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Implementation and validation of a strain rate dependent anisotropic continuum model for masonry

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ABSTRACT

A newly developed strain rate dependent anisotropic continuum model is proposed for impact and blast applications in masonry. The model presented adopts the conventional approach of considering different yield criteria in tension and compression. The analysis of unreinforced block work masonry walls subjected to impact was performed to evaluate model performance. Comparison of the numerical predictions and test data revealed good agreement. Next, a parametric study was conducted to evaluate the influence of the tensile strengths in the three orthogonal directions and of the wall thickness on the global behavior of masonry walls.

1. Introduction

Masonry is composed of individual units laid in and bonded with mortar at bed and head joints and has been widely used in different forms of construction and several parts of modern or historical structures. Due to the weak seismic performance of masonry structures, in recent decades, numerous investigations have been conducted to improve the dynamic response of such structures. Moreover, after the Oklahoma City bombing in 1995, studies dealing with the blast response of structures received increasing interest by the scientific community given the high vulnerability of masonry structures against such destructive loads. A great deal of effort accounting for experiments and numerical simulations has been spent to provide a better understanding of masonry subjected to high strain rate loads, to advance retrofitting techniques and to update available design codes. An important objective was to reduce structural damage and to enhance the blast resistance of existing structures.

Recently, evaluation of the performance and blast response of masonry walls, including the maximum deflection, possible crack distribution and mechanisms of collapse, and damage level has been addressed by different authors. Baylot et al. [1] reported the dominant failure modes of unreinforced concrete masonry unit walls (CMU walls) subjected to blast loading. Failure in the mortar joints at mid-height over the entire length led to wall rotation at the bottom edge, and the occurrence of diagonal cracking and vertical cracks at the centerline to each side was noted. Bond failure at the mortar joint and overturning at mid-height were also reported in the study by Dennis et al. [2], as mechanisms of collapse of CMU walls. Eamon et al. [3] classified the blast response of CMU walls into three groups based on the magnitude, and range of pressure. Under moderate and high pressure loads, the entire wall was broken along one or two horizontal lines and was divided into two or three parts, whereas in the case of low pressure loads, the wall was broken with a long crack at mid-height, but no remarkable rotation was noticed. Gilbert et al. [4] also categorized crack formation of unreinforced masonry walls subjected to lower velocity impacts into two categories based on the time of formation.

Although high strain rate effects on structures are generally ignored in design standards, several tests have been carried out to study retrofitting techniques to improve masonry walls' performance and blast behavior. Baylot et al. [1] studied the effect of such retrofits including attaching FRP to the back of the wall, applying sprayed-on polyurea on the back of wall, and placing a sheet of steel behind the wall to improve the blast response of CMU walls. In spite of the acceptable performance of the adopted retrofitting methods, improvements were also proposed to make their application more practical. Myers et al. [5] carried out a series of tests on retrofitted masonry walls with GFRP rods and wide

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GFRP strips subjected to increasing intensity blast tests. The treatment resulted in reduction of debris scatter and at least a 50% increase in peak pressure resistance. The application of sprayed-on polymer retrofit for strengthening masonry walls against blast loads was also studied by Davidson et al. [6]. The method showed promising performance for low and moderate detonation.

Computers enable the description of the dynamic response and localized damage of masonry structures more in detail through numerical simulations. Two common strategies, namely macro strategy and micro strategy, have been used for numerical modeling of masonry, see e.g. Lourenço [7]. Each strategy has its own advantages and disadvantages with respect to accuracy, reliability, computational costs, better understanding of local behavior, and user-friendly mesh generation. The micro approach represents more accurately the behavior of masonry with detailed failure mechanisms of the components, while in a macro approach the global behavior of the structure is usually of concern.

Several studies have been dedicated to introduce the most applied parameters in recent sensitivity studies, and to address their effectiveness on the high strain rate behavior of masonry walls. In an investigation by Milani et al. [8] for blast analysis of enclosure masonry walls, a parametric analysis was carried out to evaluate the effect of different wall thicknesses, mortar joint tensile strengths, and dynamic pressures corresponding to blast loads (in kilograms of TNT), ranging from small to large. As expected, the maximum displacement decreases considerably, when high-strength mortar, thicker walls or lower blast pressure are adopted. Similarly, Eamon [9], performed a parametric study for CMU walls and developed a chart to detect parameters governing wall behavior at three different significant hazard levels.

The present study was aimed at developing a rate dependent anisotropic continuum model for numerical simulation of the high strain rate response of masonry walls, using finite element analysis (FEA). The analysis was performed using ABAQUS commercial software. The developed 3D material model benefits from the idea of combining a Rankine type yield criterion in tension and a Hill type yield criterion in compression, including three surfaces for tension and one ellipsoid shaped surface for compression. The continuum model developed as a user-defined subroutine, was implemented into ABAQUS and assigned to 3D solid elements to simulate the masonry behavior. The macro approach was involved in numerical modeling of the masonry walls. The results obtained were compared with test data to evaluate the accuracy of the proposed material model to numerically predict the structural damage and the response of masonry walls subjected to high strain rate loads. Furthermore, a parametric study was conducted to discuss the influence of the dominant parameters on the global behavior of masonry walls.

2. An anisotropic continuum model for high strain rates

Recently, several studies have been conducted to develop high strain rate constitutive models for several materials, including masonry. Wei and Stewart [10] proposed a damage dependent piecewise Drucker–Prager strength criterion for continuum modeling of brick and mortar, used in a micro-model to simulate the blast response of masonry walls. A simple rigid-perfectly plastic homogenization masonry model, characterized by a few material parameters and numerically inexpensive and robust, was presented by Milani et al. [11]. The material model was adopted for micro numerical simulation of masonry structures subjected to out-of plane high strain rate loads. The proposed model was implemented in a finite element thin plate triangular element.

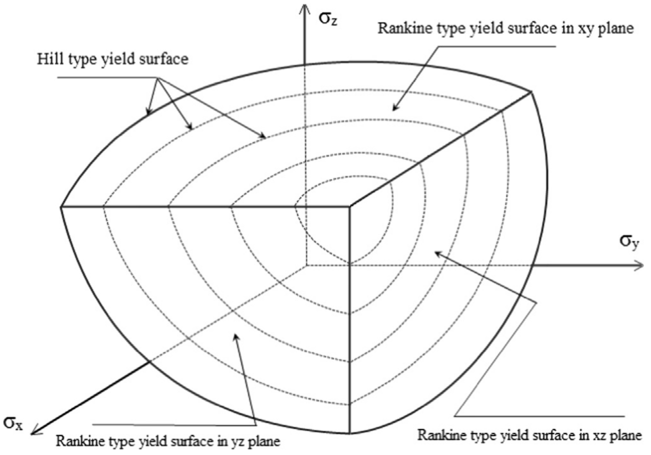

Fig. 1. Proposed composite yield surface with different strength values for tension and compression along each material axis.

This study presents a plastic stain rate dependent continuum model, which obeys a non-associated flow rule to characterize the masonry behavior at high strain rates. The newly developed model benefits from a powerful representation of anisotropic material behavior (i.e. different hardening/softening behavior is defined along each material axis) and follows the previous approach of making a composite yield surface considering individual inelastic criteria in tension and compression to model the orthotropic material behavior, see Lourenço [7] for a review. The proposed model is composed of three Rankine type yield criteria in tension, using pairs of normal and shear stresses, and a Hill type yield criterion in compression, see Fig. 1. The formulation is presented in the 3D stress space, with six stress components. For a 3D configuration, the stress vector, strain vector, and the compliance matrix are given as

$$\sigma = \left\{\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{yz}, \tau_{xz}\right\}^T \tag{1}$$

$$\varepsilon = \left\{\varepsilon_x, \varepsilon_y, \varepsilon_z, \gamma_{xy}, \gamma_{yz}, \gamma_{xz}\right\}^T \tag{2}$$

$$C = D^{-1} = \begin{bmatrix} \frac{1}{E_x} & \frac{-\upsilon_{xy}}{E_y} & \frac{-\upsilon_{zx}}{E_z} & 0 & 0 & 0 \\ & \frac{1}{E_y} & \frac{-\upsilon_{zy}}{E_z} & 0 & 0 & 0 \\ & & \frac{1}{E_z} & 0 & 0 & 0 \\ & & & \frac{1}{2G_{xy}} & 0 & 0 \\ & Sym. & & & \frac{1}{2G_{yz}} & 0 \\ & & & & & \frac{1}{2G_{xz}} \end{bmatrix} \tag{3}$$

where σ is the stress vector and ε is the strain vector. C denotes the compliance matrix and D is the symmetric orthotropic elasticity matrix. For an orthotropic material, the three symmetric planes namely xy, yz, and xz include nine independent elastic moduli. E_i and G_{jk} (i=x, y or z and jk=xy, yz or xz) are the three Young's moduli and three shear moduli, respectively, and υ_{jk} are the three Poisson's ratios.

2.1. Tensile mode

The dynamic increase factors (DIFs) are defined as the ratio of dynamic to static parameter values. Due to the high strain effects on the continuum material model, DIFs are applied to the most likely dominant material parameters to expand/contract the failure envelope at different strain rates. The orthotropic Rankine type yield criteria for tension in xy, yz, and xz symmetric planes, labeled now as i=1, 2, and 3 respectively, are introduced in terms of $k_{t,\mathrm{i}}$, stress components, and α_i. The parameter k_t is a scalar to control the composite yield surface by measuring the amount of softening