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Crack growth in masonry: Numerical analysis and sensitivity study for discrete and smeared crack modelling

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ABSTRACT

One of the most common obstacles faced by engineers when making numerical models to assess damage in historical masonry lies in defining the most suitable constitutive models when there is shortage of either material characterization or experimental data. This paper presents the implementation of a 2D finite element model (FEM) of a masonry wall by means of two strategies: a discrete cracking meso-model and a continuum smeared cracking macro-model. A sensitivity study is performed to investigate the effect of material properties variation on both modelling strategies, each of which considers the highly non-linear behaviour as well as the brittle cracking of the masonry.

The numerical models are validated through the results obtained from an experimental testing campaign which considered a brick masonry wall subjected to cyclic three-point bending. The results of both modelling strategies compared with experimental results are presented, as well as the criteria considered for material characterization and the sensitivity analysis. Results indicate the suitability of both models to reproduce experimentally observed load capacity, failure mechanism and horizontal deformations. However, the meso-model showed higher accuracy in terms of failure mechanism and plastic deformations. The sensitivity analysis indicated that some material parameters, such as fracture energy, cohesion and tensile strength, significantly govern the final cracking. This is an important criterion for adequately choosing the parameters for further models in which crack width is considered, e.g. for settlement-induced cracking analysis.

1. Introduction

This work investigates the mechanical behaviour of unreinforced brick masonry walls when subjected to differential settlements through discrete and smeared cracking numerical models.

Accumulation of differential settlements may induce various problems to masonry structures, from minor cracks and tilts to large displacements causing distortion or even collapse. Even if a building does not present structural damage, serviceability issues may emerge. Furthermore, differential settlements can increase vulnerability to natural hazards such as earthquakes or flooding [1]. Such settlements are triggered by different factors within building, local and regional scales, including non-uniform building loading, construction of local underground structures and widespread water pumping. To prevent damage propagation, damage levels must be estimated and the effects of settlements mitigated, if necessary. The aim of this paper is to critically analyse modelling strategies for cracking in unreinforced masonry walls under given boundary conditions and vertical loading.

Different analytical and numerical methods to determine settlement-induced building damage have been proposed [2]. One of the most known analytical methods to define the level of damage is the limiting tensile strain method (LTSM), proposed by Burland [3]. This method is based on the assumption that the initiation of visible cracking is related to a critical tensile strain, which lies between 0.05 and 0.1% for unreinforced brick masonry. However, the LTSM presents some drawbacks such as the assumption that the building behaves as a simple linear elastic beam presenting bending and shear deformation, which might be an inaccurate simplification for complex building geometries and brittle materials. On the other hand, numerical models using FEM to model settlement-induced damage have been widely investigated and implemented [2,4–9]. They are more suitable for complex geometries, describe the material behaviour more accurately by means of non-linear constitutive laws and allow taking into account the soil-structure interaction. Nevertheless, the use of 3D models might be computationally expensive [10] and calibration of model parameters is not straightforward.

This work aims to identify a suitable and accurate numerical modelling approach to quantify settlement-induced damage in unreinforced

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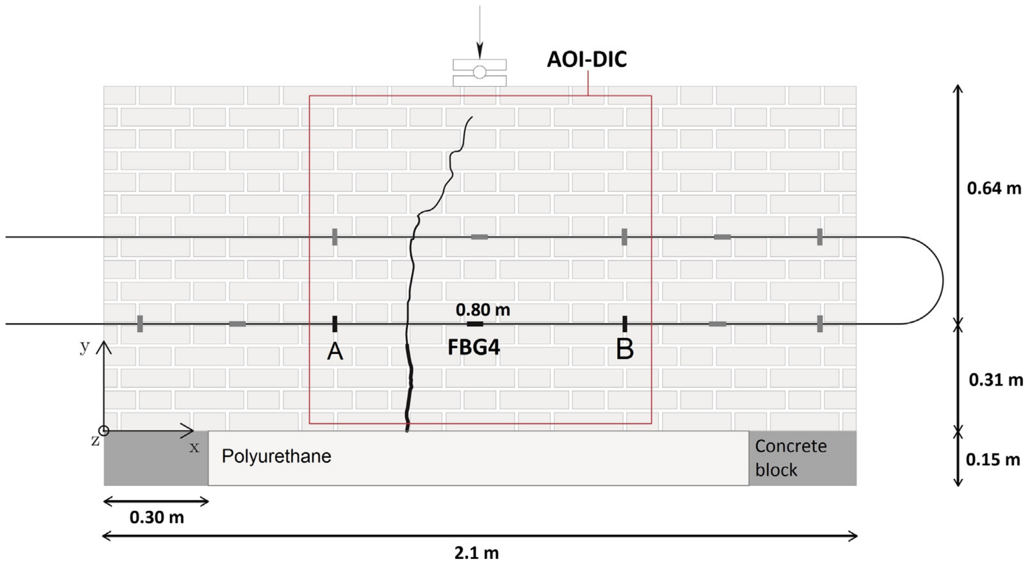

Fig. 1. Setup of three-point bending test, fibre Bragg grating sensor (FBG4) and area of interest of Digital Image Correlation (AOI-DIC), with indication of the major crack at the end of the test.

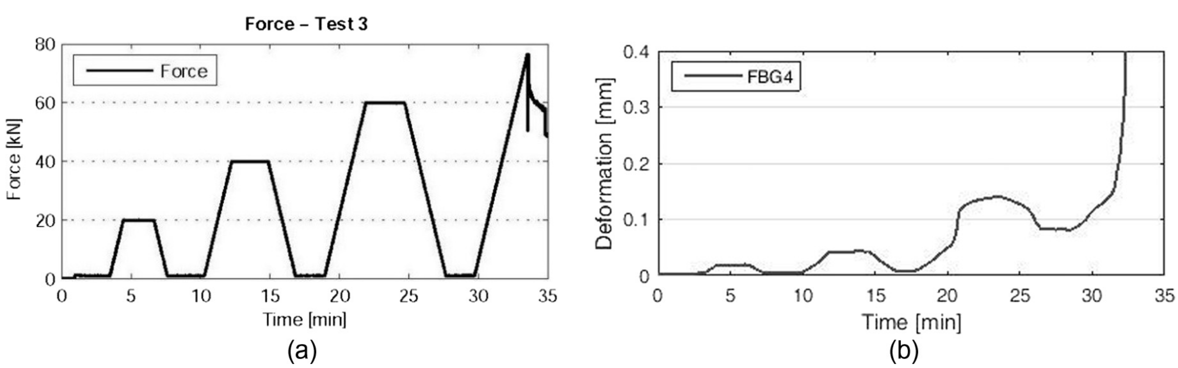

Fig. 2. Applied force (a) and horizontal deformation measured with FBG4 (b) during the cyclic three-point bending test.

masonry using discrete cracking and continuum smeared cracking models. Calibration procedures and sensitivity studies were performed to determine reference material property values and to analyse the effect of the variation of these properties on both modelling strategies, for which crack widths, load capacity and failure mechanisms were investigated. A methodology to obtain the material properties for the macro-model in terms of the properties of the meso-model was also elaborated and evaluated on experimental data.

2. Experimental input data

Experimental three-point bending tests were performed on a wall in order to induce cracking in a semi-controlled manner (the wall was not notched as the location of the crack was anticipated) and analyse the masonry non-linear behaviour. Damage progress during the cyclic loading was recorded by monitoring elastic deformations, crack width, deflection and acoustic emissions. To characterize the mechanical properties of the materials, mortar and brick samples as well as couplets were tested under compression and bending. Numerical models were built considering the obtained material properties and validated based on the monitoring results.

2.1. Test setup and monitoring

The tests were performed on a Flemish bond masonry wall of 16 courses in height (960 mm) and 1 unit in thickness (188 mm), as schematically shown in Fig. 1. The wall was made of solid clay bricks and 12 mm thick mortar joints, prepared width a hybrid cement-lime mortar. The area between the support points was filled with polyurethane plates to support the specimen's weight and simulate the existence of a compressible soil.

A more detail description of the test setup and monitoring techniques can be found in [10,11]. Three cyclic three-point bending tests were performed on the test wall. Each cyclic test consisted of several loading and unloading stages, with increasing peak force for subsequent loading cycles. However, only the monitoring results from the third test, where the failure occurred, are used here for the validation of the numerical models. During this test, a preload of 1 kN was applied after which the load was increased at a load rate of 0.333 kN/s until the peak loads of 20, 40 and 60 kN. Following each peak load, the load was decreased up to the selected preload (Fig. 2a). The wall failure, identified as an unstable growth of the large macro crack, occurred during the fourth cycle at a load of 76.4 kN. The flexural strength of the masonry member subjected to three-point bending may be calculated from the expression

$$f_{flex} = \frac{3FL}{2WH^2} \tag{1}$$

where F is the peal load, L is the length between supports, W is the cross section width of the sample and H is the height. Applying Expression (1) in the present case, a flexural strength of 1.19 N/mm^2 is obtained.

Results included the crack width measured by means of integrated optical fibres with distributed fibre Bragg grating sensors (FBGs), full-field vertical and horizontal displacement field obtained from stereo-vision digital image correlation (DIC) and vertical displacement at load application point measured with LVDTs.