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Discrete element modelling of the in-plane and out-of-plane behaviour of dry-joint masonry wall constructions

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A B S T R A C T

This paper aims to improve knowledge on the suitability of the discrete element method (DEM) to simulate the in-plane and out-of-plane behaviour of different in-configuration structural masonry walls constructed with dry joints. The study compares the results obtained from laboratory tests against those predicted using the three-dimensional distinct element 3DEC software. Significant features of the structural behaviour shown by the walls are discussed and conclusions on their ultimate capacity and failure mechanisms are addressed. A key feature of the DEM is the important role that brick discontinuities, i.e. joints, play in the mechanics of masonry. Within DEM, the bricks were modelled as continuum rigid elements while the joints were modelled by line interface elements represented by the Mohr-Coulomb law. The analysis of the results showed that the model developed is capable of representing the crack development and load carrying capacity of masonry structures constructed with dry joints with sufficient accuracy. Moreover, a collection of experimentally verified material parameters is provided to be used by other researchers and engineers and to develop a reliable model to solve engineering challenges worldwide.

1. Introduction

Masonry is a common and traditional form of construction that has been used for centuries around the world. Some of the most important cultural and historical monuments (such as the Parthenon, the pyramids, the Colosseum and the Segovia aqueduct) were constructed using masonry. Many of these masonry structures were constructed without mortar (dry joints). Examples include the famous Aqueduct in Segovia, Spain, and the Pont du Gard in France, the temples of the ancient Khmer Empire in Cambodia, the City of Great Zimbabwe in Africa and certain Medieval monasteries built in the south of Europe. Fig. 1 shows typical old masonry structures constructed with dry joints. Moreover, a number of historical and old constructions, originally built with mortar joints, have experienced significant loss of mortar due to chemical, physical and mechanical degradation. Examples include masonry arch bridges and other civil engineering structures currently in use such as tunnel linings and earth-retaining walls. In these cases, the masonry-unit to mortar-joint bond is disrupted by environmental erosion (e.g. weathering and/or the action of water leeching through the mortar joints over a prolonged period). Due to the partial or total disappearance of mortar, the behaviour of these constructions becomes similar to those made of dry-joint masonry. Research in the area of masonry constructions made of dry joints is therefore essential to understand their behaviour when exposed to external loading and assess their design in order to inform repair and/or strengthening decisions. The possibility of performing destructive tests on historical/old constructions, either in situ or by removing samples large enough to be representative, is usually impossible [23]. In addition, full-scale experimental tests are prohibitively expensive. Therefore, it is fundamentally important to have available computational tools to predict the in-service and near-collapse behaviour of such complex structures with sufficient reliability. Once such a tool has been established, a range of complex problems and scenarios can be investigated.

So far, research on numerical modelling of structural masonry has mostly investigated the characterization of mortared-joint masonry. A broad range of numerical methods is available today, ranging from the classical plastic solution methods [14] to the

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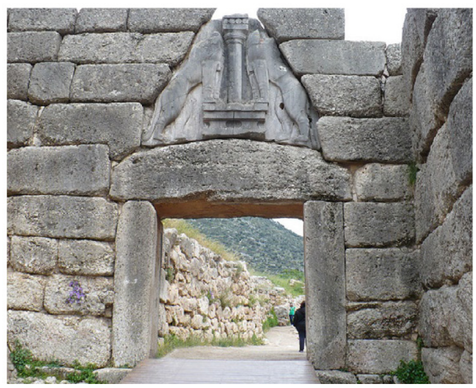
(a) Ancient Andean stoneworks in Machu Piccu, Peru

(b) Classical Inca architectural style of polished dry-stone walls of regular shape in Machu Piccu, Peru



(c) Ancient Greek stone masonry construction with dry joints in Mykenes, Greece

Fig. 1. Masonry structures constructed with dry masonry joints.

most advanced non-linear computational formulations (e.g. finite element and discrete element methods [DEM] of analysis) [25,35]. According to Lourenco [19–22], the strategies available for the numerical modelling of masonry structures would fall within one of two categories: (a) micro-scale and (b) macro-scale modelling. In macro-scale modelling, the masonry units and mortar joints smeared out into an averaged continuum. There are no distinctions between the units, the mortar and their interfaces. This model can be applied when the dimensions of a structure are large enough, compared to the constituent parts, so that a description involving average stresses and strains becomes acceptable [7]. Considerable computational time is saved by applying this method. However, unconditionally accurate results and the fine details of the behaviour cannot be captured by this type of approach. On the other hand, micro-scale modelling splits into the following two approaches: (a) simplified micro-modelling and (b) detailed micro-modelling. In the simplified micro-modelling approach, expanded units are modelled as continuous elements while the behaviour of the mortar joints and unit–mortar interface is lumped in discontinuous elements. In the detailed micro-modelling approach, both the masonry units and the mortar are discretized and modelled with continuous elements while the unit–mortar interface is represented by discontinuous elements accounting for potential crack or slip planes. Detailed micro-modelling is probably the most accurate tool available today to simulate the real behaviour of masonry given that the elastic and inelastic properties of both the units and the mortar can be realistically taken into account. In this method, a suitable constitutive law is introduced to reproduce not only the behaviour of the masonry units and mortar, but also their interaction. However, any analysis within this level of refinement requires substantial computational power. Therefore, this method is used mainly to simulate tests on small specimens to accurately determine the stress distribution in the masonry materials. The drawback of the substantial computational power required by detailed micro-modelling is partially overcome by the simplified micro-modelling strategy. In this case, each joint, consisting of mortar and the two unit–mortar interfaces, is lumped into an "average" interface while the units expand in size in order to keep the geometry unchanged. Within this approach, it is possible to consider masonry as a set of elastic blocks bonded together by potential fracture slip lines at the joints. The main methods available for modelling masonry structures using the simplified micro-modelling approach include: (a) the discontinuous finite element method and (b) the DEM. The material discontinuity introduced by the joints in dry-joint masonry constructions makes the use of interface elements an appropriate option to model such structures.

When modelling masonry using the discontinuous finite element method, discontinuities are introduced using interface elements, for which the constitutive model is in direct relation with the stress vector and the relative displacement vector along the interface [26]. Therefore, for an accurate simulation of masonry behaviour, it is essential to obtain a constitutive model for the interface elements which is able to capture the behaviour of masonry realistically and to simulate all the failure mechanisms. Page [28] first introduced masonry as a two-phase material composed of bricks and a zero-thickness interface. Bricks were represented as a linear elastic material and interfaces as inelastic, obeying the Mohr-Coulomb failure criterion. Lourenço [20] subsequently introduced a compressive cap to the failure surface in Page's model, allowing all possible failure modes. Although a micro-scale model needs more computational time, it can let many