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Original Article

Effective yield surface of porous media with random overlapping identical spherical voids

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ABSTRACT

The present paper concerns a computational study of a three-dimensional (3D) unit cells with identical spherical voids in a von Mises matrix. The objective is to estimate the effective plastic flow surface of 3D microstructures. The work originality is to deal with identical spherical overlapping voids, covering a wide range of stress triaxiality ratios. The effective plastic flow surface is computed for nine distinct loadings on four distinct microstructures. The result indicates that the classical Gurson–Tvergaard–Needleman (*GTN*) model obtained using the Fritzen et al. [40] parameters, matches with our numerical simulations.

1. Introduction

The mathematical development of yield criteria for plastic porous solids has been widely investigated, see Rice and Tracey [1], Gurson [2], Tvergaard [3], Needleman and Tvergaard [4], Becker et al. [5], Koplik and Needleman [6], Sun and Wang [7], Ponte Castaneda [8], Michel and Suquet [9], Gologanu et al. [10,11], Garajeu [12], Zuo et al. [13], Garajeu and Suquet [14], Gologanu et al. [15], Faleskog et al. [16], Ma and Kishimoto [17], Corigliano et al. [18], Pardoen and Hutchinson [19], Zhang et al. [20], Gologanu et al. [21], Negre et al. [22], Kim et al. [23], Wen et al. [24], Zaïri et al. [25], McElwain et al. [26], Monchiet et al. [27], Zaïri et al. [28], Besson [29], Laiarinandrasana et al. [30], Li and Karr [31], Nielsen and Tvergaard [32], Vadillo and Fernandez Saez [33], Zadpoor et al. [34], Lin et al. [35], Dunand and Mohr [36], Li et al. [37], Mroginski et al. [38], Fei et al. [39], Fritzen et al. [40], Madou and Leblond [41,42], Yan et al. [43], Benhizia et al. [44], Khdir et al. [45] and Khdir et al. [46].

Essentially, because of the role of porosities regarding the ductile fracture process, these voids are the consequence of manufacturing processes.

The mathematical derivations of these criteria are generally based on the continuum-based micromechanical framework, for which the starting point is the microstructural representation of the porous medium. The non triviality of the theoretical problem leads to define a basic unit cell containing one centered void for the material volume used to represent the microstructure.

Gurson [2] proposed the most widely used micromechanics-based yield criterion to analyze plastic porous solids containing spherical voids. The Gurson model

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is based on the following assumptions: isotropy, incompressibility of the surrounding matrix and rigid plasticity for the local yielding of the surrounding matrix material, which obeys to the von Mises criterion. The Gurson resulting macroscopic yield criterion for porous medium is hydrostatic pressure dependent. It integrates the porosities volume fraction as a model parameter and accounts for a possible void growth driven by the local plastic deformation of the surrounding matrix material. As pointed out by Tvergaard [3], the Gurson model gives an upper bound of the macroscopic yield stress as a function of the mean stress for voids periodic arrangement.

In order to get closer to two-dimensional finite element simulation results on a periodic unit cell, Tvergaard [3] proposed to introduce heuristic parameters in the Gurson yield criterion. These adjustable parameters have no direct physical meaning, but may be correlated to interaction effects between voids.

The extension of the Gurson model by Tvergaard [3], known as the Gurson–Tvergaard–Needleman model (GTN), was widely used by researchers to check its capability to highlight the poro-plastic behavior of many porous materials. Benzerga and Leblond [47] and Besson [48] reviewed the various extensions of the Gurson model based on enhanced micromechanical approaches or upon phenomenological generalizations to take into consideration the void shape or the matrix material features such as isotropy, kinematic hardening, visco-plasticity, compressibility and anisotropy.

Using micromechanical approaches, Ponte Castaneda [8] and Sun and Wang [7] proposed, respectively, upper and lower bounds for the overall yield surface of porous media. Using the variational technique, introduced by Ponte Castaneda [8], Garajeu and Suquet [14] proposed another upper bound which overcomes the well known basic drawbacks of the Gurson criterion at low stress triaxiality values.

The effect of void shape on the macroscopic yield response of porous materials was investigated by several authors. For more details, see Gologanu et al. [10,11], Garajeu [12], Yee and Mear [49], Gologanu et al. [15,21], Son and Kim [50], Siruguet and Leblond [51], Flandi and Leblond [52], Li and Huang [53], Li and Steinmann [54], Monchiet et al. [27], Gao et al. [55], Keralavarma and Benzerga [56], Lin et al. [35], Lecarme et al. [57], Scheyvaerts et al. [58], Zaïri et al. [59], Danas and Aravas [60], Madou and Leblond [41], Khdir et al. [45] and Khdir et al. [46]. Some studies concerned with the influence of the 3rd invariant of the macroscopic stress tensor have been presented by Hsu et al. [61] and Gao et al. [55,62].

The mathematical developments have reached a high degree of sophistication. The resulting yield criteria generally involve a certain number of parameters with no physical significance. This may be explained by the fact that these micromechanics based models consider, as a material volume element, an elementary volume element containing a single void. As the voids are diluted in the matrix material, the interactions between voids are neglected.

In order to be statistically representative, the material volume element should contain sufficient information about the porous microstructure, in particular the void distribution.

The material response of porous media was also investigated using computational micromechanics. This approach is emerging as a powerful tool to bring a better understanding of void distribution effects and interaction phenomena on the mechanical behavior of random porous media.

The main advantage of the computational homogenization is its ability to directly compute the mechanical fields on the random porous media by representing explicitly the microstructure features such as shape, orientation and distribution of voids.

Although many studies were dedicated to the development of yield criteria for plastic porous media, only a few works are devoted to three-dimensional (3D) computational homogenization involving multiple voids. To the best of our knowledge, only Bilger et al. [63,64], Fritzen et al. [40], Khdir et al. [45], Vincent et al. [65] and Khdir et al. [46] used this approach to estimate the overall yield surface of porous materials. Their computations were limited to spherical voids and ellipsoidal shape in Vincent et al. [65] and Khdir et al. [46]. The calculations of Bilger et al. [63,64] and Moulinec and Suquet [66,67] were performed on the basis of 3D Fast Fourier Transform. The pore clustering effect on the overall material response was the key point of their investigations.

Fritzen et al. [40] assumed the random porous media as a volume of porous material, which is periodically arranged. The results highlighted by Fritzen et al. [40] led to the extension of the GTN yield criterion in order to overcome the analytical/numerical discrepancies. In Vincent et al. [65], numerical simulations are performed on 3D cells containing numerous spherical or ellipsoidal (oblate) voids in a von Mises or GTN matrix. The cavities, in this study, cannot overlap (each void is surrounded by a matrix spherical shell to avoid overlapping) and the numerical method is based on Fast Fourier Transform. Khdir et al. [45] focused their investigations on the porous materials containing two populations of voids. Their results showed that, there is no significant difference between a double and a single population of voids for an identical fraction of porosities. A computational homogenization of random porous media, including spherical identical overlapping voids, is used in order to determine their overall yield surface. Vincent et al. [65,68] have derived a simple analytical expression of the effective flow surface obtained by generalizing the Gologanu et al. [11] approach to compressible materials. The material under consideration exhibits two populations of voids, where the smaller voids are spherical voids and the larger are spheroidal and randomly oriented inside the material.

The computational investigations performed in this study account for the complex coupling existing between void distribution, void shape (overlapping or non overlapping) and external loading mode, in order to compare the simulation results with some Gurson type yield criteria and verify the extension of the *GTN* yield criterion provided by Fritzen et al. [40] in the case of random porous media containing overlapping spherical voids.

2. Numerical homogenization

2.1. *Porous microstructures*

The porous media considered in the computations are made of perfectly plastic matrix, obeying to the commonly used