-plane seismic behavior of URM walls with single opening has been discussed. Specifically, a discontinuum-based approach (denoted as discrete rigid block analysis, D-RBA) has been used to numerically assess the nonlinear response of a benchmark URM pier-spandrel system under in-plane lateral loading. Experimental data and previous studies available in the literature were used to define contact properties that govern the computational modeling of masonry. Hence, spatial variation of material properties throughout the URM structure was considered according to probability distributions and relationships between some parameters.

Analysis results show that consideration of spatial variability improves the accuracy in the estimation of the ultimate lateral load, hence significantly reducing the uncertainty in the in-plane seismic load-carrying capacity. This outcome brings a solid advantage of using probabilistic approach in D-RBA and enhance the confidence in the result of adopted modeling approach since the variation of the ultimate load has been reduced significantly. It may also enhance the efficiency in the decision-making process for seismic retrofitting and strengthening projects.

REFERENCES

Aldemir, A., Erberik, M. A., Demirel, I. O., and Sucuoglu, H. (2013). “Seismic performance assessment of unreinforced masonry buildings with a hybrid modeling approach.” *Earthquake Spectra*, 29(1), 33–57.

Augenti, N., and Parisi, F. (2010). “Constitutive models for tuff masonry under uniaxial compression.” *Journal of Materials in Civil Engineering*, 22(11), 1102–1111.

Augenti, N., and Parisi, F. (2011). “Constitutive modelling of tuff masonry in direct shear.” *Construction and Building Materials*, 25(4), 1612–1620.

Cundall, P. A. (1971). “The measurement and analysis of accelerations in rock slopes.” University of London (Imperial College of Science and Technology).

Cundall, P. A., and Detournay, C. (2017). “Dynamic relaxation applied to continuum and discontinuum numerical models in geomechanics.” *Rock Mechanics and Engineering*, CRC Press, 57–102.

Ehresman, R., Taylor, N., Pulatsu, B., and Erdogmus, E. (2021). “Discrete Rigid Block Analysis to Assess Settlement Induced Damage in Unreinforced Masonry Façades.” *CivilEng*, 2(3), 541–555.

Funari, M. F., Hajjat, A. E., Masciotta, M. G., Oliveira, D. V., and Lourenço, P. B. (2021). “A parametric scan-to-FEM framework for the digital twin generation of historic masonry structures.” *Sustainability*, 13(19).

Gonen, S., Pulatsu, B., Erdogmus, E., Lourenço, P. B., and Soyoz, S. (2022). “Effects of spatial variability and correlation in stochastic discontinuum analysis of unreinforced masonry walls.” *Construction and Building Materials*, 337, 127511.

Hamp, E., Gerber, R., Pulatsu, B., Quintero, M. S., and Erochko, J. (2022). “Nonlinear Seismic Assessment of a Historic Rubble Masonry Building via Simplified and Advanced Computational Approaches.” *Buildings*, 12(8), 1130.

Itasca Consulting Group Inc. (2013). “3DEC Three Dimensional Distinct Element Code.” Minneapolis.

Kesavan, P., and Menon, A. (2022). “Investigation of in-plane and out-of-plane interaction in unreinforced masonry piers by block-based micro-modeling.” *Structures*, 46, 1327–1344.

Kumar, N., Barbato, M., Rengifo-López, E. L., and Matta, F. (2022). “Capabilities and limitations of existing finite element simplified micro-modeling techniques for unreinforced masonry.” *Research on Engineering Structures and Materials*, 8(3), 463–490.

Lemos, J. V., and Campos Costa, A. (2017). “Simulation of Shake Table Tests on Out-of-Plane Masonry Buildings. Part (V): Discrete Element Approach.” *International Journal of Architectural Heritage*, 11(1), 117–124.

Lourenço, P. B., and Gaetani, A. (2022). “Recommended properties for advanced numerical analysis.” *Finite Element Analysis for Building Assessment*, Routledge, New York, 209–320.

Lourenço, P. B., Rots, J. G., and Blaauwendraad, J. (1998). “Continuum model for masonry: Parameter estimation and validation.” *Journal of Structural Engineering*, 124(6), 642–652.

Mendes, N., Zanotti, S., and Lemos, J. V. (2018). “Seismic Performance of Historical Buildings Based on Discrete Element Method: An Adobe Church.” *Journal of Earthquake Engineering*, 00(00), 1–20.

Parisi, F., Augenti, N., and Prota, A. (2014). “Implications of the spandrel type on the lateral behavior of unreinforced masonry walls.” *Earthquake Engineering & Structural Dynamics*, 43(12), 1867–1887.

Pulatsu, B., Erdogmus, E., Lourenço, P. B., Lemos, J. V., and Hazzard, J. (2020). “Discontinuum analysis of the fracture mechanism in masonry prisms and wallettes via discrete element method.” *Meccanica*, 55(3), 505–523.

Pulatsu, B., Erdogmus, E., Lourenço, P. B., and Quey, R. (2019). “Simulation of uniaxial tensile behavior of quasi-brittle materials using softening contact models in DEM.” *International Journal of Fracture*, 217(1–2), 105–125.

Pulatsu, B., Gonen, S., Parisi, F., Erdogmus, E., Tuncay, K., Funari, M. F., and Lourenço, P. B. (2022). “Probabilistic approach to assess URM walls with openings using discrete rigid block analysis (D-RBA).” *Journal of Building Engineering*, 61, 105269.

Roca, P., Cervera, M., Gariup, G., and Pelà, L. (2010). “Structural analysis of masonry historical constructions. Classical and advanced approaches.” *Archives of Computational*

Methods in Engineering, 17(3), 299–325.
Saloustros, S., Pelà, L., Cervera, M., and Roca, P. (2018). “An Enhanced Finite Element Macro-Model for the Realistic Simulation of Localized Cracks in Masonry Structures: A Large-Scale Application.” *International Journal of Architectural Heritage*, 12(3), 432–447.
Stein, M. (1987). “Large sample properties of simulations using latin hypercube sampling.” *Technometrics*, 29(2), 143–151.