Computers and Geotechnics 68 (2015) 1–7

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

Numerical evaluation of geomaterials behavior upon multiplane damage model

Mohsen Ghadrdan *, Seyed Amirodin Sadrnejad, Tahereh Shaghaghi

Civil Engineering Faculty, K.N. Toosi University of Technology, 470 West Mirdamad Ave., Tehran 19697, Iran

ARTICLE INFO

Article history:
Received 27 July 2014
Received in revised form 3 February 2015
Accepted 12 March 2015
Available online 1 April 2015

Keywords:
Multiplane model
Multilaminate model
Damage function
Anisotropy
Crack

ABSTRACT

Among the various numerical simulating constitutive models for geomaterials, the constitutive models which formulated within multilaminate framework have an excellent position. The major advantage of these models is because of its simplicity of working instead of complicated microscopic models such as discrete particles models and do not have the shortcomings of macroscopic models based on the stress or strain invariants.

The object of this study is to deal with the problem exists in the present multilaminate models built on a numerical integration upon 13 sampling points, which both compatibility and equilibrium conditions are not simultaneously satisfied. To overcome this problem, a logical 17 sampling points of numerical integration is presented. The obtained results show a good match with experimental tests.

1. Introduction

Material compliance matrix as a tensor containing the interrelation between stress/strain components presents material behavior aspects that may be activated during material deformation. There are many factors that influence behavior and damaged resistance of material that mathematically make a compliance matrix as a fourth-order tensor. It is important to develop a powerful constitutive model for material compliance matrix in order to understand the effects of different factors and their interactions influencing the material behavior. Therefore, a correct summing the directional effects up to present all in a compliance matrix can be significant and important to see their effects and interactions in material behavior.

Multi-phase materials such as concrete consisting of contacts between grains, paste, moisture and voids are discrete media that mostly are considered continuum including micro-cracks for ease. The accurate behavior of such complex materials is to be investigated through micromechanics-based models. The macroscopic as an overall or averaged behavior of multi-phase materials is determined not only how discrete grains and other phases are arranged through medium, but also by what kinds of interactions are operating among them. To investigate the behavior of these multi-phase materials based on micro-mechanical concepts, certainly, the spatial distribution of contact points and orientation of grains must be identified.

Among the various numerical simulation models, the multilaminate models have an excellent position. In these models, instead of presenting constitutive relations in the shape of stress and strain tensors, the stress and strain vectors, which are in turn the projections of stress or strain tensors, are used. This method not only provides a more physical conceptual base, but also leads to more simple mathematical formulation. On the other hand, invariant-based continuum macroscopic models lose some of the important features of material behavior because they are basically not able to capture and store the data properties in the different directions around a material point, whereas the multilaminate models inherently include the directional characteristics of a material point.

Multilaminate and microplane are two of the most important families of micro-mechanic based models. Both frameworks predict the behavior of the material by considering the response on several so-called "integration planes" [1]. The basic idea, namely that of the constitutive material behavior as a relationship between strain and stress tensors which can be assembled from the behavior of material, on the planes with different orientations within the material such as slip planes, micro cracks, and particle contacts, might be traced back to the "slip theory of plasticity" which was firstly used for modeling the behavior of polycrystalline metals [2–10]. This theory was soon recognized as the most realistic constitutive model for plastic-hardening metals. It was used in arguments about the physical origin of strain hardening, and was

* Corresponding author. Tel.: +98 912 4683803.
E-mail address: mq1365@gmail.com (M. Ghadrdan).

http://dx.doi.org/10.1016/j.compgeo.2015.03.008
0266-352X/

shown to allow easy modeling of anisotropy as well as the vertex effects for loading increment to the side of a radial path in stress space. The theory was also adapted to anisotropic rocks and soils under the name multilaminate model [11–19]. There are many constitutive studies have been made using the multilaminate framework, with which they formulated a critical state model on 13 independently acting planes to see rotation of principal stress/strain axes and anisotropy [1,20]. A certain formulations considered that only the inelastic shear strains (slips), with no inelastic normal strain, were taking place on what is presented as microplane model [21]. Microplane model showed that the static constraint induces unstable localizations of softening into a plane of one orientation, which makes it very difficult to generalize the model for post-peak strain-softening damage of quasi-brittle materials [22–26]. This problem solved to some extent by using kinematic constraint instead of static constraint, in which the strain vector on any inclined plane in the material is the projection of the macroscopic strain tensor. Furthermore, strain localization as a result of strain concentration in a zone with a limited thickness is an important subject in the prediction of failure and residual bearing capacity. In [17,27–30], nonlocal approach was employed for modeling the post-peak behavior of quasi-brittle materials within multilaminate and microplane models. The main focus of this paper is to present a logical method of adjusting multilaminate numerical integration to satisfy compatibility condition, as such, strain localization has not been considered.

The present multilaminate models are built on a numerical integration upon 13 sampling points, which both compatibility and equilibrium conditions are not simultaneously satisfied [1,31]. To circumvent this problem a logical 17 sampling points of numerical integration is presented as "multiplane" model. Validity of the proposed model is investigated through experimental tests.

2. Conceptual discussion on justifying the need to multiplane framework

In general continuum mechanics, to define strain distribution at a point, the components are simply considered on the outer surface of a typical *dx*, *dy*, *dz* element. This method makes the solution to be considered uniform and the homogeneous strain distribution of the nine components over the outer surface of such *dx*, *dy*, *dz* element on three perpendicular coordinate axes. There is a further consideration in addition to the requirement that the displacements of a cemented or granular medium provide due to slippage/widening/closing between particles that make a contribution to the strain in addition to that from the compression of particles. Consider two neighboring points on either side of the point of contact of two particles. These two points do not in usual remain close to each other but describe complex trajectories. Fictitious average points belonging to the fictitious continuous medium can be defined which remain adjacent so as to define a strain tensor. The problem presents itself differently for disordered particles compared with the ordered sphere of equal sizes. In this case, small zones, in which there is no relative movement of particles, may even appear. This can lead to specific behavior such as periodic instabilities known as slip–stick, creating non-homogeneity in strains and displacements.

The effects of non-homogeneity in the mechanical behavior of non-linear materials are very important and must somehow be considered. Furthermore, these non-homogeneities are mostly neglected in mechanical testing because strains and stresses are usually measured at the boundary of the samples and therefore have to be considered reasonably within the whole volume.

Solving non-linear problems, the mechanical behavior depends strongly on the stress/strain path as well as their histories. Upon these conditions, it may be claimed that the consideration of strain components along three perpendicular coordinate axes may not reflect the real historical changes during the loading procedure. In the most extreme case, the definition of a sphere shape element *dr* (instead of *dx*, *dy*, *dz* cube) carrying distributed strain similarly on its surface can reflect strain components on infinite orientation at a point when *dr* tends to zero.

The finite strain at any point in three dimensions by coordinates (x, y and z) relates to the displacements of the sides of an initial rectangular-coordinate box with sides of length dx, dy, and dz to form the three sides of a parallelepiped. This configuration of strain is established by considering the displacements of the corner points $(x,0,0)$, $(0,y,0)$, and $(0,0,z)$. This kind of strain approach leads to define a (3×3) strain tensor including six or nine components to present the displacement gradient matrix at a node. Accordingly, any displacement and corresponding gradient have to be defined as independent components on three perpendicular coordinate axes.

Figs. 1 and 2 depict a sphere element and a typical deformed shape of it respectively. Obviously, there is certain history of displacement on any random orientation through the element. These are abbreviated in only three x, y and z planes, when a box-shape *dxdydz* element is employed. To avoid not missing any directional historical information of strain, a spherical element carrying strain components over its surface, as tangent and normal to the surface must be employed. This form of strain, which certainly represents a better distribution, includes all directional information. Certainly, to obtain the strain components as presented on planes around box element, strain variation is integrated over the sphere surface. However, a predefined numerical integration may

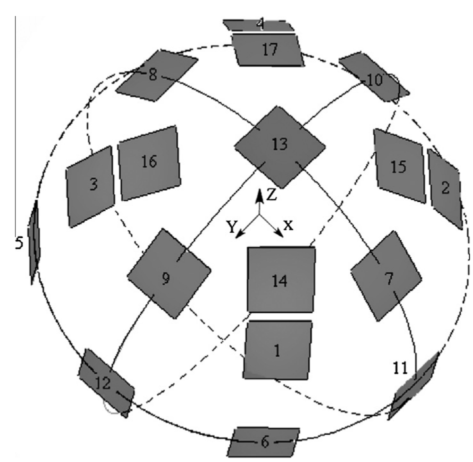

Fig. 1. Position of 17 integration points on the unite sphere surface.

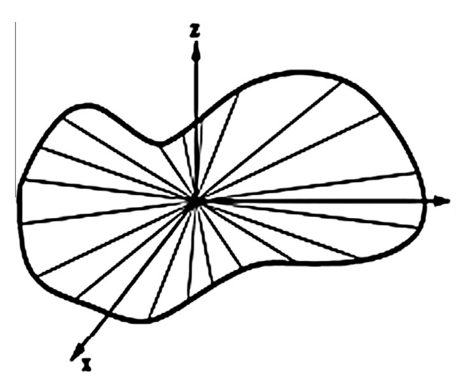

Fig. 2. Typical deformed element and orientations.