Amirkabir Journal of Civil Engineering

Amirkabir J. Civil Eng., 53(11) (2022) 1077-1080
DOI: 10.22060/ceej.2021.18672.6920

3D Continuous Micro-Model Based on Multi-laminate Concept for the Nonlinear Numerical Analysis of Masonry Panels

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ABSTRACT: This paper presents a continuous micro model for the prediction of the behavior of a masonry structure. A model based on multi-laminate theory is developed to model the fracture in unreinforced masonry. The main purpose of this paper is to develop a constitutive model for practical applications which has few and easily measurable parameters and is capable of reproducing advanced features of the behavior of masonry brickworks such as cohesive-frictional response (strength dependence on confinement), dilatancy, and dilatancy control with confinement, anisotropy (inherent and induced which is caused by cracking formation), hardening-softening and different levels of brittle behaviors. The yield surface used in this model consists of a generalized Mohr-Coulomb yield surface together with a cut-off tensile. This can address both pre and post-peak behaviors. The capability of this model is confirmed for simulating the masonry behavior under lateral loading by comparing the numerical simulation results with experimental data in the literature..

Review History:

Received: Jul. 03, 2020
Revised: Feb. 05, 2021
Accepted: Feb, 13, 2021
Available Online: Feb. 27, 2021

Keywords:

Micro modeling
Micro-plane model
Multi-laminate model
Induced anisotropy
Softening behavior.

1- Introduction

Generally, numerical modeling of masonry walls is classified into three main categories including micro modeling, macro modeling, and equivalent element. The two latter approaches are characterized by a very low, Nevertheless, such simplified elements usually provide a coarse description of the real masonry element behavior [1, 2]. A masonry wall is a composite material constructed of three main components: brick, mortar, and interface of brick-mortar. In micro modeling, each component of the masonry wall is modeled separately. The micro-modeling strategies for masonry walls are summarized in three main groups: detailed micro-modeling, simplified micro-modeling, and continuous micro-models. The detailed micro-modeling can only be used for small specimens due to difficulties in pre and post-processing. The restriction of the simplified micro-modeling is that the joint interaction with masonry units (i.e., bricks) cannot be modeled correctly due to egregious difference between mechanical properties of bricks and mortar joints causing the extension of important lateral stress of wall to the area adjacent to the joint [3, 4].

The main purpose of this paper is to develop a constitutive model based on multi-laminate theory for practical applications that is capable of reproducing advanced features of the behavior of masonry brickwork. The multi-laminate models can simulate induced anisotropy intrinsically. Also, the advantage of the continuous micro-models mainly resides in its simple and efficient format that it inherits from classical damage mechanics models. The recurrent disadvantage of standard continuum damage models, i.e., their poor capability of representing the dilatant behavior of mortar joints under shear stress states, has been overcome by the proposed model.

2- Multi-laminate Framework

According to the multi-laminate framework, the mechanical behavior of a material can be simplified by assuming the body to be a combination of solid particles and an infinite number of imaginary sliding planes which are randomly oriented in space. The overall plastic deformation of a body is then a result of plastic movement along these planes [5].

The micro-level effective stress σ_i' on each sampling plane is obtained using:

$$\sigma_i' = [\sigma_{ni}', \tau_i]^T = \begin{bmatrix} N : \sigma^{mac} \\ T : \sigma^{mac} \end{bmatrix} \quad (1)$$

$$N = n \otimes n, T = n.I^{sym} - n \otimes n \otimes n \quad (2)$$

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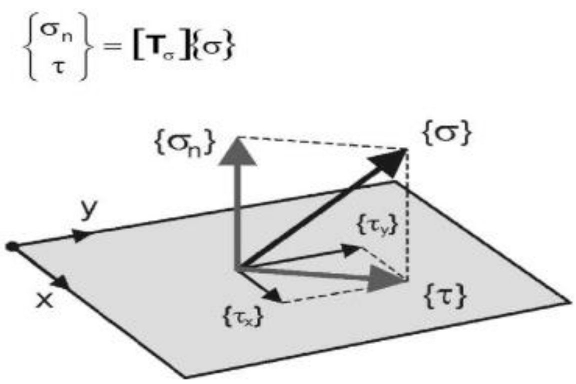


Fig. 1. Transformation of global stress in integration points into local stresses on a sampling plane.

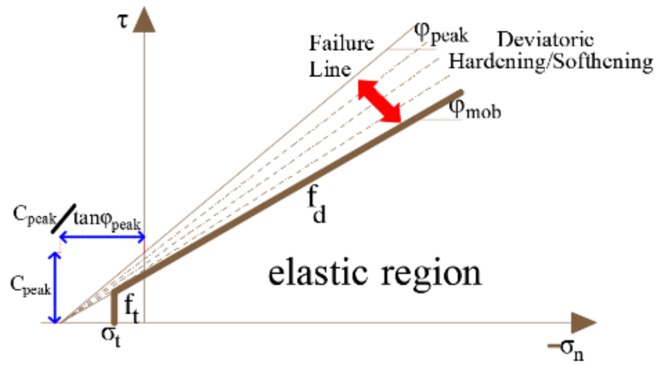


Fig. 2. Yield and failure on a sampling plane.

Table 1. Experimental data [6] and model parameters.

	E (MPa)	*ν*	*C* (MPa)	*Ø*	*ψ*	f_t (MPa)
brick	6740	0.17	4.35	30	20	1.5
mortar	1700	0.06	0.35	40	30	0.24

Where σ' is the effective stress tensor and n_i is the normal unit vector of the plane i.

To obtain the global plastic strain increment $\Delta\varepsilon^p$, the contributions from all sampling planes have to be taken into account by the transformation of the micro-level plastic strain increment $\Delta\varepsilon_i^p$ and the numerical integration over the surface of the unit sphere:

$$\Delta\varepsilon^p = \int_S T_i \Delta\varepsilon_i^p dS = \int_S \Delta\lambda_i T_i \frac{\partial g_i}{\partial\sigma_i'} dS = \sum_{i=1}^{np} \Delta\lambda_i T_i \frac{\partial g_i}{\partial\sigma_i'} W_i \quad (3)$$

Where S denotes the surface of the unit sphere and T_i is the transformation matrix of the sampling plane i which contains partial derivatives of the local effective stress vector concerning the global effective stress vector.

Yield functions are denoted as f_d and f_t, called deviatoric and tension parts of the yield curve, respectively.

The yield function f_d is an extended Mohr-Coulomb criterion by introducing the mobilized friction angle ϕ'_{mob} :

$$f_d = \tau + \sigma_n'.\tan\phi'_{mob} - \frac{c'_{mob}.\tan\phi'_{mob}}{\tan\phi'_{peak}} = 0 \quad (4)$$

$$\tan\phi'_{mob} = \tan\phi'_i + \left(\tan\phi'_{mod} - \tan\phi'_i\right).\frac{\varepsilon^p_{\gamma,d}}{\varepsilon^p_{\gamma,d} + A_{mat}} \quad (5)$$

The third part of the yield curve f_t is a function of the cut-off criterion:

$$f_t = \sigma_n' - \sigma_t' \quad (6)$$

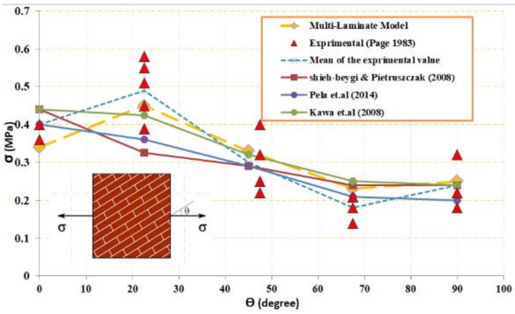
$$\sigma_t' = \sigma'_{t,\max}\exp\left(-h_v\varepsilon_{di}\right) \quad (7)$$

3- Simulation of tests conducted by Page

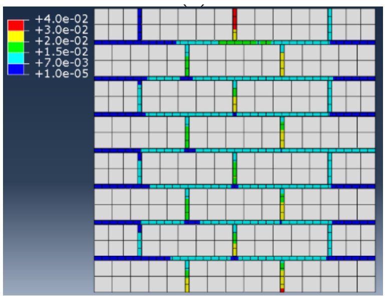
To assess the performance of the proposed constitutive model, the experimental panel tests conducted in [6] are numerically reproduced here. The test specimen consisted of a 360×360 mm2 panel of running bond brick masonry. The tests were conducted for five different orientations, 0, 22.5, 45, 67.5, and 90. For each orientation, here only uniaxial tension is considered.

4- Results and Discussion

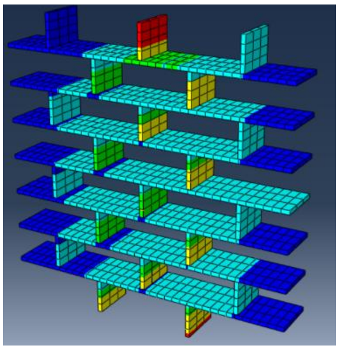
The directional strength characteristics obtained from numerical simulations are presented in Fig. 3 and are compared with the data of page and another numerical model [7-9]. Predominant failure modes are similar to those predicted numerically. The assessment of failure load is quite consistent with the page's results, as shown in Fig. 3(a). This can be due to that the sample is relatively small and the results are significantly affected by the constraints imposed along the boundaries.



(a)



(b)



(c)

Fig. 3. (a) Failure envelope for uniaxial tension at different orientations of the bed joints, (b, c) Crack propagation pattern within the mortar joints in specimens subjected to uniaxial tension perpendicular to the head joints, θ = 0

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HOW TO CITE THIS ARTICLE

H. Tavanaeifar , A.H. Akhaveissy, 3D Continuous Micro-Model Based on Multi-laminate Concept for the Nonlinear Numerical Analysis of Masonry Panels, Amirkabir J. Civil Eng., 53(11) (2022) 1077-1080.

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