Engineering Structures 80 (2014) 40–52

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Plasticity based approach for failure modelling of unreinforced masonry

Nitin Kumar [a], Amirtham Rajagopal [a,*], Manoj Pandey [b]

[a] Department of Civil Engineering, Indian Institute of Technology Hyderabad, Andhra Pradesh, India
[b] Department of Mechanical Engineering, Indian Institute of Technology Madras, Tamil Nadu, India

ARTICLE INFO

Article history:
Received 30 May 2013
Revised 7 August 2014
Accepted 12 August 2014
Available online 15 September 2014

Keywords:
Masonry modelling
Plasticity
Composite interface model
Failure criteria

ABSTRACT

In this work, a plasticity based composite interface model is proposed for failure analysis of unreinforced masonry. The hyperbolic composite interface model consists of a single surface yield criterion, which is a direct extension of Mohr-Coulomb criteria with cut in tension region and a cap in compression region. The inelastic behaviour includes potential crack, slip, and crushing of the masonry joints. A micro mechanical based approach is adopted for failure modelling of the masonry. The model is developed by using a fully implicit backward-Euler integration strategy. It is combined with a local/global Newton solver, based on a consistent tangent operator compatible with an adaptive sub stepping strategy. The model is implemented in standard finite element software (ABAQUS) by using user defined subroutine and verification is conducted in all its basic modes. Finally, the model is validated by comparing with experimental results available in the literature.

1. Introduction

Masonry is a heterogeneous anisotropic continuum; made up of the brick and mortar arranged in a periodic or non periodic manner. In particular, the inhomogeneity is due to the different mechanical properties of its constituents, and the anisotropy is due to the different masonry patterns, that can be obtained by variation of geometry, nature and arrangement of mortar and brick. The behaviour of masonry is very complex and highly non-linear due to the behaviour of its constituents, which are quasi-brittle in nature and have a large difference in their stiffness. It represents a very particular mechanical behaviour, which is primarily due to the lack of homogeneity and standardization (see [1,2]). The structural response of such a composite material derives from the complex interaction between its constituents. Under the in-plane loading, masonry is subjected to a biaxial state of stress and thus masonry constituents may fail in individual or combined mechanisms (see [3–6]). These failure mechanism are used in micro modelling of masonry to understand its behaviour.

Many computational studies have been carried out at various scales to understand and simulate the behaviour of masonry. The modelling of masonry at different scales depends up on the level of accuracy and simplicity desired. This includes micro-modelling and macro-modelling. In micro-modelling, the unit and mortar are represented by continuum elements and unit-mortar interface is represented by a discontinuous interface element. This detailed micro-modelling procedure leads to very accurate results, but requires an intensive computational effort. This drawback can be partially overcome in simplified micro-modelling, by making an assumption that mortar and two unit-mortar interface is lumped into a joint between expended units. The units are expended in order to keep the geometry of structure unchanged. The computational cost of simplified micro-model can be further reduced, by replacing expanded units by the rigid element. Using rigid elements decreases the number of degrees of freedom, which consequently reduces the computational time. In macro-modelling, masonry is considered as a composite, which does not make any distinction between units and joints. The material is regarded as a fictitious homogeneous anisotropic continuum.

2. Literature review

There has been several experimental studies reported in literature for understanding behaviour of the masonry for instance (see [7–12]). Masonry exhibits a quasi-brittle behaviour due to its constituents, thus failure analysis of a masonry structure abides in the realistic modelling of the fractures and associated softening behaviour. Therefore modelling techniques of masonry are analogous to that developed in concrete and rock mechanics. Many plasticity based constitutive models have been proposed in the recent years that can simulate initiation and propagation of crack under combined normal and shear stresses [13–18].

* Corresponding author.
E-mail address: rajagopal@iith.ac.in (R. Amirtham).

http://dx.doi.org/10.1016/j.engstruct.2014.08.021

Aryan and Hegemier [19], Page [20] made early attempts to study the masonry failure using simplified micro modelling. Stankowski et al. [21,22] proposed a plasticity based constitutive model to describe the fracture and slip of the interface in cementitious materials. This model uses a curvilinear Mohr-Coulomb yield function with a tension cut-off and the yield function has a smooth transition between shear and tension region. They considered the tensile strength softening without changing shape of yield function (i.e. degradation of tensile strength is considered whereas cohesion and friction angle are considered to be unchanged). Lotfi et al. [23,24] have developed an interface model that incorporates additional softening mechanisms i.e. the degradation of cohesion and friction angle with additional attention being paid to include the dilatancy. The models presented there can simulate initiation and propagation of crack under combined normal and shear stresses in tension-shear and compression-shear region. However, it fails to simulate masonry under high compression stress. Lourenço [25–27] introduced multi-surface interface model for analysis of masonry structures. The constitutive model is illustrated by three yield functions: a tension cut-off for mode-I failure, a Mohr-Coulomb failure envelope for mode-II failure and a cap model for compressive failure. The model is capable of simulating masonry under tension-shear, compression-shear and even under high compression stress. Due to presence of three yield criteria, singularity problem arises at the non-smooth corner in transition zone from tension to shear and shear to compression. Many other plasticity based constitutive model have also been proposed in recent years. Giambanco et al. [28] presented an interface model suitable to simulate the behaviour of mortar joint in the masonry, using the Mohr-Coulomb bilinear limit surface with tension-cut off. The model considers the softening response that occurs, along with decohesion process in the presence of shear and tension. Oliveira and Lourenco [29,30] extended the Lourenco and Rots model to damage formulation for simulating the cyclic behaviour of interface element. Dolatshahi et al. [31] used the Lourenco and Rots model and have shown that in a computational scheme, the use of rigid elements along with non-linear line interfaces leads to a reduced number of degrees-of-freedom, which consequently reduces the computational time. Dhanasekar et al. [32] carried out explicit finite element analysis of wide spaced reinforced masonry shear wall. The wall is modelled using macroscopic material characteristics for the unreinforced masonry panels and damaged concrete plasticity for the grouted cores containing reinforcement. Anand et al. [33] did a finite element failure analysis of composite masonry walls subjected to both vertical and horizontal loads. It is shown that cracking in the collar joint is initiated at a much smaller magnitude of the horizontal inplane load compared to the vertical load.

There has been interesting works on understanding the failure modes of solid brick masonry under in-plane loading (see [34]) and numerical modelling of masonry using finite element method [20] for understanding the behaviour of columns under horizontal loads [35], and under cyclic loads [36]. There has also been some other works on 3D analysis of masonry columns under cyclic loading [37], 3D analysis of masonry columns with grouted reinforcement under cyclic loading [38]. The study on masonry wall under inplane loading [39,40], masonry wall under monotonic loading [41], and masonry wall subjected to seismic loading [42,4] are notable.

There has been very recent works on nonlinear analysis of masonry structures [43]. An equilibrated macro element for nonlinear analysis of masonry structures [44] has been developed for understanding the in plane structural response of masonry panels under lateral loading [45]. Understanding nonlinear behaviour of masonry has been attempted at various scales. A coarse scale model in the context of assumed stress formulation has been implemented in [46] with non associative plasticity. Several mesoscale modelling approaches [47] has been developed for modelling nonlinear behaviour of masonry [48]. A mesoscale cohesive crack model to simulate cyclic behaviour of concrete and masonry structures was presented in [49]. A nonlinear finite element modelling of reinforced masonry shear walls for bidirectional loading response was made in [50]. Similar nonlinear finite element analysis was made to understand the out of plane behaviour of masonry walls with and without CFRP reinforcement in [51]. Ref. [52] have studied the influence of boundary conditions and size effects on the drift capacity of unreinforced masonry walls. Numerical investigation on the influence of FRP retrofit layout and geometry on the inplane behaviour of masonry walls was done by Gian et al. [53]. A new discrete element model for the evaluation of the seismic behaviour of unreinforced masonry buildings has been made by Ivo et al. [54]. Amaryllis et al. [55] have proposed methodology for identification of suitable limit states from nonlinear dynamic analyses of masonry structures.

There has been very recent works to understand the inplane and out of plane behaviour of masonry walls subjected to cyclic loading. A three dimensional cyclic meso-scale numerical procedure for simulation of unreinforced masonry structures is developed in [56]. Nebojsa et al. have undertook a study on modelling the behaviour of seismically strengthened masonry walls subjected to cyclic in-plane shear [57]. Medeiros et al. [58] developed a numerical modelling of non- confined and confined masonry walls. An explicit finite element analysis for the in-plane cyclic behaviour of unreinforced masonry structures was made in [59]. Manos et al. studied the behaviour of masonry assemblages and masonry infilled reinforced concrete frames subjected to combined vertical and cyclic horizontal seismic type loading [60]. Analytical models for cyclic compressive behaviour of brick masonry have also been proposed [61]. In plane cyclic behaviour of masonry walls jacketed with fibre reinforced mortar and fibre grids was made by Viorel et al. [62]. There has also been some recent works on behaviour of masonry walls under combined loadings [63].

The recent advances in computational modelling of masonry structures has been towards understanding their behaviour under cyclic or seismic loads. A comparative analysis on the seismic behaviour of unreinforced masonry buildings with flexible diaphragms was made in [64]. Unreinforced and confined masonry buildings in seismic regions: Validation of macro element models and cost analysis was done in [65]. An equivalent frame model for the nonlinear seismic analysis of masonry buildings was developed in [66]. A seismic vulnerability index for confined masonry shear wall buildings and a relationship with the damage has recently been studied in [67]. Modelling and analysis of time dependent behaviour of historical masonry under high stress loads is presented in [68]. A new discrete element model for the evaluation of seismic behaviour of unreinforced masonry buildings is presented in [69]. Parametrical study of unreinforced flayed masonry walls subjected to horizontal loading through numerical modelling is made in [70].

Structural analysis of a multi-span railway masonry bridge combining in-situ observations, laboratory tests and damage modelling was done in [71]. Effect of in-plane damage on out of plane strength of unreinforced masonry walls was presented in [72]. Modelling of masonry of infilled frames with respect to cracking and damage is presented in [73]. Performance evaluation of masonry in-filled frames under cyclic loading based on damage method has been presented in [74]. A simplified homogenisation based discrete element model for the non-linear static analysis of masonry walls subjected to out-of-plane loaded has been presented in [75].

There has been several other recent works on numerical modelling of masonry structures with structural strengthening using