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Finite element modelling of deformation characteristics of historical stone masonry shear walls

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ABSTRACT

Two dimensional nonlinear finite element analysis based on experimental test data has been carried out to model deformation characteristics, such as load–displacement envelope diagrams and failure modes of historical stone masonry shear walls subjected to combined axial compression and lateral shear loading. An experimental research work was carried out on three different types of historical stone masonry shear walls that can be considered representative of ancient stone masonry constructions. Those three types of masonry are: (i) sawn dry-stack or dry-stone masonry without bonding mortar, (ii) irregular stone masonry with bonding mortar, and (iii) rubble masonry with irregular bonding mortar thickness. Plasticity theory based micro modelling techniques has been used to carry out the analysis. The stone units were modelled using eight node continuum plane stress elements with full Gauss integration. The joints and unit-joint interfaces were modelled using a six node zero thickness line interface elements with Lobatto integration. This paper outlines the experimental research work, details of numerical modelling carried out and report the numerical lateral load–displacement diagrams and failure modes. The numerical analysis results were compared with the experimental test results and good agreement was found.

1. Introduction

Stone masonry is the most ancient, durable, and widespread building method devised by mankind. Stone structures built without mortar rely on the skill of the craftsmen and the forces of gravity and frictional resistance. Stone has been a successful building medium throughout the ages and around the world because of its unique range of benefits. The structures are remarkably durable and, if correctly designed, can be made earthquake resistant. They resist fire, water, and insect damage. The mason needs a minimum of tools; the work is easily repaired; the material is readily available and is recyclable. Dry stone masonry, aesthetically, complements and enhances the landscape. Archaeologists have determined that the Chinese built dry stone terraces at least 10 000 years ago. In Britain, ancient tribes built dry stone shelters just after the last ice age, 8000 years ago. High quality stone tools recently found in Europe are 2.2 million years old. The technique of dry stacking in construction has existed in Africa for thousands of years. The Egyptian pyramids and the Zimbabwe ruins, a capital of ancient Shona Kingdom around 400AD, are good examples. In addition to the neglect and destruction of historic structures, the craft is handicapped due to lack of technical information and skilled preservation personnel. Construction and engineering data that professionals need are scarce and, if recorded at all, are difficult to locate.

A large part of historical buildings are built with: (i) sawn dry-stack or dry-stone masonry without bonding mortar; (ii) irregular stone masonry with bonding mortar; (iii) rubble masonry with irregular bonding mortar thickness; (iv) a combination of the three techniques. When bonding mortar is used, it is usually low strength. In addition, masonry with mortar joints can experience a significant loss of mortar due to combined chemical, physical and mechanical degradation. Due to the partial or total disappearance of mortar, the behaviour of these constructions can then become similar to those made of dry joint masonry.

The primary function of masonry elements is to sustain a vertical gravity load. However, structural masonry elements are required to withstand combined shear, flexure and compressive stresses under earthquake or wind load combinations consisting of lateral as well as vertical loads. Only few experimental results are available on the behaviour of stone masonry walls, e.g. Chiostrini and Vignoli [1] addressed strength properties and Tomaževič [2] reported tests on strengthening and improvement of the seismic performance of stone masonry walls. More recently, Corradi et al. [3] carried out an experimental study on the strength properties of double-leaf roughly cut stone walls by means of in-situ diagonal compression and shear-compression tests.

A comprehensive experimental and numerical study on historical dry stone masonry walls has been reported by Lourenço et al. [4]. Displacement controlled experimental study for masonry walls under combined compression and shear loading was

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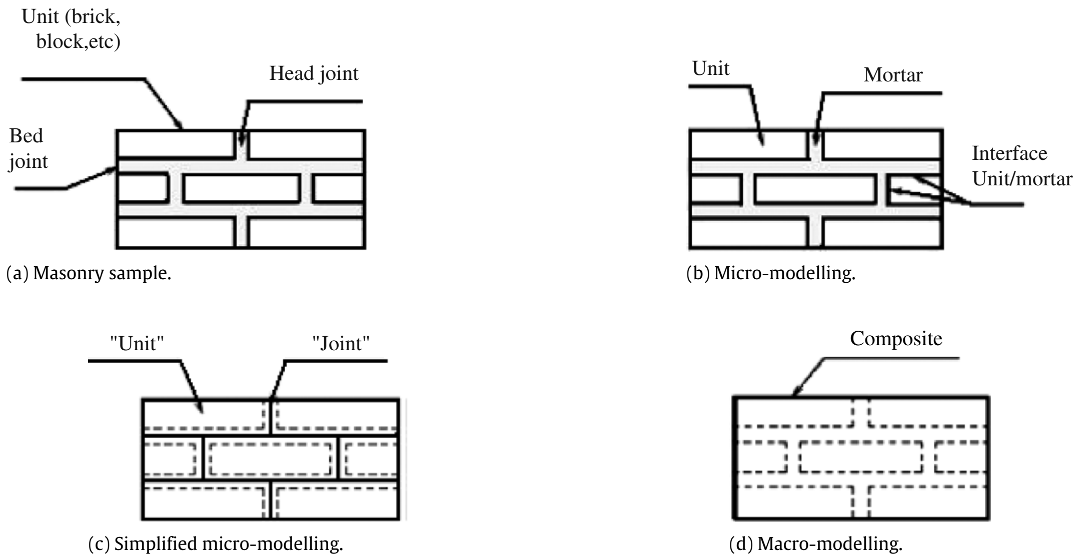

Fig. 1. Micro- and macro-modelling techniques.

done for monotonic loading. Based on the material properties obtained from the experimental tests, numerical analysis was carried out to model the monotonic load–displacement diagrams using non-linear finite elements. Similar numerical modelling using rigid blocks limit analysis and discrete element analysis has been carried out by Azevedo et al. [5] and Orduña and Lourenço [6]. However, these studies were limited to regular (sawn) dry stack mortarless stone masonry only. A detailed literature survey on numerical modelling of monuments and historical constructions including structure and component level are presented by Lourenço [7] and Lemos [8].

A research programme was carried out by Vasconcelos [9] at University of Minho to experimentally evaluate the in-plane seismic performance of ancient stone masonry without and with bonding mortar of low tensile strength to simulate existing ancient stone masonry structures. Monotonic and reversed cyclic loading tests with three different pre-compression loading (low, moderate and high) were performed to investigate the strength, deformation capacity, load–displacement hysteresis response, stiffness characterisation and failure modes. The data obtained from this experimental research has been used as a base for the present numerical analysis. The objective of the analysis carried out here was limited to modelling the peak load points of reversed cyclic hysteresis diagrams, or the so-called load–displacement envelope diagram, and failure modes of three different types of ancient stone masonry subjected to three different axial pre-compression loads.

Masonry is highly anisotropic due to the presence of discrete sets of horizontal and vertical mortar joints. Lourenço, Saadeghvaziri and Mehta, Papa [10–12] have divided models for masonry into two categories: micro and macro. Fig. 1 shows details of micro- and macro-modelling techniques. Fig. 1(b) shows a detailed micro-modelling where joints are represented by mortar continuum elements and discontinuum interface elements. Fig. 1(c) shows simplified micro-modelling where joints are represented by discontinuum elements. Fig. 1(d) shows macro-modelling where joints are smeared out in the continuum. In the micro-modelling techniques, it is possible to model the unit-mortar interface and mortar joint which is responsible for most cracking as well as slip. Young's modulus, Poisson's ratio, inelastic properties of both unit and mortar are taken into account in micro-modelling. The interface represents a potential crack/slip plane with dummy stiffness to avoid interpenetration of the continuum. Due to the zero

Table 1
Type of experimental test walls.

Stone masonry wall type	Description
Type I: Dry-stack sawn	Sawn stone assemblage without bonding mortar
Type II: Irregular	Irregular stone assemblage with bonding mortar
Type III: Rubble	Rubble stone assemblage with bonding mortar

thickness of the interface elements, the geometry of the unit has to be expanded to include the thickness of the joint. In the macro-modelling technique, mortar is smeared out in the interface element and in the unit.

In micro models, masonry units and mortar are separately discretised using continuum or discrete elements, whereas in the macro model (also known as equivalent material model), masonry is modelled as a single material using average properties of masonry. Page [13] made an attempt to use a micro-model for masonry structures assuming units as elastic continuum elements bonded with interface elements. Arya and Hegemier [14] proposed a von Mises strain softening model for compression with a tension cut-off for the units. Joints were modelled using interface elements with softening on both the cohesion and friction angle. The collapse load obtained from their model shows good agreement with experimental results from shear wall testing. Ghosh et al. [15] concluded that macro-modelling could predict the deformations satisfactorily at low stress levels and inadequately at higher stress levels when extensive stress redistribution occurs. Pande et al. [16] categorically stated that macro-modelling would not accurately predict the stress distribution within the units and mortar. In micro-modelling, two approaches are followed in finite element analyses. In the first, both the units and the mortar joints are discretised by using continuum finite elements, whereas in the second approach interface elements are used to model the behaviour of mortar joints. Several researchers [12,17,18] have reported that the interface elements used in heterogeneous models reproduce essentially the interaction between two adjoining masonry units, and further degrees of freedom are not required to be introduced.

For masonry walls subjected to either vertical load only or a combined shear and vertical loading, 2-D analyses are found effectively producing stress results that are close to those produced by 3-D analyses. Dhanasekar and Xiao [19] proposed a special 2D element and validated its results using a 3D model of masonry prisms. To determine the internal stress distribution