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Detailed micro-modelling of the direct shear tests of brick masonry specimens: The role of dilatancy

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ABSTRACT

The mechanical parameters (shear strength of bed joints) derived from triplet tests can apparently be significantly different from those obtained through the so called “shove test” procedure executed on the same type of masonry. It was observed that this discrepancy may be caused by a wrong estimation of the compressive stress in the bed joints of the shove test. This article describes a numerical technique implemented in Abaqus to provide a sound interpretation of the phenomena involved in the failure of a mortar bed joint. The level of accuracy required to accomplish the objectives of the present study has driven the attention toward the detailed micro-modelling approach. Units and mortar joints have been modelled with continuum elements whereas the cohesive interfaces with zero thickness have been used for the unit-mortar interfaces. The material nonlinearities of masonry have been attributed to mortar and unit-mortar interfaces. The dilatancy of the bed joint during the shear failure process can generate, under certain boundary conditions, a local increase of the normal compression stress. Hence, particular attention has been dedicated to the modelling of this phenomenon. Several triplet tests and shove tests have been used as experimental benchmark for the numerical simulations. With the aim to accurately calibrate the parameter that controls the dilatancy, this work has paid attention also to the numerical-experimental comparison in terms of normal expansion of the joints, whereas commonly the comparison is generally carried out only in terms of shear stress-displacement curve. With the proposed technique, the triplet test and the shove test can be simulated with great accuracy. Thanks to these features, it has been also possible to relate the two types of test by highlighting the factors that affect the local normal stress during the shear failure process, providing a more detailed explanation of why and how the shove test results must be carefully interpreted in order to derive a realistic estimate of the shear strength of bed joints.

1. Introduction

Eurocode 6 [11] defines the characteristic shear strength of unreinforced masonry by means of Coulomb’s law. The triplet test EN 1052-3 [12–15] has been adopted as the standard laboratory test in Europe for the characterization of the initial shear strength under zero compressive load. An equivalent in-situ test to be used for existing structures is the so called “shove” test [5]. The comparison of strength parameters determined through laboratory-simulated shove tests with those obtained via triplet tests may result in significant differences [33,10,9]. It was observed that the discrepancies may be caused by the difficult estimation of the compressive stress acting on the mortar joints under investigation of the shove test (σ_j). In particular, the actual compressive stress induced by the flat-jacks on the tested bed joints is influenced by the removal of the adjacent units. The normal stress σ_j may include a non-negligible contribution coming from far-field boundary conditions, such as those due to pre-existing overburden loads generating stresses on the surrounding masonry.

In addition to this, the direct shear test of masonry samples is often accompanied by volumetric expansion. This mechanism, known as dilatancy, has already been identified for masonry by various researchers (e.g. [6,42,37,38,39,40,46,26,28,30,29]). This article dedicates particular attention to this phenomenon because the partial constraint imposed on dilatancy of a bed joint by the surrounding masonry, may increase the amount of the compression in the tested bed joints ([22]). A correct comparison between the triplet test and the shove test implies the definition of a reliable value of σ_j, since the shear strength of a joint is affected by the normal stress. This article describes a numerical technique that can be used to understand the factors that affect the value of σ_j in the shove test. The validation of the model required both

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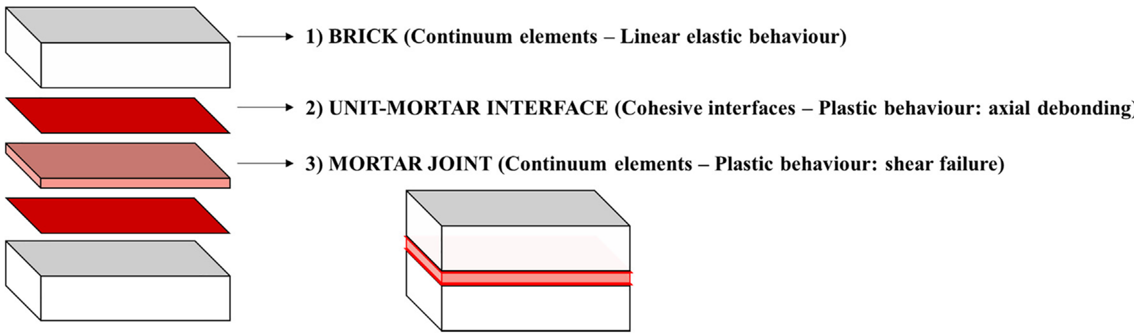

Fig. 1. Scheme of the detailed micro-modelling approach used in this study to simulate the direct shear test of masonry samples.

experimental and numerical research. The experimental benchmark for the numerical simulations is represented by several laboratory tests.

The main modelling strategies for masonry are summarized in three main groups, listed in descending order of refinement (e.g. [42] and [25]):

- *Detailed micro-modelling* (three-phase material). Units, mortar and unit-mortar interfaces are explicitly modelled (e.g. [19,2,24]).
- *Simplified micro-modelling* (two-phase material). Expanded units are represented by continuum elements whereas the behaviour of the mortar joints and unit-mortar interfaces are lumped in discontinuous elements that act as interfaces with zero thickness (e.g. [43,3,17,31,32,41,7]).
- *Macro-modelling* (one-phase material). Units, mortar and unit-mortar interfaces are smeared out in a homogeneous continuum (e.g. [35,23,36]).

The detailed micro-modelling approach provides a great accuracy of the results but the computational burden limits the size of the numerical models. The simplified micro-modelling and the macro modelling are usually preferred because they allow the structural analysis of larger models. In this study, the detailed micro-modelling seemed to be the most suitable to better capture the phenomena associated to dilatancy, hence units and mortar joints are modelled with continuum elements and the cohesive interfaces with zero thickness are used for the unit-mortar interfaces (see Fig. 1). For each phase of the masonry a different constitutive law has been selected. The material nonlinearities of masonry have been attributed to mortar and unit-mortar interfaces. Bricks have been modelled as a linear elastic material (this assumption is justified further on).

The choice of the constitutive model for mortar joints deserves a detailed discussion because this phase of masonry is responsible for the dilatancy mechanism. An example of the importance of this phenomenon in modelling the behaviour of masonry is shown in Zijl [47] and Spada et al. [43]. Dilatancy is rather well framed in the study of rock mechanics (e.g. [34,20]) and geotechnical engineering (e.g. [45,8]). However, the study of the relationships between dilatancy angle, shear strength and the local increase in compression has received relatively little attention in masonry (e.g. [6,28,40,46,47,41]). It will be shown that the numerical technique proposed in this article is able to model dilatancy in bed joints in such a way that allows to capture its interaction with the compressive stress in bed joints in experimental tests.

In numerical simulations, the mechanical parameters that control the dilatancy of masonry are generally defined without calibration of the numerical expansion with experimental data (e.g. [19,17,41,7]). The mechanical parameters are generally calibrated using the shear stress-displacement curve as the only experimental reference (e.g. [43,31,41]). The comparison in terms of expansion of the specimen, which gives the possibility to calibrate the parameters that control the dilatancy (e.g. dilatancy angle), is typically neglected. This article proposes the procedure for the calibration of the dilatancy angle with experimental data.

The modelling technique proposed in this article has been used to simulate the experimental results of several triplet tests and shove tests carried out on calcium silicate masonry samples. The numerical model has been implemented in Abaqus ver. 6.13. The constitutive laws used for units, mortar and unit-mortar interfaces are characterized by relatively few parameters. Each parameter has a clear physical meaning and the input values can be inferred from standard experimental tests. To simulate dilatancy with the accuracy required by this study, the standard *Mohr-Coulomb Plasticity* model available in Abaqus is not adequate, hence a new user-defined routine (i.e. *Modified Mohr-Coulomb Plasticity* in Appendix A) has been implemented allowing the possibility to use as input data the experimental relation among the dilatancy angle, the shear displacement and the compression stress, and allowing a more efficient calibration of the parameters.

2. Material nonlinearities

The aim of the proposed numerical technique is to accurately simulate the direct shear test of masonry samples. In this model, the nonlinear behaviour of masonry is governed by the mortar joints and the unit-mortar interfaces. Units have been modelled as a linear elastic material. The inability to predict damages in brick is a model limitation justified by the fact that this phase of the material does not show damage in the experimental tests of this study. More in general, the direct shear test serves to characterize the mechanical parameters of the mortar joints and the executions with the failure of the bricks should be disregarded (e.g. EN 1052-3).

Unit-mortar interfaces have been modelled with cohesive interfaces with zero thickness, governed by the standard traction-separation law with damage initiation and softening. The shear failure has been attributed exclusively to the continuum elements used to model the mortar joints.

2.1. Nonlinear model for mortar joints

The nonlinear behaviour of the mortar joints is modelled with the "*Modified Mohr-Coulomb Plasticity*" constitutive law. The standard version of the model present in Abaqus ver. 6.13 ("*Mohr-Coulomb Plasticity"*) gives the possibility to simulate dilatancy with a constant value of dilatancy angle. This approach is not suitable for the objectives of the present study because it results in unlimited expansion of the specimens. Experimental data show that dilatancy decrease with shear