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Macro- and micro-scale modelling of masonry structures using the Discrete Element Method

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1 INTRODUCTION

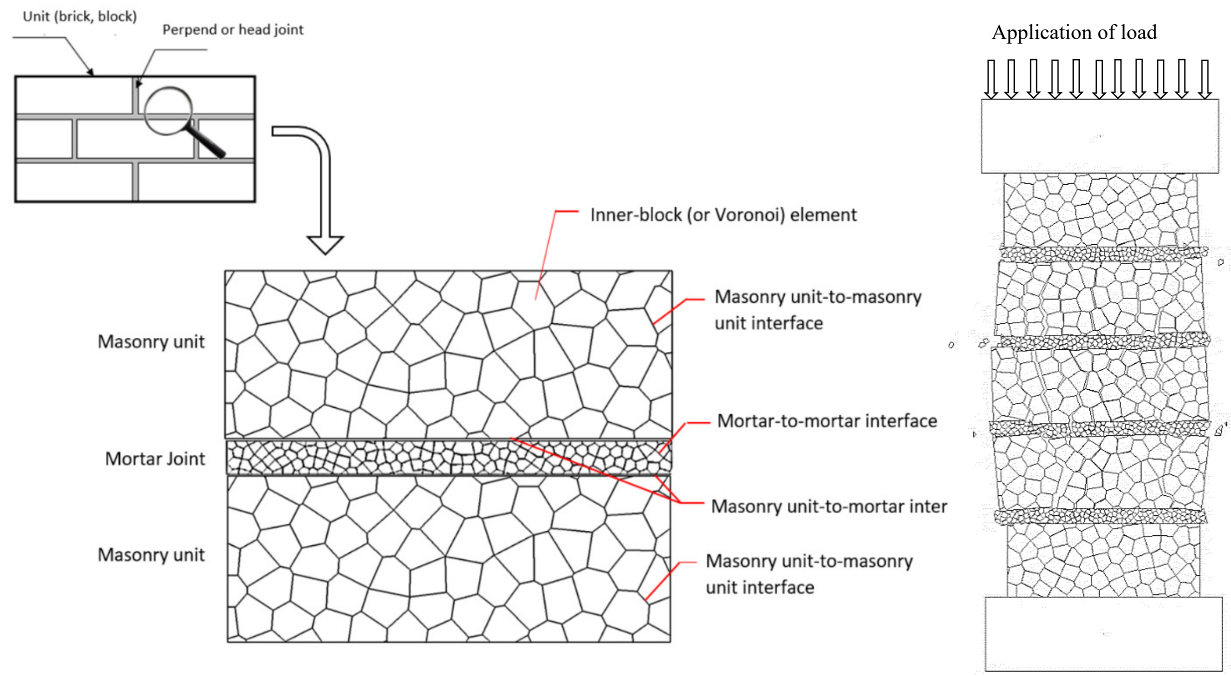
Masonry is a heterogeneous anisotropic material, which is composed of units (e.g. bricks, stones, blocks etc.), bonded together with or without mortar. It is probably the oldest building material that is commonly used today. Although masonry is easy to construct, its mechanical behavior is non-linear and thus complex to understand. The need to predict the in-service behavior and load carrying capacity of masonry structures has led researchers to develop several computational strategies and tools that are characterized by different levels of complexity. Such models range from considering masonry as an anisotropic continuum (e.g. macro-models) to the more detailed ones considering masonry as an assemblage of units and mortar joints (e.g. micro-models) (Lourenco 1996). Although, the macro-modelling approach based on the Finite Element Method (FEM) of analysis is an efficient approach for the purpose of design or the understanding of the global behavior of a structure, the approach is lacking success since progressive failure or collapse mechanism cannot be obtained; since failure is smeared out in the continuum. An alternative and promising approach which can represent the discrete nature of masonry is presented by the Discrete Element Methods (DEM). The approach was initially developed by Cundall (1971) to model sliding of rock masses in which failure occurs along their joints. It was later applied to model the mechanical behavior of masonry structures (Lemos 2007; Sarhosis et al. 2016). This paper aims to highlight the ability of DEM to simulate the mechanical behavior of masonry at different scales. Two examples are investigated including: a) the mechanical behavior of a masonry prism subjected to direct compression; and b) the mechanical behavior of a masonry arch bridge with backfill material. In both cases results are compared with experimental findings and comparisons are made. Reliable prediction of masonry strength can allow one to reduce the costly and timely experimental testing, gain a better insight into the structural capacity of the mechanisms which drive failure of material and structure and avoid the reliance on conservative empirical formulas.

2 REPRESENTATION OF THE DISCRETE NATURE OF MASONRY PRISMS IN COMPRESSION

A numerical model has been developed to simulate the direct compression of a masonry prism tested in the laboratory by Oliveira (2003). The masonry prism is composed of five bricks. The bricks had average dimensions of 285 mm ×13 mm × 5 mm. Joints were all made of cement mortar and had the same thickness and equal to 10 mm.

In the proposed modelling approach, the micro-structure of masonry units and mortar was considered as an assemblage of densely packed irregular in shape and size discrete elements bonded together by a zero thickness interface (see Fig. 1a). Such irregular elements could be a few millimeters in size and are able to move independently to each other and open or slide, thus allowing for cracking in either brick, mortar and/or brick-mortar interface. Inner-blocks can be subdivided into simple triangular finite elements (designated as zones), which give a much better approximation of the strain field than an assumption of uniform strain in the whole inner-block. In this example, the discrete deformable inner-block elements containing internal meshing are assumed elastic, but a non-linear material behavior may also be used if necessary.

From the numerical simulations it was observed that the peak appears to take place when one of the bricks splits in two by coalescence of the vertical tensile cracks that progressively develop (Fig. 1b). Total failure followed when the resisting core started to break. The proposed computational approach shows significant advantages when compared to standard continuum models, since it allows one to observe crack initiation and propagation in a realistic manner. In particular, the approach allows one to model cracking as a real discontinuity among particles and not as a modification in the material properties. Further details about this study can be found at Sarhosis & Lemos (2018). Comparison of experimental against numerical findings are shown in Figure 3a.



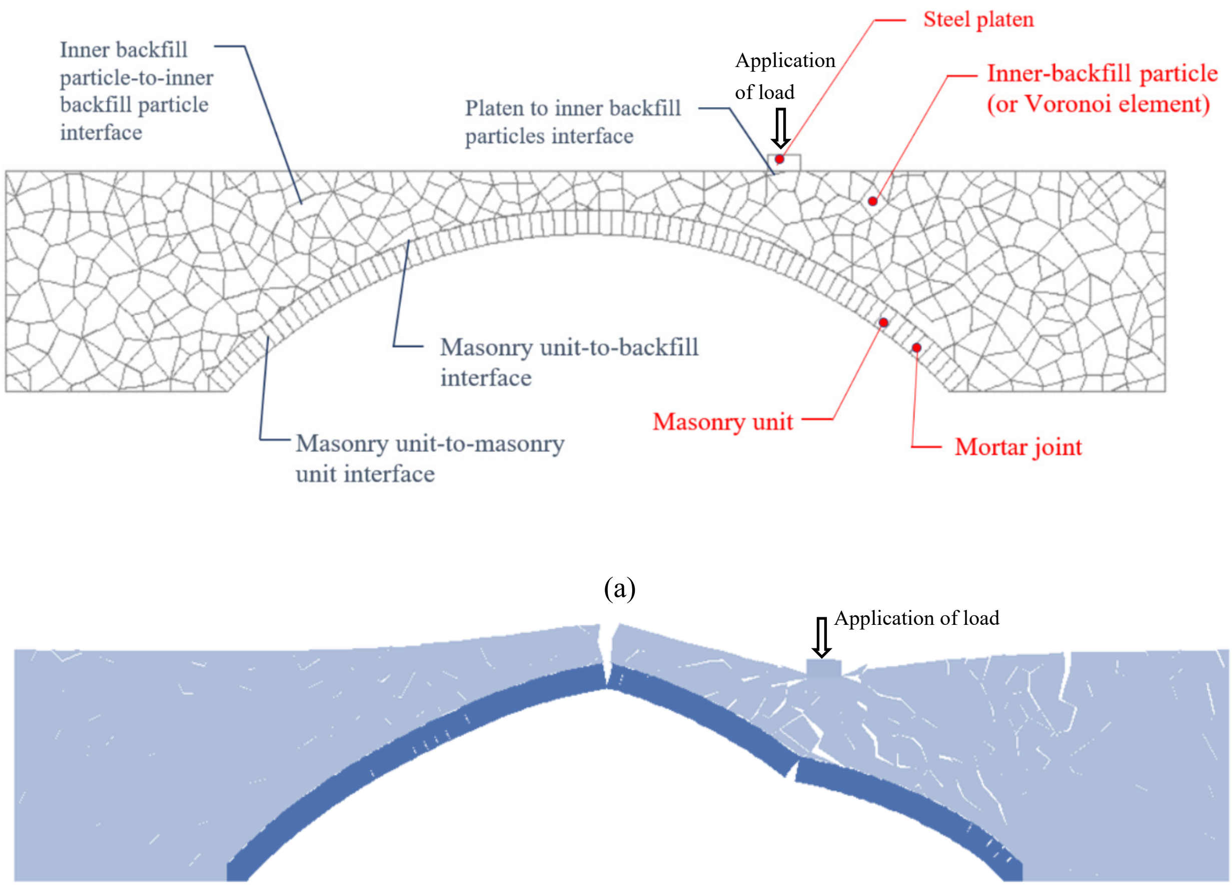
(a) (b)

Figure 1. (a) Representation of masonry units and mortar joints by means of polygonal elements; (b) failure mode of a masonry prism subjected to direct compression.

3 REPRESENTATION OF THE DISCRETE NATURE OF MASONRY ARCH BRIDGES

An attempt has been made to simulate the load carrying capacity and failure mode of the Prestwood Bridge, located in Staffordshire, UK when subjected to vertical in plane load. Prestwood Bridge is an old masonry arch bridge which has a span of 6.550 m and a rise of 1.428 m (Page 1987). The vault barrel, which is a single ring of bricks laid as headers, has a thickness of 0.220 m. The width of the bridge is 3.8 m.

Geometric models to represent the geometry of the masonry arch bridge were created in the discrete element software *UDEC* (Itasca 2014). The developed 2D numerical model simulates plain strain conditions. Masonry units or voussoirs were represented by an assembly of rectangular deformable blocks. Mortar joints were represented by a zero-thickness interface. These interfaces can be viewed as interactions between the blocks and are governed by appropriate stress-displacement constitutive laws. Interaction between the blocks is represented by sets of point contacts, with no attempt to obtain a continuous stress distribution through the contact surface. The discontinuous nature of backfill or soil was represented by a series of irregular in shape particles of polygonal/Voronoi shape (Mayya & Rajam 1995). Such fictitious irregular deformable particles, here named "*inner-backfill particles*", are shown in Figure 2a. Inner-backfill particles were connected together by zero thickness interfaces. Interfaces can be viewed as the location where mechanical interaction between inner-backfill particles takes place and could be potential fracture slip lines. The inner-backfill particles were simulated as linear elastic, isotropic material while their interaction with each other was controlled by Coulomb friction law. The size of Voronoi elements varied from 10, 20 and 30 cm. A good agreement between the experimental and the numerical results (Fig. 3b) was obtained demonstrating the huge potential of this modelling approach proposed herein. The Voronoi models have the advantage of naturally modelling crack initiation and propagation as real discontinuity between soil particles. However, further research is required to be carried out and investigate methodologies used for the calibration of the interface material properties between inner soil elements and how such micro-parameters affect the global behavior of the bridge.



(b)

Figure 2. (a) Representation of backfill in a masonry arch bridge as a series of polygonal particles; (b) Failure mode of a masonry arch bridge showing cracking both in voussoirs and backfill.

4 CONCLUSIONS

In this study, the multi-scale capability of DEM to simulate the mechanical behavior of masonry is investigated. In particular, DEM models to simulate the mechanical behavior of a masonry prism subjected to direct compression and a full scale masonry arch bridge containing backfill material. Results from the numerical models were compared against experimental findings (Figure 3). A fair to good agreement between the experimental and the numerical results was obtained which demonstrates the huge potential of the DEM. For further information about these models, please refer to Sarhosis et al 2019 and Sarhosis & Lemos 2018.

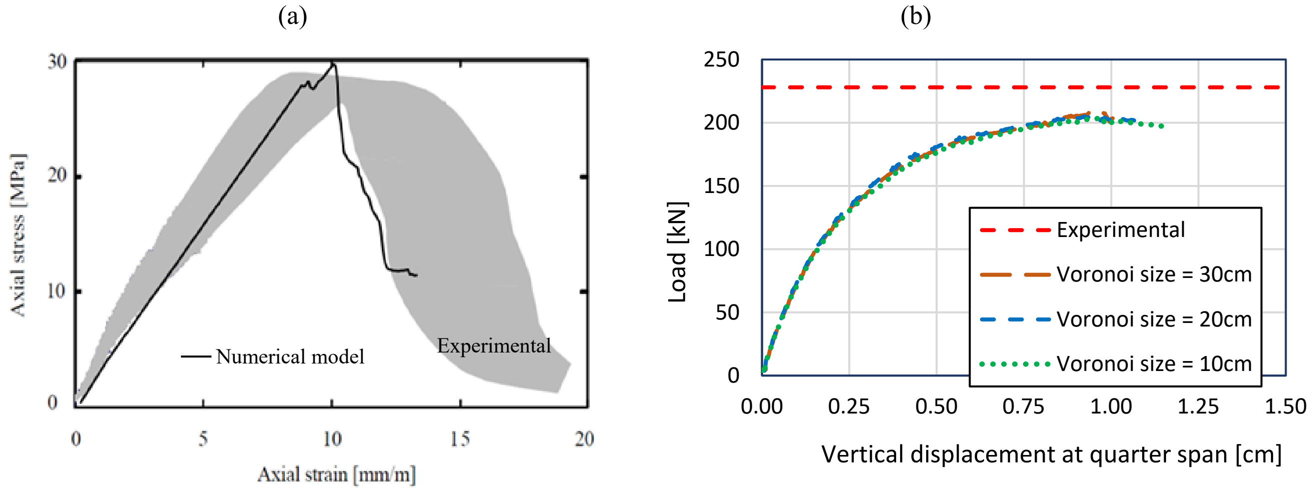


Figure 3. Experimental against numerical results: (a) Masonry prism in compression; (b) Masonry arch bridge with soil represented as a series of different in size Voronoi elements.

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