VOID SIZE EFFECTS ON THE MACROSCOPIC YIELD STRENGTH OF DUCTILE MATERIALS WITH SPHEROIDAL NANOCAVITIES

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Summary We investigate the interfacial stress effects on the macroscopic yield strength of plastic porous media containing nanosized spheroidal cavities. To this end, we perform the limit analysis of a confocal spheroidal unit cell, containing a confocal spheroidal cavity, and subjected to arbitrary mechanical loadings. The solid matrix is assumed to obey to the von Mises criterion with associated flow rule. The void size effects are captured by considering at the interface between the matrix and the cavity the plastic version of the Gurtin stress interface model. At this interface, the jump of the traction vector is related to the interfacial residual stress and interfacial plastic strain. At the macroscopic level it is shown that the yield criterion for the nanoporous material exhibits unusual features such as (i) an increase of the yield stress when the void size decreases, (ii) asymmetry between the yield stress in uniaxial tension and compression.

STATEMENT OF THE PROBLEM AND METHODOLOGY

The elastic properties as well as the yield strength of a solid are significantly affected by the presence of surfaces and interfaces (see for instance [8, 1] for numerical results). Surface effects are attributed to the presence of few layers of atoms which experience a different local environment than atoms in the bulk and have a different equilibrium positions and energy. The classical three-dimensional linear elasticity theory generally neglects these effects since the considered objects and structural elements are, at less, microsized but never of the size of one or few nanometers. For such nanosized objects, the interfacial effects become predominant since the area of surface per unit of volume is very high. Surface effects in standard continuum theories are treated within the framework of the Gurtin and Murdoch stress interface model [7] which assumes a jump of the traction vector while the displacement field is considered continuous across the surface. The jump condition may comply with a generalized Young-Laplace equation which extends to solid-solid interface the well known equation that describes capillarity effects in fluid mechanics. Thus, the discontinuity of the traction vector consists of two parts, the first one is attributed to the presence of interfacial residual stresses, independent of the deformation, and the second one being related to elastic deformation of the interface. Stress surface model have been used to model the inclusions size dependency of elastic properties of nanocomposites [3, 11]. Recently, Dormieux and Kondo [2] generalize the Gurson model [6] in order to predict void size effects. To this end, they make use of a plastic version of the Gurtin stress interface model (see for instance [10]) which relates the interfacial stress to the plastic deformation at the cavity surface. The resulting model shows a void size dependency of the macroscopic yield strength of nanoporous media: for nanosized cavities, the strength domain appears to be significantly larger than that predicted by the Gurson model. Nevertheless, in [2], the authors restrict their analysis to the case of spherical cavities. In this contribution, we provide an extension of their model to the case of spheroidal cavities. By doing so, we also extend the work of Gologanu et al. [4, 5] by incorporating void size effects. Following the methodology described in [9], we derive a closed-form expression of the macroscopic dissipation including the surface plastic dissipation. A parametric form of the macroscopic plastic surface of the nanoporous material is thereafter obtained by means of the Hill-Mandel macrohomogeneity condition.

RESULTS

In this section, we propose to illustrate the salient features of the new model, namely the effects of the void size on the macroscopic yield strength of the ductile material containing spheroidal nanocavities. The illustrations are proposed for axisymmetric loadings represented by the values of the stress components $\Sigma_q = \Sigma_{33} - \Sigma_{11}$ and $\Sigma_m = (2\Sigma_{11} + \Sigma_{33})/3$. By a_1, we denote the radius along the axis Ox_3 of the spheroidal cavity while b_1 represents the radius of the spheroid in the plane Ox_1x_2. On Figure 1, we represent the macroscopic yield surface for the case of a prolate and a oblate cavity. At the left the macroscopic plastic surface is plotted for a prolate nanocavity with an aspect ratio $a_1/b_1 = 5$. The porosity $f = 0.1$ is considered and various values of the non dimensional parameter $k = \tau_0/(b_1\sigma_0)$ are considered. σ_0 denotes the yield stress of the von-Mises matrix for uniaxial tension, τ_0 is the yield interfacial stress. To check the accuracy of the approximate criterion (corresponding to the full line with the points), we compare the results with numerical ones obtained for the exact two-field criterion (corresponding to the circles). A very good agreement is observed between the "approximate" and the "exact" two field criteria. At the right of figure 1, we display similar results for the case

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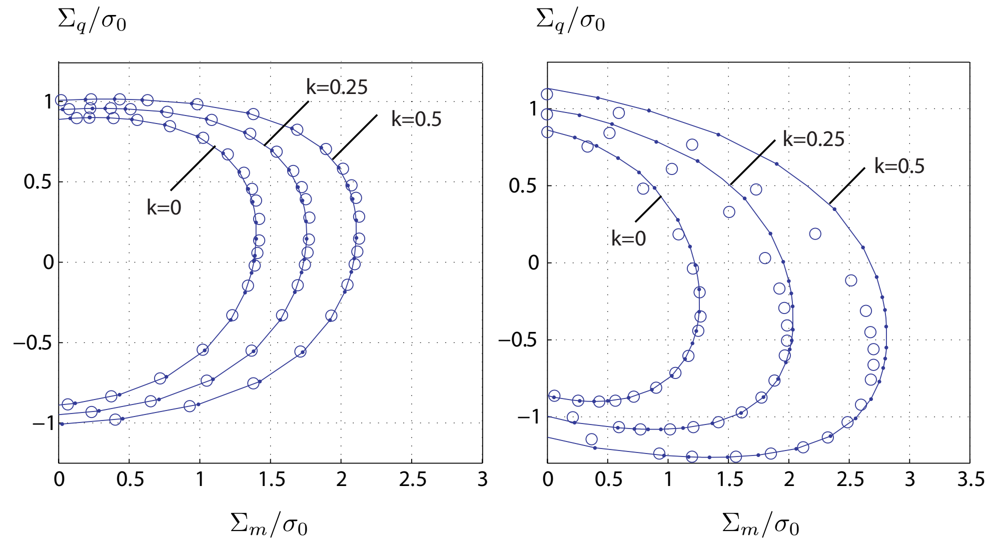

Figure 1. Yield loci for a prolate cavity with an aspect ratio $a_1/b_1 = 5$ (at the left) and for an oblate cavity with an aspect ratio $b_1/a_1 = 5$ (at the right). The porosity is $f = 0.1$. Comparison between the approximate (full line with points) and the exact, numerical, two-field criteria (Circles). The non dimensional parameter k is defined as $k = \tau_0/(a\sigma_0)$

of an oblate cavity with the aspect ratio is $a_1/b_1 = 1/5$. Again, a very good agreement is observed between the "approximate" and "exact" two field criteria when low values of the parameter $k = \tau_0/(a\sigma_0)$ are considered. When increasing k some slight differences are noted in the region of positive values of Σ_q and high values of the mean stress Σ_m. Beyond these differences, it can be also noted that the approximate criterion seems to preserve the upper bound character of the Limit Analysis based approach since the predictions of the approximate two field criterion are larger then the numerical ones. Clearly, the results shows an important effect of the the cavity size on the macroscopic yield locus, the yield surface being larger when the parameter $k = \tau_0/(a\sigma_0)$ increases; this corresponds to a decrease of the size of the void. It must be also noted that the size effect seems to be more significant in the case of an oblate cavity than for a prolate one. The reason may be found in the fact that, for the same volume, the area of the void surface is greater for an oblate cavity than for a prolate one.

References

[1] **J. Diao, K. Gall and M.L. Dunn.** Yield Strength Asymmetry in Metal Nanowires. *Nano Letters*, 4(10), 1863-1867, 2004.

[2] **L. Dormieux, D. Kondo.** An extension of Gurson model incorporating stresses effects. *International Journal of Engineering Science*, 48, 575-581, 2010.

[3] **L. Duan, J. Wang, Z.P. Huang, B.L. Karihaloo** Size-dependent effective elastic constants of solids containing nano-inhomogeneities with interface stress. *Journal of the Mechanics Physics and Solids*, 53, 1574-1596, 2005.

[4] **M. Gologanu, J.-B. Leblond, J. Devaux.** Approximate models for ductile metals containing non-spherical voids Ű case of axisymmetric prolate ellipsoidal cavities. *Journal of the Mechanics Physics and Solids*, 41 (11), 1723-1754, 1993.

[5] **M. Gologanu, J.B. Leblond, G. Perrin, J. Devaux.** Approximate models for ductile metals containing non-spherical voids - case of axisymmetric oblate ellipsoidal cavities. *Journal of Engineering Materials and Technology*, 116, 290-297, 1994.

[6] **A.L. Gurson.** Continuum theory of ductile rupture by void nucleation and growth: Part I. - Yield criterion and flow rules for porous ductile media. *Journal of Engineering Materials and Technology*, 99, 2-15, 1977.

[7] **M.E. Gurtin, A.I. Murdoch.** A continuum theory of elastic material surfaces. *Archive for Rational Mechanics and Analysis*, 57, 291-323, 1975.

[8] **R.E. Miller, V.B. Shenoy.** Size-dependent elastic properties of nanosized structural elements. *Nanotechnology*, 11, 139-147, 2000.

[9] **V. Monchiet, O. Cazacu, E. Charkaluk, D. Kondo.** *Approximate criteria for anisotropic metals containing non spherical voids. International Journal of Plasticity, 24, 1158-1189, 2008.*

[10] **V. Monchiet, G. Bonnet.** Interfacial models in viscoplastic composites materials. *International Journal of Engineering Science*, 48(12), 1762-1768, 2010.

[11] **P. Sharma, S. Ganti** Size-dependent Eshelby's tensor for embedded nanoinclusions incorporating surface/interface energies. *ASME Journal of Applied Mechanics*, 71, 663-671, 2004.