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A finite-discrete element model for dry stone masonry structures strengthened with steel clamps and bolts

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ABSTRACT

This paper presents a new robust finite-discrete element numerical model for analysis and prediction of the collapse of dry stone masonry structures strengthened with steel clamps and bolts. The model includes fracture and fragmentation of the blocks as well as a cyclic behaviour, yielding, stiffness degradation, failure and the influence of pulling out of the clamps and the bolts from the stone block. The developed model can be used for the estimation of the seismic resistance of historical dry stone masonry structures reinforced with steel clamps and steel bolts, which is very important for the structures classified as cultural heritage.

1. Introduction

A large part of cultural heritage all over the world are historical structures built as dry stone masonry. However, some of them which were originally built with mortar joints have experienced a significant loss of mortar during time and the behavior of these structures becomes similar to those made of dry stone masonry. Most of these structures have been damaged due to seismic activity [1]. With the aim of increasing their resistance, many of dry stone historical structures were further strengthened by steel clamps and bolts.

In order to evaluate the resistance of these structures and to be able to preserve the cultural heritage it is necessary to develop a numerical model which could take into account all the effects occurring in dry stone masonry structures including the fragmentation of the blocks and non-linear behaviour of steel clamps and bolts during dynamic loading.

The most commonly used numerical tool for the analysis of masonry structures is the finite element method where the material is regarded as a fictitious homogeneous orthotropic continuum [2–6]. These models encounter a significant limitation to simulate strong discontinuities between different blocks of the masonry. For overcoming these limitations joint interface elements were developed to model the discontinuities [7–12]. Most of these models cannot take into account the mutual mechanical interaction, finite displacement and rotation including complete detachment such as recognizing new contacts. To overcome this limitation some finite element formulations with large displacements [13,14] and contact detection have been developed [15].

It is noted that other attractive tools for modelling of dry stone masonry structures are based on a discrete element method [16–23]. The common idea in different applications of the discrete element method to masonry structures is the idealization 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 [24–28]. The most advanced and most often used numerical methods which combine the advantages of the finite and discrete element method are Discontinuous Deformation Analysis (DDA) [29] and Combined Finite-Discrete Element Method (FEM/DEM) [30–32]. These methods are designed to handle contact situations in which transition from continua to discontinua can appear. DDA is more suitable for static problems, while FEM/DEM is more suitable for problems involving transient dynamics until the state of rest or steady state is achieved.

Within the framework of the FEM/DEM 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 [33], is considered through contact elements which are implemented within a

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finite element mesh [34,35]. The interaction between discrete elements is considered through the contact interaction algorithm based on the principle of potential contact forces [36,37] and the Coulomb-type law for friction [38]. The method uses an explicit numerical integration of the equation of motion.

The FEM/DEM method was successfully applied in the analysis of dry stone masonry structures and showed good agreement with experimental results [39]. This model is capable of predicting the collapse mechanism of dry stone masonry structures under seismic loads as well as for determining the safety of the structure with regard to the occurrence of the collapse load. Due to this reason the combined finite-discrete element method is used as a basis for developing a new numerical model for steel clamps and steel bolts which is presented in this paper. This model can be useful in making the right decisions regarding the restoration of dry stone masonry structures which have experienced deterioration over time. It can be important because the most part of these structures are classified as cultural heritage.

2. Types of steel clamps and bolts

Historical dry stone masonry structures are commonly strengthened with two types of steel clamps (Fig. 1). Steel clamps of type I (Fig. 1a) are inserted on the lateral surface of the structure into the previously made holes that are subsequently backfilled. These types of clamps are most commonly used in strengthening of dry stone walls. Considering the dynamic response of structure in plane, extracting of this type of clamps from stone block cannot occur. Steel clamps of type II (Fig. 1b) are inserted on the top side of stone blocks into the previously made holes. They are often used in the construction of dry stone arches. Unlike clamps type I, in the case of dynamic response of structures in the plane, clamps type II can extract from the previously made holes due to the relative displacements of the stone blocks. In that case, clamps type II lose its carrying purpose which is necessary to take into account in numerical modelling. Both types of steel clamps have only tension bearing capacity. The steel bolts are most commonly used when connecting the capitals and columns or capitals and upper beams (Fig. 1c) and they dominantly have shear bearing capacity.

Due to the presence of many parameters which affect on behaviour of clamps and bolts in dry stone masonry structures such as the elastic properties of stone and steel, the width and depth of the hole into which the clamps and bolts are inserted, elastic properties of infill material, geometry of clamps and bolts, etc., it is very difficult to develop numerical model which can take into account all types of failure mechanisms and especially the influence of local interaction between the bolt or clamp on one side and masonry block on another.

In order to be able to analyse such dry stone masonry structures by the finite-discrete element method, a new robust numerical model for steel clamps and bolts has been implemented into a Y2D computer program which will be presented below.

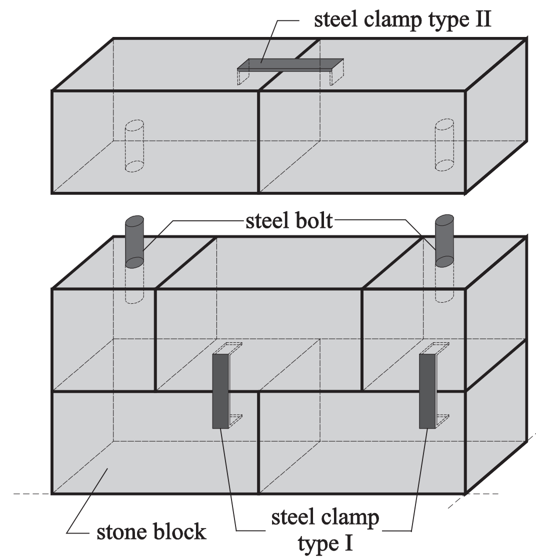

Fig. 2. Steel clamps and bolts.

Schematic presentations of steel clamps type I and II and steel bolts modelled in this paper are shown in Fig. 2.

3. Discretization of a dry stone structure with steel clamps and bolts

In this numerical model each stone block is modelled as a discrete element which is discretized by constant triangular finite elements. Contact interaction between stone blocks is considered through the contact interaction algorithm based on the principle of potential contact forces [36,37] which include the Coulomb-type law for friction [38]. Material non-linearity, fracture and fragmentation are considered through the contact elements which are implemented within the finite element mesh of each block.

The steel clamps type I and II and steel bolts were modelled with one-dimensional elements which can be placed in arbitrary positions inside the stone finite elements.

Discretization of dry stone masonry structure with embedded steel clamps types I and II and bolts is shown in Fig. 3.

4. Material model of the stone block

The most important features that characterize the non-linear behaviour of dry stone masonry structures due to seismic activity are mutually sliding of blocks along contact surfaces, the rotation

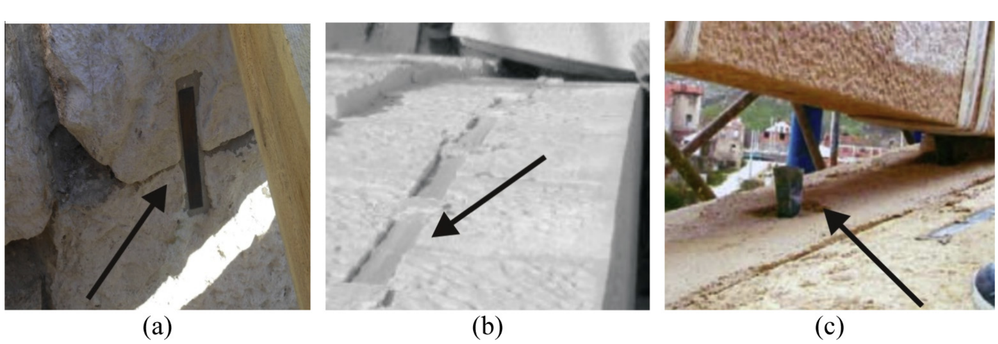

Fig. 1. Steel clamps and bolts: (a) steel clamp inserted on the lateral face of the structure; (b) steel clamp inserted on the top side of stone blocks; (c) steel bolts [40].