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Constitutive behavior of porous ductile materials accounting for micro-inertia and void shape

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ABSTRACT

The goal of this paper is to characterize the mechanical behavior of porous materials by taking into account the void shape and micro-inertia effects. A representative volume element (RVE) defined by two confocal prolate spheroids is used to describe the porous material. The matrix behavior is assumed to be rigid and non linear viscous. Based on the work of Molinari and Mercier (2001), the macroscopic stress is decomposed into static and dynamic parts. In the present work the static contribution is described by the Gologanu et al. model (1993). The dynamic stress is obtained by choosing the trial velocity field proposed by Gologanu et al. (1993). With the proposed modeling a link is established between the macroscopic dynamic stress, on the one hand and, on the other hand, the macroscopic strain rate tensor and its time derivative. To validate our model, finite element simulations have been performed. Two shapes of void (spherical and prolate with an aspect ratio of 5) and two volume fraction of voids (0.001 or 0.1) are considered. The influence of micro-inertia on the macroscopic flow stress surface is analyzed and it is shown that the flow surface obtained by the analytical approach is in good agreement with finite element computations.

1. Introduction

This work presents a multiscale model for porous ductile materials containing prolate spheroidal voids and subjected to dynamic loading. Fracture in ductile materials is in general considered to be a three stage process involving void nucleation, growth and coalescence. Owing to its crucial importance for industrial applications and hazard predictions of metallic structures, this fracture process has been widely studied in the literature throughout the last decades (readers may refer to the recent review of Benzerga and Leblond (2010) for a detailed description of the mechanisms of ductile fracture and associated models).

In quasi static conditions, among the first models referring to void growth, one has to mention Mc Clintock (1968) for cylindrical voids and Rice and Tracey (1969) for spherical voids. These authors were able to derive the evolution of void radius assuming that a void was embedded in an infinite matrix. One of the outcomes of the Rice and Tracey (1969) contribution is the proposition of an admissible velocity field to describe void growth. This kinematic field was further used by Gurson (1977) in the derivation of a constitutive model for porous materials. He considered a representative volume element containing a void (spherical or cylindrical) embedded in a finite matrix. The matrix behavior was assumed to be rigid perfectly plastic. Based on a limit analysis, Gurson obtained a macroscopic yield criterion for the voided solid. The Gurson model and its extensions are nowadays widely used for analytical modeling or finite element computations. The analysis was

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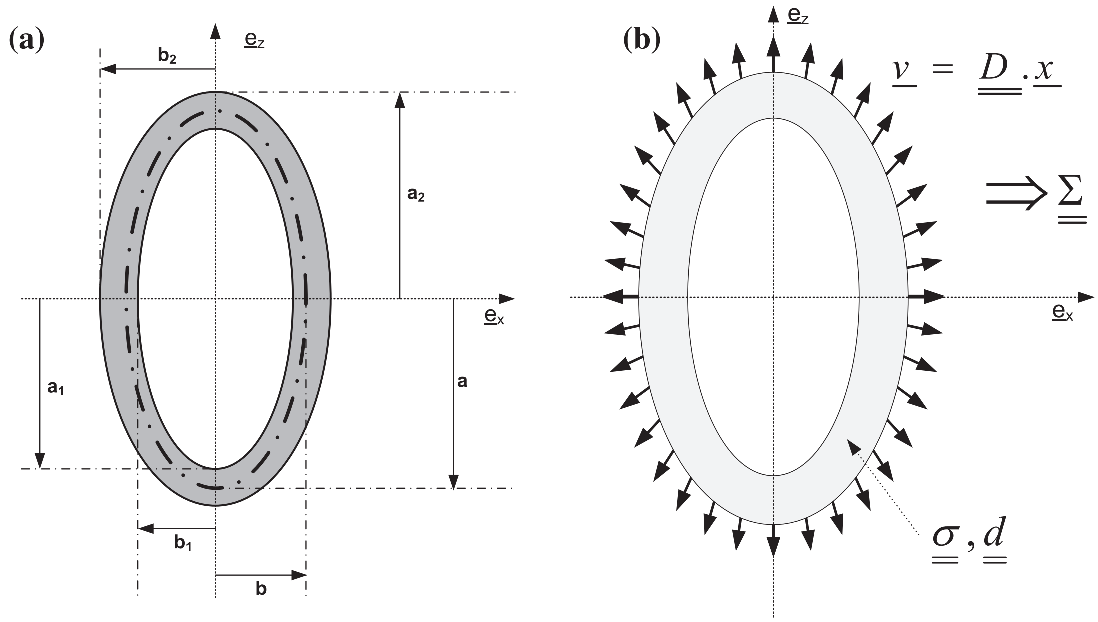

Fig. 1. RVE configuration: (a) A prolate spheroid with semi axes a_1 and b_1 is embedded into a confocal prolate spheroid with semi axes a_2 and b_2. The dotted-dashed line corresponds to the trace of any inner confocal spheroid of semi axes a and b. (b) Homogeneous strain rate boundary conditions are applied at the external boundary of the RVE.

restricted to spherical or cylindrical voids neglecting void shape changes during deformation. The aspect of void shape evolution was investigated by Budiansky et al. (1982) who analyzed the effect of the stress state on the evolution of the shape of a single void in an infinite matrix. It was shown that, depending on stress triaxiality, an initially spherical void can evolve toward different limit shapes (from needle to penny-shape). Since the void shape is known to be a key factor to precisely define the behavior of porous materials, many studies have analyzed how the mechanical behavior of porous medium is affected by void shape. For that purpose, homogenization based methods are convenient. Firstly, a representative volume element (RVE) has to be defined. Generally, the RVE associated to a porous material is taken to be a hollow sphere (as in the Gurson model) or its ellipsoidal/spheroidal counterparts. Secondly, the choice of a salient trial velocity field is an important issue. Usually, there is no exact analytical solution for the velocity field around a void of complex shape under general kinematic boundary loading. Many contributions have been recently proposed to define admissible velocity fields for specific void geometries. One can refer to Lee and Mear (1992), Monchiet et al. (2007, 2008, 2014), Monchiet and Kondo (2013), Gărăjeu et al. (2000) or Gologanu et al. (1993, 1994, 1997) when spheroidal voids are considered. Recently, Leblond and Gologanu (2008) have proposed a velocity field valid for arbitrary ellipsoids subjected to homogeneous strain rate boundary conditions. This velocity field has been adopted by Madou and Leblond (2012) to derive the behavior of porous materials containing arbitrary ellipsoidal voids. In the present paper we will concentrate on a porous medium containing prolate spheroidal voids, subjected to axisymmetric loadings. For this kind of void geometry, many velocity fields are available in the literature, as seen above. The Gologanu et al. (1993) velocity field is adopted here. The methodology proposed in the paper is nevertheless versatile so that any other admissible fields of the literature could have been used instead.

In some applications (impact, perforation), ductile fracture occurs when the material is subjected to dynamic conditions. In addition, even for quasi-static loading, in the vicinity of the crack tip, dynamic loading may be experienced by the material during fracture. In these particular cases, it has been shown that taking account of the dynamic effects at the microstructural level is a fundamental issue. These effects are particularly significant for large strain rate, typically ranging from $10^4\,s^{-1}$ to $10^6\,s^{-1}$. Dynamic effects at the microstructural level (named in the following as micro-inertia effects) originate from the local acceleration of the dense matrix in the vicinity of voids. In fluid mechanics, the effect of local acceleration in bubble cavitation is well established since the pionneer works of Rayleigh (1917) and Plesset (1949). In solid mechanics, one may refer to Carroll and Holt (1972) who considered the dynamic compaction of powder. This paper is one of the first contribution in solid mechanics showing that micro-inertia has to be integrated in the modeling of large strain rate processes. The contribution of Carroll and Holt (1972) was restricted to spherical loading, as it was the case for Ortiz and Molinari (1992). Molinari and Mercier (2001) proposed an analytical expression of the dynamic stress contribution due to micro-inertia in a general case. One may also refer to Wang (1997) for a different definition of the dynamic stress contribution. To validate the concept of micro-inertia in solid mechanics, the spallation