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Dynamic interface model for masonry walls subjected to high strain rate out-of-plane loads

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ABSTRACT

The present study proposes a dynamic constitutive material interface model that includes non-associated flow rule and high strain rate effects, implemented in the finite element code ABAQUS as a user subroutine. First, the model capability is validated with numerical simulations of unreinforced block work masonry walls subjected to low velocity impact. The results obtained are compared with field test data and good agreement is found. Subsequently, a comprehensive parametric analysis is accomplished with different joint tensile strengths and cohesion, and wall thickness to evaluate the effect of the parameter variations on the impact response of masonry walls.

1. Introduction

Masonry is a highly durable form of construction, widely used to build load bearing and partition walls in modern structures. Masonry is also used in many historical buildings and monumental structures. Until Oklahoma City bombing in 1995, studies dealing with the blast behavior of structures were a field of limited interest in the civil engineering community. After this terrorist incident, a great deal of effort has been done to devise solutions to reduce destructive damages and casualties due to such devastative loads. Beyond doubt, masonry structures are usually vulnerable to explosive blast loads. In this regard, conducting experiments and validating numerical models with field test data leads to a better understanding of the blast response of masonry walls and the relevance of the different masonry material properties, which, consequently, results in innovation of strengthening techniques and of assessment and design methods.

A series of experimental studies in masonry panels and structures has been carried out to report their blast response, including maximum deflection and failure mechanisms of collapse, and to evaluate their performance. Varma et al. [1] provided the maximum deflection, the damage level, the reflected pressure, and the reflected impulse of 27 full scale tests with different thickness on brick panels subjected to blast loading. Evaluation of structural masonry damage and fragmentation of non-retrofitted masonry walls has also been of interest in a number of studies. The formation of cracks in horizontal mortar joints, and bond failure at the joint with overturning about mid-height were reported as most likely dominant failure mechanisms of unreinforced masonry walls with concrete masonry units (CMU) by Baylot et al. [2] and Dennis, Baylot, and Woodson [3], respectively. The crack patterns of unreinforced masonry walls were classified into two groups based on the time of formation in Gilbert, Hobbs, and Molyneaux [4]. These walls were subjected to low velocity impacts. Eamon, Baylot, and O'Daniel [5] classified the CMU wall behavior against blast loads into three categories, using different ranges of pressure magnitude namely high, moderate and low.

It is noted that the majority of existing structures were not designed with blast loading in mind. Hence, despite the large costs usually involved in laboratory tests, various retrofitting techniques have been evaluated to find effective techniques to improve the blast resistance of existing structures, aiming at the reduction of casualties and losses. Baylot et al. [2] adopted three different retrofitting methods, namely bonding FRP, applying sprayed-on polyurea and placing a sheet of steel on the back of the wall, to improve the blast response of CMU walls. Muszynski and Purcell [6]

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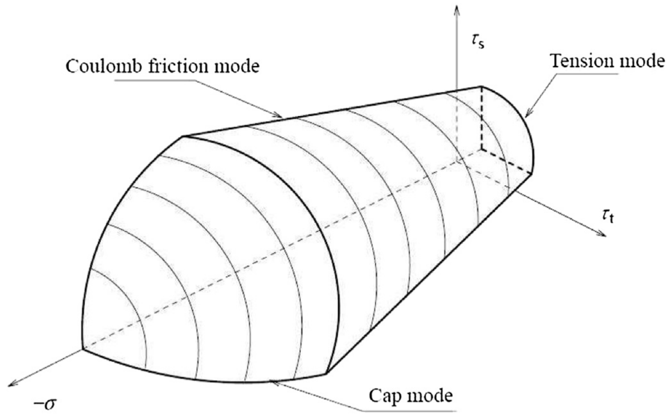

Fig. 1. 3D Failure envelope of the interface cap model [8].

carried out tests on retrofitted concrete masonry walls with CFRP, technique which led to a remarkable reduction in displacement. Davidson et al. [7] reported also the application of a sprayed-on polymer retrofit for strengthening masonry walls against blast loads.

Due to the costs of laboratory tests, it is impossible to carry out a large number of tests. This would allow obtaining a comprehensive field test database, including most likely responses. Currently, given the development of computer technology, it is easy to have more detailed and accurate predictions, including dynamic response and localized damage through numerical simulations. Two common strategies have been developed for numerical simulation of masonry in the literature, namely micro strategy and macro strategy, see e.g. Lourenço [8]. Using the micro approach, a more accurate representation of the behavior of a masonry structure is usually obtained with detailed failure mechanisms of the components, while, in a macro approach, the global behavior of the structures is usually of more concern. Within, the macro approach, homogenization techniques incorporate the geometry at micro-level and became rather popular in the last decades, see Lourenço et al. [9] for a review. Depending upon the required accuracy, reliability, availability and computational costs, one of the approaches can be selected.

Recently, a numbers of investigations have been performed to identify and determine relevant parameters for blast response of masonry walls. A parametric study was conducted by Wei and Stewart [10] to study the influence of mortar and brick strength, boundary conditions and wall thickness on response of the wall. As expected, increasing the mortar or brick strength decreases the maximum deflection of the wall. Also, an increase in the number of the fixed edges or wall thickness causes a reduction in the maximum deflection of the wall. A sensitivity analysis for CMU walls was considered in a study by Eamon [11]. Here, a chart was presented to identify variables significantly affecting the wall behavior at three different hazard levels.

In present paper, a newly developed dynamic interface model accounting for strain rate effects is proposed for numerical simulations of the structural response of masonry walls subjected to low velocity impact using the finite element (FE) code ABAQUS. The rate-dependent failure envelop is divided into three parts, namely tension mode, coulomb friction mode, and compressive cap mode on the basis of the corresponding failure mechanisms. After implementing the material model into ABAQUS as a user subroutine, a micro approach is used for numerical modeling of masonry walls. The developed model is attributed to interface elements to simulate the mortar behavior between two boundaries. A comparison between numerical results and field test data obtained by Gilbert et al. [4] is performed to evaluate the performance of the proposed material model and the accuracy of the simulation in predicting the impact response and damage of masonry walls. Finally, a parametric study is carried out to discuss the effectiveness of the main parameters changes on the global behavior of masonry walls.

2. A plastic interface model for high strain rates

In recent years, a number of investigations has been conducted to evaluate the high strain rates effects and to derive constitutive models for different materials subjected to high strain rate loading. A plastic damage material model was utilized to characterize the brick and mortar behavior in micro numerical simulation of blast response of unreinforced walls by Wei and Stewart [10]. The damage dependent piecewise Drucker-Prager strength criterion was involved for continuum modeling of brick and mortar. No interface behavior was considered in the analysis. A simple rigid-perfectly plastic homogenization masonry model was developed by Milani, Lourenço, and Tralli [12] for micro numerical simulation of masonry structures subjected to out-of plane high strain rate loads. The proposed model is characterized by a low number of input material parameters, and also by being numerically inexpensive and robust. The aforementioned model was assigned to an FE thin plate triangular element. A Drucker-Prager with a cap failure criterion was adopted for bricks and joints sub-domains, and a Mohr-Coulomb failure criterion with compressive linearized cap and tension cut-off was utilized for bricks–joints interfaces. For the macro numerical prediction of blast response and damage of masonry panels, Wei and Hao [13] introduced a continuum damage model with strain rate effects based on homogenization techniques. The proposed failure envelop can be defined at different strain rate levels and is divided into four parts. A compressive cap was considered due to masonry failure under tri-axial compression.

In the present study, a rate dependent interface model is introduced to characterize the mortar behavior. Depending upon the main failure mechanisms of masonry walls, the failure envelop is divided into three parts namely, tension cut-off, Coulomb friction, and elliptical cap, see Fig. 1. Hence, each part has its own failure criterion presented in terms of k, where the k parameter is a scalar involved to measure the amount of softening and hardening in order to control the yield surface, and in terms of the stress $\boldsymbol{\sigma}$. For a 3D configuration, $\boldsymbol{\sigma} = \{\sigma,\tau_s,\tau_t\}^T$, $D = diag\{k_n,k_s,k_t\}$ and $\varepsilon = \{\Delta u_n,\Delta u_s,\Delta u_t\}^T$. The subscripts n, s, t denote the normal and two perpendicular shear components.

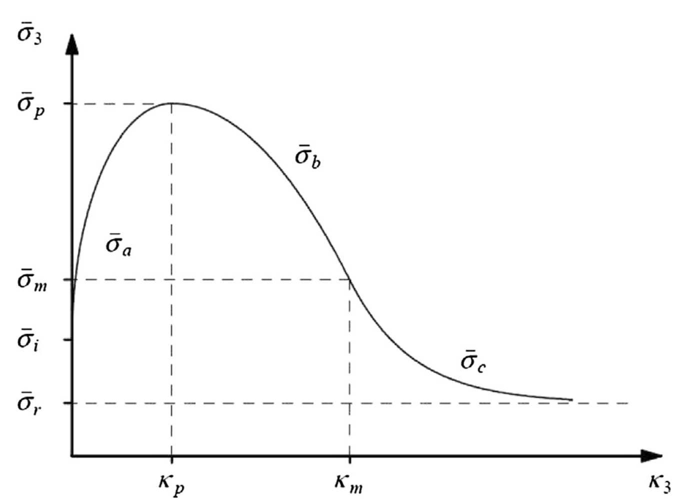

Fig. 2. Hardening/softening law for cap mode [8].