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ASSESSMENT OF THE SEISMIC CAPACITY OF STONE MASONRY WALLS WITH BLOCK MODELS

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Abstract. *The application of discrete element models based on rigid block formulations to the analysis of masonry walls under horizontal out-of-plane loading is discussed. The problems raised by the representation of an irregular fabric by a simplified block pattern are addressed. A test problem provides a comparison of various regular and random block patterns, showing their influence on the failure loads. An example of application of a rigid block model to a wall capacity problem is presented.*

1 INTRODUCTION

The safety assessment of historical masonry structures under seismic loads requires numerical models with the ability to represent the types of failure modes observed in earthquakes and laboratory tests. Block models, based on the discrete element method, are one of the tools available to simulate phenomena such as sliding and separation along joints, which lead to progressive structural damage and collapse. Their application to structural components or monuments of a relatively small size, for which the individual blocks can be numerically represented, poses no major difficulties [1]. The success of this type of application has encouraged the extension of these models to more complex structures, for example, involving masonry walls formed by irregular blocks, for which the numerical idealization requires much more drastic simplifications that need to be critically assessed.

The paper addresses the application of rigid block models to analyze the out-of-plane behavior of masonry walls under horizontal loads. The influence of the idealized block patterns on the results is discussed. In these analyses, the seismic action is represented as a static load, which makes the comparisons clearer. It should be remarked, however, that the advantages of rigid block models are more significant in dynamic analysis with explicit algorithms, because of the lower run times in comparison with deformable block models. An application to the evaluation of the ultimate capacity of a large wall in a historical building is also presented.

2 RIGID BLOCK MODELLING OF MASONRY WALLS

Discrete element models employing polyhedral rigid blocks have proved very effective in the dynamic analysis of structures and monuments composed of blocks of hard rock with dry joints. Classical column-architrave structures are a typical case in which the numerical model may reproduce the individual blocks with reasonable accuracy, even damaged geometries [2].

Modern brick walls, for which unit shapes are known, but not their precise location, may be analyzed with either discontinuum or homogenized continuum models [3]. For large structures, the latter are more straightforward and less time consuming, even if failure modes are more rigorously simulated with the former.

The analysis of a wall formed by coursed or irregular masonry with mortared joints as a continuum appears more natural, since in practice the actual block geometry is not known. A discrete block model of such a wall is necessarily a simplified representation intended to follow the block pattern, not the exact shapes. The advantages of discrete element models for analyzing failure modes, always involving breakage into blocks, have encouraged research in this area. Several approaches have been attempted, resorting to various levels of geometrical and mechanical complexity. Casolo [4] adopts a very simple block pattern, with continuous orthogonal joints, with all the complexity of masonry behavior being accounted for by elaborate joint constitutive models. At the opposite end, bonded particle models [5] employ large random assemblies of particles to simulate the irregular masonry units and the mortar [6], while relatively simple contact laws are used. In this paper, an intermediate approach is adopted, using standard Mohr-Coulomb joint models, and comparing various geometrical schemes, namely regular and random block patterns. The effect of block size was investigated by De Felice and Giannini [7] with a similar type of model.

For dynamic problems, it is necessary to verify that the simplified rigid block representation provides a good approximation of the dynamic response. Comparisons of the natural frequencies in the linear range, assuming elastic contacts, with analytical solutions for walls have shown that sufficient accuracy can be obtained, particularly if three or more contact points across the thickness of the wall are used [8].

3 ANALYSIS OF INFLUENCE OF BLOCK PATTERNS

The influence of the joint patterns adopted for the rigid block representation of the wall was analyzed with a simple test problem (Fig. 1). The wall was assumed to be simply supported in the out-of-plane direction at both lateral ends, by means of 2 fixed blocks, representing the effect of cross walls. The wall dimensions are 20x10 m, with 0.80 m thickness. For simplicity, a Coulomb friction model was adopted for the joints, without cohesion or tensile strength. A Young's modulus of 2.5 GPa was assumed. The joint stiffness listed in Table 1 correspond to an average joint spacing of 1 m. For different spacings, these values were scaled to maintain an average elastic isotropy. Static analyses were conducted, in which a horizontal mass force was applied in the out-of-plane direction. This load was increased in steps until failure. The analyses were performed with the code 3DEC [9].

Joint properties	
Normal stiffness	2.5 GPa/m
Shear stiffness	1.0 GPa/m
Friction angle	35°

Table 1: Joint properties for test problem.

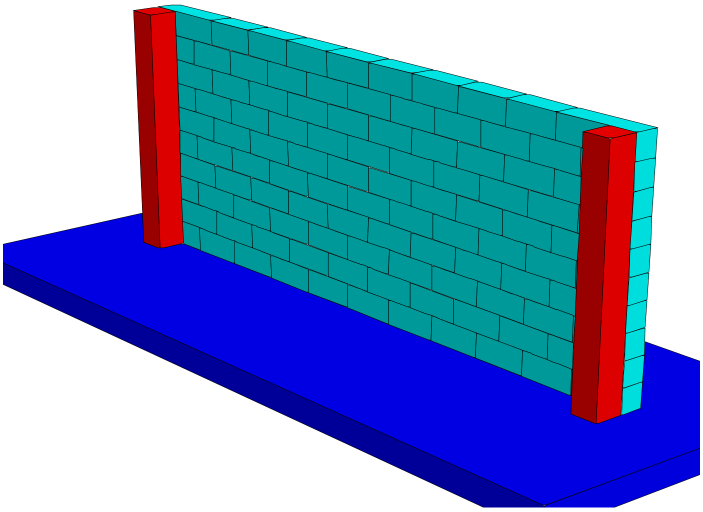
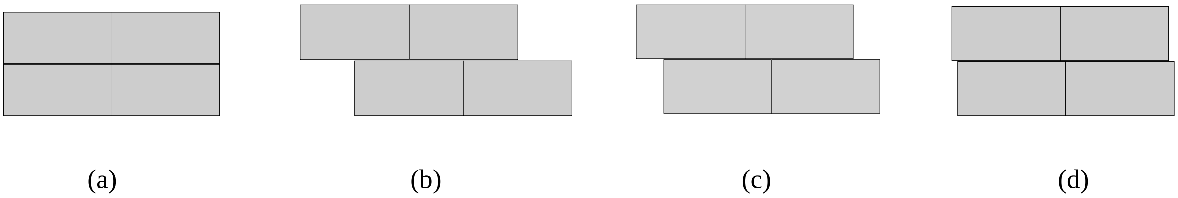


Figure 1: Test problem (case of vertical joint offset of 1.0).

3.1 Regular block patterns

The model in Fig. 1 corresponds to the case of blocks with dimension 2x1 m, with staggered vertical joints with an offset of 1.0 m. For these block dimensions, 3 other cases were considered: continuous vertical joints (no offset), and staggered vertical joints with offsets of 0.5 and 0.1 m. The block patterns are shown in Fig. 2.



(a) (b) (c) (d)

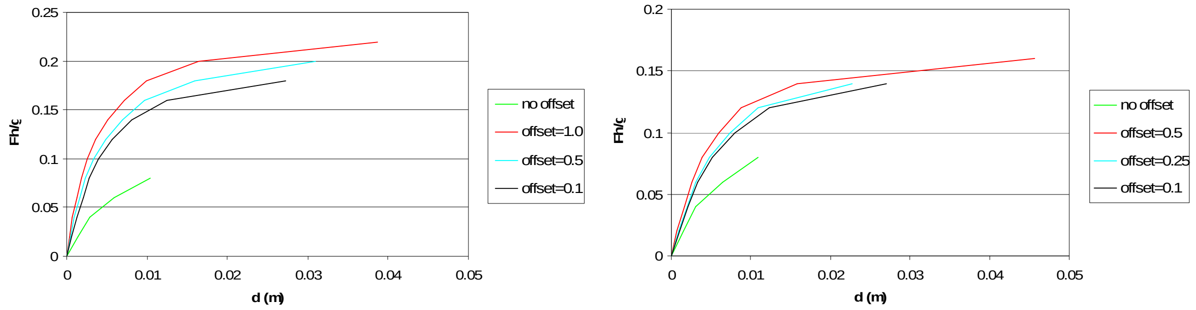
Figure 2: Block patterns (block dimensions 2x1 m): (a) no offset; (b) offset=1.0; (c) offset=0.5; (d) offset=0.1.

A second series of tests were conducted with square blocks, dimensions of 1x1 m. The 4 block patterns are illustrated in Fig. 3: continuous vertical joints, and 3 cases of discontinuous joints with offsets 0.5, 0.25 and 0.1 m.

(a) (b) (c) (d)

Figure 3: Block patterns (block dimensions 1x1 m): (a) no offset; (b) offset=0.5; (c) offset=0.25; (d) offset=0.1.

The results for the case of blocks with dimensions 2x1 m are shown in Fig. 4, on the left. The curves represent the out-of-plane displacement of the middle point at the top of the wall (horizontal axis) versus the horizontal gravity force (vertical axis). The horizontal force was incremented in steps of 0.1g, up to failure. The last point in each curve corresponds to the last equilibrated state. On the right of Fig. 4, the corresponding curves for the case of blocks 1x1 m are plotted.



(a) (b)

Figure 4: Horizontal force vs. displacement curves for the 4 block patterns: (a) blocks 2x1 m; (b) blocks 1x1 m.

Considering first the case of rectangular blocks, it can be seen that the most significant difference is between the case of continuous vertical joints and the models with staggered joints. Even a small offset increases substantially the wall capacity. The chart for the case with square blocks, on the right, shows that the capacity of the wall with continuous joints is not altered (within the resolution of the load increment used). The staggered joint models display lower strength than those with rectangular blocks. This is related to the fact that the smaller areas of block contact along the horizontal joints lead to a reduced restraint of relative block rotation necessary to create the failure mode. These results show that the typical “brick wall” pattern often used as a representation of an irregular masonry wall may overestimate its strength. This is particularly significant, since numerical models often use larger block sizes than the real ones to save computational effort. Therefore the overestimation of the actual imbrication of the wall stones may adversely affect the safety assessment. Considering continuous joints is a rather conservative assumption, as offsets certainly exist, but may be defensible if the actual wall units are much smaller than the numerical blocks.

3.2 Voronoi block patterns

The numerical generation of block assemblies that represent correctly the various types of traditional masonry is a topic still demanding more research. It is easy to create a random block pattern, for example, using Voronoi polygons, as reported here. However, these models are not sufficiently realistic. Most masonry walls display block patterns where horizontal joints are more or less well defined, reflecting the way in which they were built. In the absence of a more elaborate methodology, in the present study, an irregular block pattern was obtained using a 2D Voronoi polygon generator. An average edge length of 1 m was assumed, to be comparable with the square blocks in the previous section. The 3DEC blocks were created assuming a uniform shape across the wall thickness. Fig. 5 shows one the several bock assemblies employed in this study. Joint properties were the same as in Table 1.

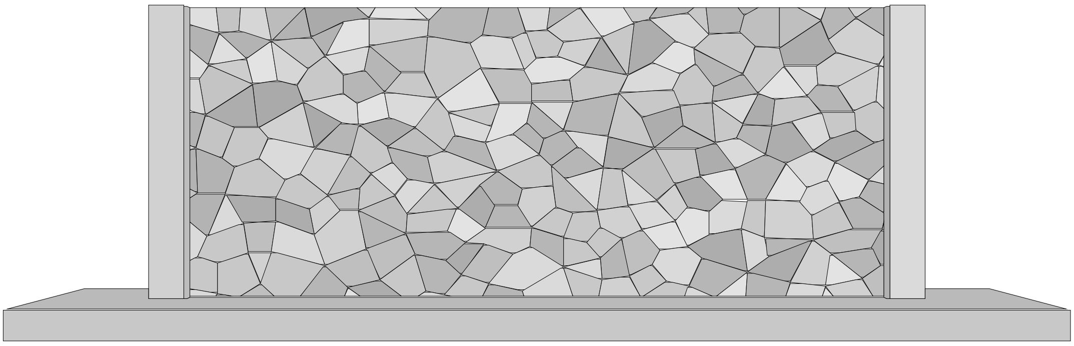


Figure 5: Model with Voronoi block pattern (case 1).

The results of the simulations with 3 Voronoi block systems are compared in Fig. 6 with two of the square block models already presented (with continuous vertical joints and offset of 0.1 m). First, it is interesting to note that the three randomly generated Voronoi patterns follow fairly similar deformation curves. The initial deformability of the system is close to that obtained with continuous vertical joints. However, the strength is higher, but still below the value obtained with imbricated joints with the smallest offset. The Voronoi pattern does not involve discontinuous joints, so it tends to underestimate the block interlocking.

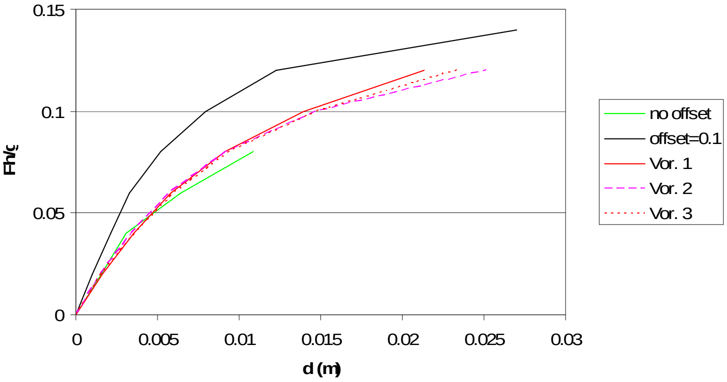


Figure 6: Horizontal force vs. displacement curves for regular and Voronoi block patterns.

The failure mode of the first model with the Voronoi pattern is shown in Fig. 7 (where the deformations were magnified as this plot refers to the initial stages of the collapse process).

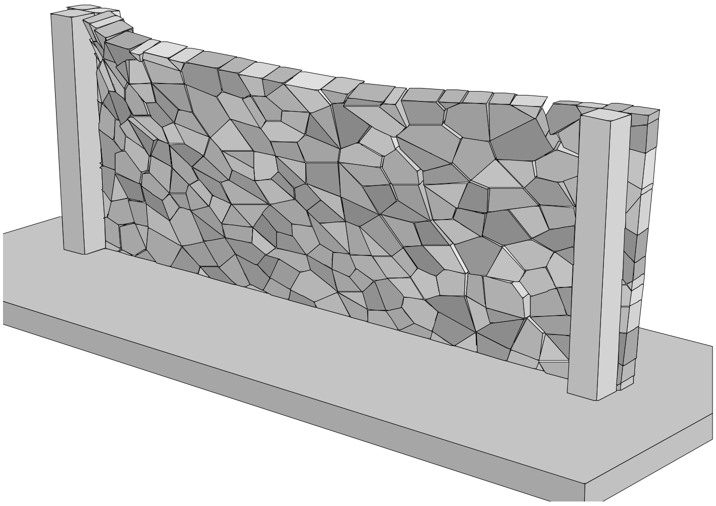


Figure 7: Failure mode of model with Voronoi block pattern (case 1).

4 LOCAL MODELING OF WALL FAILURE

The safety assessment of historical buildings usually involves two scales of numerical analysis: global and local. Global models are simplified, not only in terms of geometrical detail, but also in terms of material models, often linear elastic assumptions being adopted. The global dynamic behavior can be calibrated against in situ experiments. The local models are used to assess the safety of critical components, and need to represent the nonlinear behavior, whether pushover methods or dynamic analysis are used. Discrete element models are one of the tools available for this local modeling scale.

The local modeling of a structural component raises the problem of setting the boundary conditions, such that the effect of the surrounding structure is satisfactorily represented. In the example presented in this section (Fig. 8), elastic supports are used to provide the support of the wall at both ends, in the two horizontal directions. The stiffness of these elastic supports was calibrated so that the two lowest frequencies and mode shapes matched reasonably well the in situ measurements provided by ambient vibration tests.

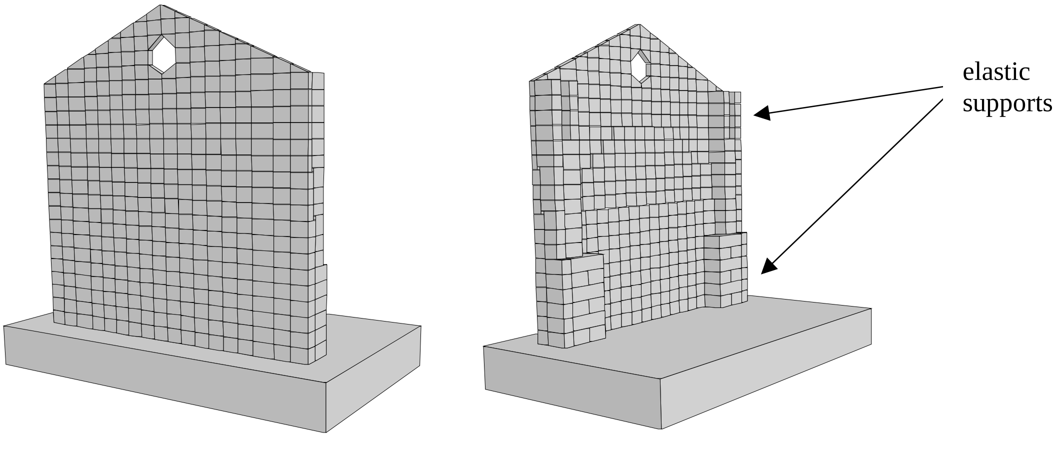


Figure 8: Rigid block model for local wall failure analysis.

The wall shown in Fig. 8 has a maximum height of about 38 m, at the centre, and a thickness varying thickness from 1.6 m at the base to 0.8 m at the top, with thicker buttresses near both ends. The rigid block model adopted a continuous joint pattern, which is a conservative assumption, according to the results of the previous section. A Mohr-Coulomb model with cohesion and tensile strength was employed. The evaluation of the seismic capacity was based on pushover analyses [10]. Unlike the previous section, the seismic forces acting in the out-of-plane direction were not assumed uniform in height, but were applied to the rigid blocks according to the first mode shape (Fig. 9), which dominates the response of the wall.

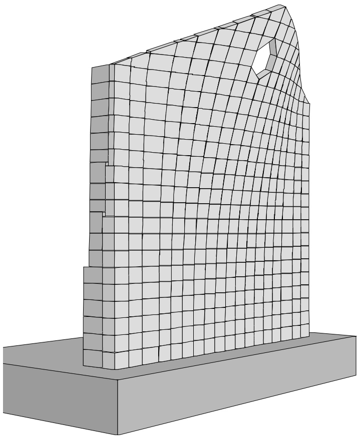


Figure 9: First mode shape of rigid block model.

Parametric studies were conducted to assess the influence of the main model parameters. In particular the effect of joint shear strength on the wall capacity is plotted in Fig. 10. The 2 curves correspond to values of cohesion of 0.5 and 0.2 MPa, and friction angles of 35° and 25°, respectively. In both cases, the joint tensile strength was 0.1 MPa. The assumed continuity of the vertical joints allows failure mechanisms, involving sliding near the buttresses, which become important when the joint shear strength is reduced, as seen in the different evolution of the two curves.

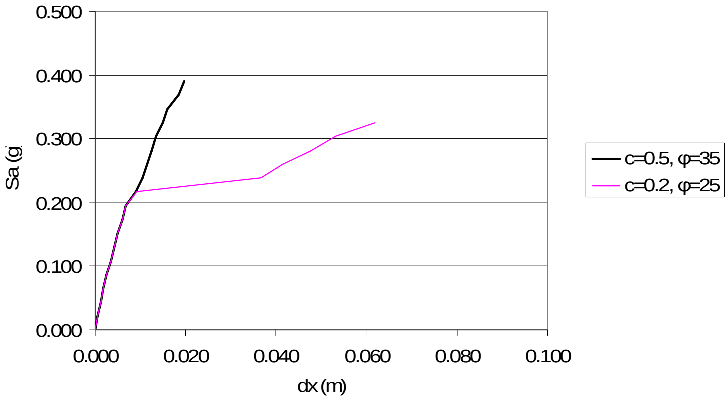


Figure 10: Spectral acceleration vs. displacement curves for 2 values of joint strength.

5 CONCLUSIONS

Discrete element models provide a powerful tool to analyze the deformation and failure modes of masonry, either in static or dynamic analysis. The successful application of these discontinuous representations involves judicious selection of model geometry and parameters. For simple stone structures, the model may reproduce the actual size and shape of individual blocks, so its generation is straightforward. For large and complex structures, however, the discrete block model is a considerable idealization. The effect of the simplified block patterns on the results needs to be assessed. For irregular masonry fabric, the use of random block generators, for example, based on Voronoi polygons, allows more realistic assemblies, avoiding the bias introduced by simple orthogonal joint sets. For a more effective use of these tools, further research on block generators capable of representing the various types of fabric found in historical masonry is still required.

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