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A combined finite-discrete element analysis of dry stone masonry structures

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ABSTRACT

This paper presents the performance of a combined finite-discrete element method (FEM/DEM) for the material and geometric non-linear analysis of the structural response of dry stone masonry structures under monotonic, cyclic and seismic loads. In the proposed modelling approach each stone block is modelled as a discrete element which is discretized by triangular finite elements. Material non-linearity including fracture and fragmentation of discrete elements as well as cyclic behaviour during dynamic load are considered through contact elements which are implemented within a finite element mesh. The numerical analysis based on experimental test data has been carried out to simulate the main features of dry stone structures. The performed analysis shows high accuracy of the numerical results in comparison with the experimental ones and demonstrates the potential of the FEM/DEM method for realistic modelling of the response of dry stone masonry structures.

1. Introduction

The dry stone masonry building technique is one of the oldest techniques which has survived to the present. Most of ancient dry stone masonry structures were constructed by assembling regular stone blocks without the addition of mortar between bed and head joints, and if used, the mortar was usually of low strength and hence it has experienced mechanical degradation over time which means that its influence on the behaviour of such structures is negligible.

Many such structures are situated in seismically active areas and are therefore vulnerable. In the earthquake that occurred in 2003 in Iran about 30,000 people were killed mostly due to the collapse of dry stone masonry structures. The earthquake which struck Pakistan in 2005 took 80,000 human lives, and four million people were left homeless [1]. These earthquakes, which occur each year throughout the world, very often cause damage to dry stone masonry structures and monuments which are classified as world cultural heritage. The earthquake that hit Italy in 1997 caused the collapse of the vault of the St. Francis Basilica in Assisi [2]. In order to minimise human casualties and preserve the cultural heritage, it is necessary to get a better insight into dry stone masonry structures under seismic load.

The main motivation for writing this paper was to present a numerical model suitable for seismic analysis of dry stone masonry structures. Its application enables the evaluation of the seismic resistance of dry stone masonry structures and assists in making right decisions when undertaking certain interventions to increase the seismic resistance.

The main characteristic of the stone structure is its composite nature consisting of stone blocks separated by bed and head joints which may or may not be filled with mortar. The composite nature of dry stone masonry structures is the cause of extremely complex behaviour which represents a real challenge for numerical modelling.

The most commonly used numerical tool for the seismic analysis of masonry structures is the finite element method. In the context of the finite element method micro and macromodelling techniques have been developed. Macro-modelling is probably the most popular and common approach due to its lower calculation demands. In this approach the material is regarded as a fictitious homogeneous orthotropic continuum [3–7]. Macro-models encounter a significant limitation in their inability to simulate strong discontinuities between different blocks or parts of the masonry, especially dry stone structures. A possible way of overcoming these limitations consists of the inclusion of joint interface elements within the finite elements to model the response of discontinuities [7–12]. The disadvantages of such an approach are that most finite element method algorithms cannot take into account the mutual mechanical interaction, finite displacement and rotation including complete detachment such as recognising new contacts. To overcome this limitation some finite element formulations with large displacements and contact detection are developed [13].

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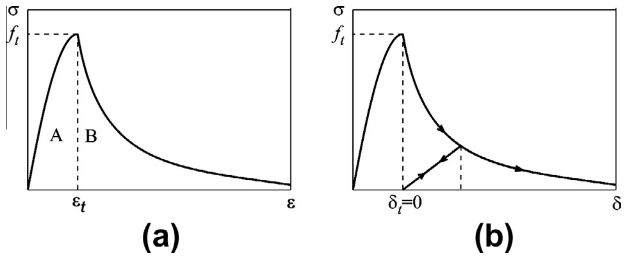

Fig. 1. (a) Strain hardening and strain softening curves defined in terms of strains and (b) the strain softening curve defined in terms of displacements.

Another approach in the analysis of dry stone masonry structures is based on a discrete element method. The original discrete element method which was initially oriented towards the study of jointed rock [14,15] was later extended to other engineering applications including the modelling of masonry structures [16–18]. The common idea in different applications of the discrete element method to masonry is the idealisation of the material as a discontinuum where joints are modelled as contact surfaces between different blocks. This approach is suitable for modelling different types of non-linear behaviour including large displacements and rotation with complete detachment of blocks.

In recent times an increasing number of models attempted to combine the advantages of finite and discrete element methods [19–23]. Cundall [19] and Hart [20] used deformable blocks with an internally finite element mesh: triangles in 2D and tetrahedral in 3D. Both codes have routines for automatic contact detection and update. Barbosa [21] presents a discrete-finite element model in which deformable blocks are represented by a quadrilateral isoparametric finite element, using numerical integration. Petrinic [22] developed a 2D model using polygonal blocks, discretized into a triangular element finite element mesh, and rigid disks. Shi and Goodman [23] developed a discontinous deformation analysis method where deformable blocks are assumed to be in the state of uniform strain and stress. The improved deformability model within a discontinous deformation analysis was achieved either by introducing higher order strain fields for each block or by the so-called sub-block concept in which an individual block is subdivided into a set of simply deformable sub-blocks between which fracturing is enabled [24].

One of the approaches which combines the advantages of the finite and discrete element method is a combined finite-discrete element *method* (FEM/DEM) presented by Munjiza [25–27]. The FEM/DEM was developed mainly for the simulation of fracturing problems considering deformable blocks that may split and separate during the analysis. Within the framework of this method the blocks are discretized by constant strain triangular finite elements. Material non-linearity including fracture and fragmentation of discrete elements as well as cyclic behaviour during dynamic load are considered through contact elements which are implemented within a finite element mesh. The interaction between discrete elements is considered through the contact interaction algorithm for the normal forces and through the Coulomb-type law for friction. The contact interaction is resolved on the principle of

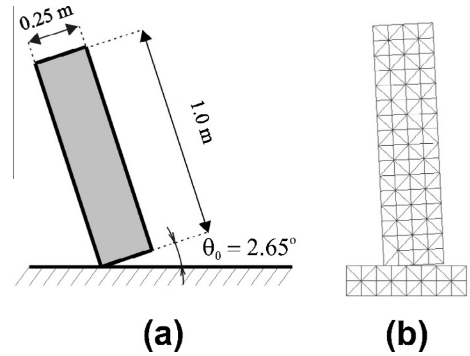

Fig. 3. Test specimen: (a) geometry of the block and (b) finite element mesh.

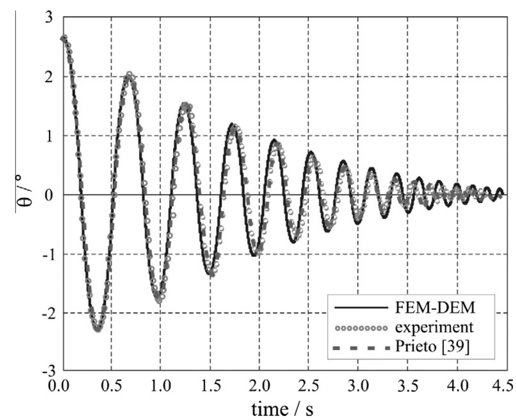

Fig. 4. Free rocking motion response.

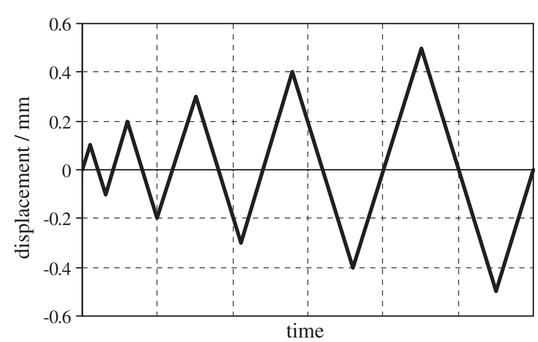

Fig. 5. Displacement history for cyclic shear test on dry masonry joints.

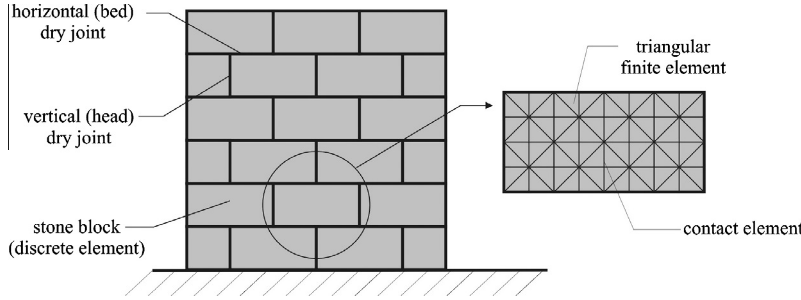

Fig. 2. Discretization of dry stone masonry structure.