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# Nonlinear micromechanical model for tuff stone masonry: Experimental validation and performance limit states

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## HIGHLIGHTS

- A micromechanical finite element model of tuff stone masonry is proposed.
- The accuracy and robustness of the micromechanical model were assessed.
- Axial and diagonal compression tests in displacement control were simulated.
- Local limit states were related to overall response and statistically characterised.
- Sensitivity analysis and Monte Carlo simulations were carried out.

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## ABSTRACT

In last decades, several computational strategies have been proposed for masonry structures, which form a large fraction of worldwide built heritage. In this study, a micromechanical model is proposed for tuff stone masonry by assuming a periodic composite with two components, namely tuff stones and mortar. A pressure-dependent failure rule was assigned to each component and mechanical properties were assigned according to material test results. The accuracy and robustness of the micromechanical model were assessed by simulating nonlinear response and crack patterns of masonry in different geometrical, boundary and loading conditions related to axial and diagonal compression tests. A satisfactory numerical-experimental comparison was found. Sensitivity to tensile and compressive strengths of masonry components was evaluated. Local limit states were associated with the overall nonlinear response of masonry and were statistically characterised for performance-based assessment. Finally, Monte Carlo simulations were performed to assess the influence of masonry inhomogeneity on experimental test simulations.

## 1. Introduction

Masonry is one of the oldest construction materials worldwide and is still used either in traditional or new forms to build up several kinds of structures, such as buildings and earth retaining walls. A number of masonry components can be detected in buildings, such as load-bearing or partition walls, arches, vaults, domes, and also infill walls in framed structures. From a mechanical viewpoint, most of masonry assemblages can be assumed to be two-component composite materials made of masonry units (i.e. stones, bricks or blocks) and mortar/dry joints.

Several computational strategies are currently available in literature to simulate the mechanical behaviour of masonry structures, but experimental data are needed to assess the accuracy of numerical and analytical models [1]. The influence of different mechanical properties of masonry constituents and their complex interaction can be comprehensively investigated through a micromechanical modelling of the composite material [2–4]. Indeed, the micromechanical approach allows one to simulate the nonlinear response of a masonry component or system to any loading process, given a set of boundary conditions. In a micromechanical model, masonry units and joints are distinctly modelled as materials with different geometry and mechanical properties to be defined through appropriate laboratory tests. In some cases, micromechanical modelling may explicitly account for unit-mortar interfaces [3,5] which are modelled through interface elements and act as planes of potential crack, slip and crushing. Micromechanical modelling was applied in several research studies to a number of masonry types such as clay brick masonry [6–10], adobe brick masonry [11–14], and tuff stone masonry [15,16]. In this context, a remarkable problem is how to simulate

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micromechanical response of masonry to different loads, from quasi-static to impulsive conditions. This can be of special interest in a number of situations such as impact loading of vehicles, bomb explosions, and domestic gas deflagrations. Other FE modelling strategies are based on a macro-modelling approach where masonry is treated as an equivalent continuum medium with average mechanical response derived from that of single constituents through linear or nonlinear homogenisation [17]. In that case, the homogenisation procedure establishes a relationship between local behaviour of a masonry unit or mortar joint and overall behaviour of a representative volume element (RVE). Nonetheless, the reliability of the homogenised masonry material model and scale effect of the RVE should be accurately verified in order to produce realistic predictions of mechanical response.

In this study, a micromechanical finite element (FE) model is proposed and experimentally calibrated for tuff stone masonry, which is a common construction material in many countries of the Euro-Mediterranean area. Tuff stone masonry is herein considered as a running bond masonry composed of tuff stone bricks and mortar joints. The FE model was developed within LS-DYNA computer program [18] to predict the nonlinear response of tuff stone masonry to static, dynamic and impulsive loads. That software was used by other researchers to assess nonlinear response of clay brick masonry walls under earthquake actions [19] and concrete masonry walls under blast loading [20–24]. Numerical simulations of tuff stone masonry specimens subjected to different boundary conditions and load patterns are presented herein to show the ability of the micromechanical FE model to reproduce the experimental behaviour and observed damage.

## 2. Methodology

The main objective of this paper was to develop and validate a micromechanical FE model for tuff stone masonry through an explicit FE software able to perform nonlinear analysis of structures, either in static or dynamic conditions. Micromechanical modelling was performed by properly defining material properties and volumetric stress–strain behaviour of constituents via laboratory test results on tuff stones and mortar. The numerical model was then experimentally validated by simulating the experimental behaviour of different specimens subjected to axial compression [25] and diagonal compression [26]. Those specimens were different each other in terms of size, boundary conditions, and load patterns. The scope of those simulations was to assess the numerical robustness of the FE micromodel. Numerical-experimental comparisons were carried out in terms of force–displacement diagrams and crack patterns.

Secondly, a number of limit states associated with different failure modes of masonry constituents were statistically characterised for each load pattern. In that way, establishing a relationship between local limit states of masonry and observed damage plays a key role in performance-based assessment of structures, where response analysis under a given hazardous event is followed by damage analysis to predict not only structural performance but also repair/replacement costs.

Finally, the influence of material properties was assessed by two alternative procedures. That investigation was first based on a sensitivity analysis where material properties were changed according to statistical variability provided by experimental tests. Afterwards, a stochastic FE analysis was carried out by simulating uncertainty in material properties according to discrete and continuous probability models. That procedure accounted for the actual inhomogeneity of tuff stone masonry. Key masonry properties such as peak resistance and ultimate displacement were statistically characterised, evaluating the propagation of uncertainties from constituent level to masonry level. Other uncertainty sources related to geometry and capacity model were not modelled because of the lack of data in the case of tuff stone masonry. The characterisation of uncertainty in the macromechanical behaviour of masonry may be useful for probabilistic FE simulations and structural safety evaluations.

## 3. Micromechanical finite element modelling and simulation

Micromechanical FE modelling of tuff stone masonry was carried out by using solid elements for both tuff stones and mortar joints. Unit-mortar interface was not modelled according to past numerical investigations performed on full-scale wall specimens subjected to in-plane lateral loading tests [15,16]. In those studies, the influence of unit-mortar interfaces on the overall behaviour of tuff stone masonry walls was found to be negligible. Different effects may be detected in other masonry assemblages such as clay brick masonry, where bricks and mortar have more distinct properties and hence a detailed modelling of unit-mortar interfaces may be needed.

### *3.1. Material model for masonry constituents*

A material model developed by Krieg [27], which is named 'soil and foam' in LS-DYNA [18], was assigned to tuff stones and mortar joints of masonry. That material model is generally used for crushable foams and geomaterials such as rock, soil, and concrete, whose compressibility is relatively high, yield strength depends on the mean stress, and tensile strength is significantly smaller than compressive strength. The soil and foam material model was also applied to masonry (see e.g. [20–24], [28] and [29]), showing successful results compared to other material models available in LS-DYNA [20]. It is also emphasised that this material model has a considerable amount of user experience and needs few input data to characterise mechanical behaviour. Material self-weight is defined in terms of density. Elastic response of material is assumed to be linear and is defined by means of Young's modulus and Poisson's ratio. The yield criterion of the soil and foam model is based on Drucker–Prager strength theory. In detail, the plasticity theory developed by Krieg has a yield surface which is a parabola of revolution about the hydrostatic axis with a planar cap in tension (Fig. 1). The yield function can be defined as follows:

$$F(p, \sigma_e) = \sigma_e - \sqrt{3(a_0 + a_1 p + a_2 p^2)} \tag{1}$$

where $\sigma_e$ is the Von Mises stress, $a_0$, $a_1$, $a_2$ are yield function constants of the material, and $p$ is the hydrostatic pressure. Let $I_1$ and $J_2$ denote the first invariant of the stress tensor and second invariant of the deviatoric stress tensor, which measures shear stresses. As $\sigma_e = \sqrt{3J_2}$, the yield condition can be written as follows:

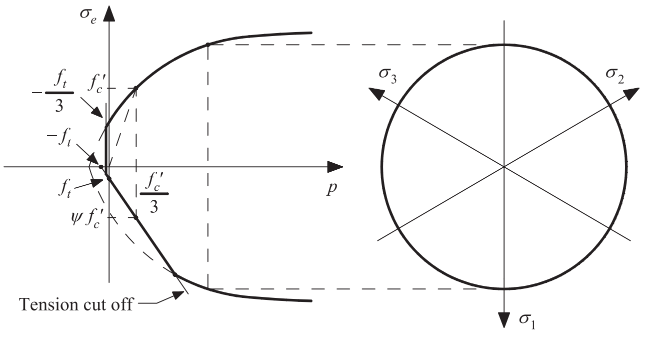

**Fig. 1.** Yield surface of soil and foam material model.