An extended model for ductile fracture in structural materials

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In ductile fracture of structural materials, damage initiates at second-phase particles or brittle phases. Therefore, the spacing between these sets the relevant scale of analysis. The paper begins by an account of microscopic mechanisms highlighting the role of microstructure evolution on macroscopic fracture properties. A unifying framework for analyzing ductile damage by void nucleation, growth and coalescence will then be presented. It relies on rate-dependent constitutive descriptions that incorporate certain forms of plastic anisotropy along with the shape, relative spacing and orientation of particles in addition to their volume fraction, thus emphasizing three-dimensional aspects of the fracture process. One peculiar feature of this framework is that crack initiation and growth are natural outcomes to competing plastic mechanisms. A heuristic formalism that was proposed in previous work by the author for coupling plastic anisotropy with ductile damage will be corroborated based on a rigorous micromechanical treatment, validated with numerical limit-analysis results and finite element simulations of porous unit cells for representative materials under special circumstances. Non-traditional factors such as void rotation and the effect of the third invariant of the stress tensor will be discussed. The application of the modeling methodology will be illustrated for structural steel. We show that in developing quantitative predictions of ductility and toughness there is no substitute for a detailed understanding of the operating mechanisms at the relevant scale. We also demonstrate the promising capabilities of the approach at not only predicting global fracture properties but also key microstructural variables at well-identified stages of the fracture process.

FRACTURE CRACK PROPAGATION TOWARD FRICTION STIR WELD

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ABSTRACT

Friction stir welding is being considered for several aircraft applications. In addition to the property and microstructural changes in the weld and heat affected zone, the friction stir weld process also produces a residual stress field. All of these factors can influence the crack trajectory, crack propagation rate and residual strength. Cracks propagating towards FSW (Friction Stir Weld) in un-stiffened panels were modeled under monotonic loading. Effective strain criterion was used to activate a crack and to determine the direction of the crack propagation, respectively. The experimental data was used to model experimental behaviors with the developed finite element code.

# MODELING OF ELECTROMAGNETIC FORMING PROCESSES IN FINITELY STRAINED SOLIDS

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Electromagnetic forming (EMF) is a high velocity sheet metal forming technique that has significant advantages over conventional ones (e.g. speed, controllability, absence of contact). In EMF, a transient electric current in a forming circuit induces electric currents in a workpiece and the resulting Lorentz forces cause it to deform plastically. Current EMF models do not consistently account for the coupling between electromagnetic and thermo-mechanical interactions and in most engineering simulations, separate numerical solutions to the electromagnetic and finite strain mechanical problems are combined in lock-step.

The present work addresses these issues by introducing a fully coupled Lagrangian (reference configuration) least-action variational principle, involving magnetic flux and electric potentials and the displacement field as independent variables. The corresponding Euler-Lagrange equations are Maxwell's and Newton's equations in the reference configuration, which are shown to coincide with their current configuration counterparts obtained independently by a direct approach. The general theory is subsequently simplified for EMF processes by considering the eddy current approximation.

Next, an application is presented for axisymmetric EMF problems. It is shown that the proposed variational principle forms the basis of a variational integration numerical scheme that provides an efficient staggered solution algorithm. As an illustration a number of such processes are simulated, inspired by recent experiments of freely expanding uncoated and polyurea--coated aluminum tubes.
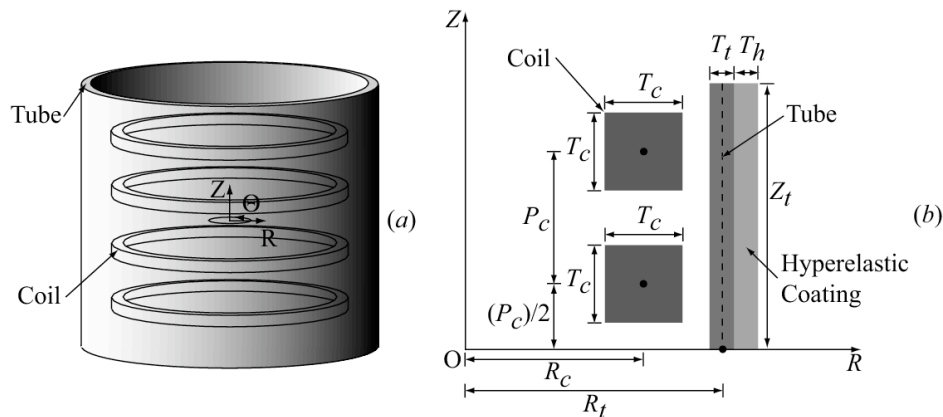
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Damage evolution in porous materials with two populations of voids under internal pressure

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This talk is devoted to the effective mechanical behavior porous materials with two populations of voids of very different size subjected to internal pressure. The smallest voids are intragranular and spherical in shape whereas the largest pores located at the grain boundary are ellipsoidal and randomly oriented. This microstructure is typically that of uranium dioxide (UO_2) which is a nuclear fuel.

In a first step, attention is focused on the effective properties of these materials with fixed microstructure. Rigorous upper bounds can be derived for the effective poro-plastic constitutive relations of these materials through tow rather different variational approaches. The first approach, based on an extension to compressible materials of the velocity fields proposed by Gologanu, Leblond, Perrin (1994), is accurate at high stress-triaxiality. The second one, which derives from the variational method of Ponte Castañeda (1991), is accurate when the stress triaxiality is low. A N-phase model is proposed to match the best of the two bounds at low and high triaxiality. The effect of internal pressures is discussed. In particular it is shown that when the two internal pressures coincide, the effective flow surface of the saturated biporous material is obtained from that of the drained material by a shift along the hydrostatic axis. However, when the two pressures are different, the modifications brought to the effective flow surface in the drained case involve not only a shift along the hydrostatic axis but also a change in shape and size of the surface.

In a second step, the evolution of the microstructure is addressed. Differential equations governing the evolution of the microstructural parameters in terms of the applied loading are derived and their integration in time is discussed. Void growth results in a global softening of the stress-strain response of the material. A simple model for the prediction of void coalescence is proposed which can serve to predict the overall ductility of polycrystalline porous materials under the combined action of thermal dilatation and internal pressure in the voids.

Hot Spots in Plastic Deformation of Polycrystals

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ABSTRACT

Most studies of the mechanical behavior of materials are on issues of strength and fracture, which generally focus on the mean or average behavior. Many of the life-limiting properties depend, however, on the tails of distributions. Fatigue is more likely to start at a large particle than a small one, for example. It is therefore interesting to extract information from simulations of plastic response and relate the peaks in stress, for example, to the microstructural features. Do the "hot spots" concentrate at or near grain boundaries, for example? Given a 3D representation of a polycrystalline material, various methods are available to calculate its properties. For mechanical response, use of finite element methods is standard. Converting a 3D image into a finite element mesh is simple if one (cubic) element per voxel is used; this, however, leads to large meshes and the interfaces are stair-stepped. Generating a conforming 3D mesh that follows the boundaries is a non-trivial problem that still lacks a standardized solution. An alternative approach is to model the mechanical properties on the image itself, which can be done with a spectral method†. Preliminary results from calculating the response under uniaxial tension on a sample of a nickel alloy are given. Stress concentrations and their relationship to grain boundaries are of particular interest, for example, since they can determine the location of rapid damage accumulation. Accordingly, distance functions are calculated in order to quantify the relationship between stress localization and microstructural features. In general, stress rises with proximity to grain boundaries, triple lines and quadruple points.

† Lebensohn, R.A., *N-site modeling of a 3D viscoplastic polycrystal using Fast Fourier Transform.* Acta Materialia, 2001. **49**(14): p. 2723-2737.

Dilatational viscoplasticity of polycrystalline materials: homogenization estimates vs. full-field calculations

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Abstract

Many engineering problems (e.g. dynamic loading of polycrystalline materials, forming aggregates with initial porosity, creep-induced pore growth) require the determination of how the microstructure and the type of mechanical loading influence the viscoplastic behavior of polycrystals with intergranular cavities. For tensile solicitations, the determination of the dilatational component of the strain-rate is critical, since the latter is directly connected with void growth and, eventually, with the ductile fracture of the material. In this study we present results of two complementary formulations, one mean-field approach based on second-order nonlinear homogenization [1, 2] and one full-field approach based on fast Fourier transforms (adapted from [3]) to study the influence of different microstructural features (e.g. overall porosity, void shape, texture of the material phase, single-crystal anisotropy etc) and type of loading (e.g. triaxiality) on the dilatational viscoplastic behavior of voided polycrystals.

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Fiber-reinforced rubbers at finite strain: Constitutive models, microstructure evolution and macroscopic instabilities

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In this talk, we will present a new constitutive model for the effective response of fiber-reinforced elastomers at finite strains. The matrix and fiber phases are assumed to be isotropic, incompressible, hyperelastic solids, while the fibers are assumed to be perfectly aligned and distributed randomly leading to overall transversely isotropic behavior for the composite. The model has been derived by means of the "second-order" homogenization theory, which makes use of suitably designed variational principles utilizing the idea of a "linear comparison composite." Compared to other constitutive models that have been proposed thus far for this class of materials, the present model has the distinguishing feature that it allows the consideration of composites with phases characterized by constitutive behaviors that are more general than NeoHookean, along with the fact that it accounts for the evolution of the shape, orientation, and distribution of the fibers, resulting from the finite changes in geometry at large deformations. Certain features of the predictions of the model for the overall response of the composites under consideration will be discussed. Emphasis will be given on the predictions of the model for the onset of macroscopic instabilities in fiber-reinforced elastomers, for cases where such instabilities may be expected to occur from physical experience. It is important to remark that, in spite of the (assumed) strong ellipticity of the phases, the macroscopic response may lose strong ellipticity at sufficiently large deformations, which in turn suggests that the evolution of the microstructure may play a critical role in the overall behavior of the composite.

J-T Characterized Stress Fields of Surface-Cracked Metallic Liners Bonded to a Structural Composite

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ABSTRACT

Surface crack tip stress and deformation fields in a tensile loaded metallic liner bonded to a structural composite are developed using a two-parameter *J-T* characterization and three-dimensional elastic-plastic modified boundary layer (MBL) finite element solutions. The Ramberg-Osgood power law hardening material model with deformation plasticity theory is implemented. The crack tip constraint effects that arise from the thin liner bonded to a stiff composite and the validity of *J-T* characterized crack tip fields are explored as functions of normalized crack opening, far-field and *T*-stresses. The increased elastic constraint imposed by the composite backing on the liner results in a decrease in plastic zone size and enhanced range of validity of *J-T* characterization. The higher accuracy of MBL solutions in predicting the surface crack tip fields in the bonded model is attributed to an increase in crack-tip triaxiality, and a consequent increase in the characteristic length of the specimen, thereby increasing the effective liner thickness from a fracture standpoint. Results from this study will facilitate implementing testing standards for surface cracked tension specimens bonded to a structural composite.

Crystal Plasticity Modeling and EBSD Study of Crack Tip Deformation Fields in Ductile Single Crystals

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ABSTRACT

The effects of crack tip constraint on near-tip stress and deformation fields in FCC single crystals have been studied under mode I plane strain condition using crystal plasticity modeling in a Finite Element framework. Validation is done by comparing simulation results with *in-situ* electron back-scatter diffraction (EBSD) for lattice rotation at kink shear bands and scanning electron microscopy (SEM) for traces of slip shear bands on tensile and bent Al single crystal specimens. It is shown that for three point bent samples, the dominant slip band occurs at about 125^0 to the crack plane, whereas, in tensile samples, it develops at 55^0. In tensile samples, a kink band develops at 45^0, while the slip band at 125^0 is suppressed. The kink shear bands at $\pm 90^0$ to the notch line form in all cases. The near-tip angular stress variation shows the occurrence of four constant stress sectors separated by discontinuities, and an elastic sector at the crack-flank in the tensile samples. *In-situ* EBSD and SEM observations confirm the appearance of all the predicted kink and slip bands by crystal plasticity model, and suggest that analytical model predictions are partially correct while discrete dislocation models predictions are unsatisfactory.

Construction of fatigue laws from cohesive forces models

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We consider a 2d elastic body submitted to a plane strain loading in which a crack propagates along a predefined crack path $\hat{\Gamma}$. The growth of the crack is governed by a cohesive force model of Dugdale-type in which we introduce the so-called *cumulated opening* δ as an internal variable memorizing the history of the normal displacement jump $[\![u]\!] \cdot \mathbf{n}$ through $\hat{\Gamma}$, $\dot{\delta} = ([\![\dot{u}]\!] \cdot \mathbf{n})^+$, the $+$ denoting the positive part. The cohesive normal stress $\sigma \mathbf{n} \cdot \mathbf{n}$ on $\hat{\Gamma}$ is obtained from the Dugdale surface energy density $\phi_D(\delta) = \min\{\sigma_c \delta, G_c\}$, where σ_c is the critical stress, G_c is the critical energy release rate and the ratio $\delta_c := G_c/\sigma_c$ is a material characteristic length. We assume that $\hat{\Gamma}$, identified with the segment $[0, L]$, can be divided at each time t into three intervals: the non cohesive zone Γ_t^d, the cohesive zone Γ_t^c and the sound zone Γ_t^b. The cumulated opening is equal to δ_c at the tip of the non cohesive zone and there is no singularity at the tip of the cohesive zone. When the ratio δ_c/L is small, the problem can be investigated with a two-scale method. Indeed, in the case of a cyclic loading, the crack evolution enjoys the following properties: (i) at each cycle, the growth of the length of the non cohesive zone is small; (ii) the length of the cohesive zone is always small; (iii) a quasi-stationary regime takes place in the sense that the evolution is approximately the same from a cycle to the next one. Therefore, a great number N of cycles is needed so that the non cohesive crack length be equal to ℓ, with ℓ of the order of L. If we consider cycles close to N and consider the ith cycle numbered from N, $i \in \mathbb{Z}$, the corresponding displacement field $\mathbf{u}^i$ is in a first approximation independent of i, say $\mathbf{u}$. This approximation $\mathbf{u}$ corresponds to the response of the body *on a large scale*, *i.e.* with a *non cohesive crack* of length ℓ and without any cohesive zone. This field is singular at ℓ, with a stress intensity factor K_I depending on ℓ but not on i. But $\mathbf{u}$ is a good approximation of $\mathbf{u}^i$ only far from the crack tip. In the same manner, the growth rate of the crack length and the length of the cohesive zone are both small and independent of i at each cycle i. They are denoted $\dot{\ell}$ and d respectively. The rate $\dot{\ell}$ can be identified with the macroscopic rate $d\ell/dN$. The determination of $\dot{\ell}$ and d requires to obtain a more accurate approximation of $\mathbf{u}^i$ near the crack tip. After a rescaling of the zone near the crack tip, the *small scale* problem giving the approximation $\mathbf{v}^i$ of $\mathbf{u}^i$ is set on an infinite domain with a semi-infinite straight crack along the axis $y = 0$ where (x, y) denotes the new coordinates system. By virtue of the quasi-stationarity property, the $\mathbf{v}^i$'s are related to $\mathbf{v}^0$ by $\mathbf{v}^i(x, y) = \mathbf{v}^0(x - i\dot{\ell}, y)$ and $\mathbf{v}^0$ itself must satisfy a problem which can be solved in a closed form with the help of the complex potentials theory [4]. Moreover $\mathbf{v}^0$ must be non singular at $x = 0$. Thus, d and the jump of v_2^0 through $y = 0$ are given by

$$d = \frac{\pi}{8(1-\nu^2)} \frac{E}{\sigma_c} \frac{G}{G_c} \delta_c \qquad \text{with} \qquad G = \frac{1-\nu^2}{E} K_I^2, \tag{1}$$

$$[\![v_2^0]\!](x) = V\left(1 + \frac{x}{d}\right) \frac{G}{G_c} \delta_c, \quad x \geq -d, \tag{2}$$

1

where V denotes the function defined on $\mathbb{R}_*^+$ by

$$V(l) = \begin{cases} \sqrt{1-l} + l\ln(1-\sqrt{1-l}) - l\ln\sqrt{l} & \text{si } 0 < l \leq 1 \\ 0 & \text{si } l \geq 1 \end{cases} \tag{3}$$

In (1), G represents the potential energy release rate corresponding to a non cohesive crack with length ℓ. It is related to the stress intensity factor K_I of $\mathbf{u}$ by Irwin's formula. It remains to determine $\dot{\ell}$. From the condition $\delta^0(-d) = \delta_c$, we obtain by induction that $\delta_c = \sum_{i=1}^{\infty} [\![v_2^0]\!](i\dot{\ell})$. Using (2), we obtain the following equation giving $\dot{\ell}$ in terms of G:

$$1 = \frac{G}{G_c} \sum_{i=0}^{\infty} V\left(\frac{i\dot{\ell}}{d}\right). \tag{4}$$

This equation has no solution if $G < G_c$, an infinite number of solutions if $G = G_c$ and a unique solution if $0 < G < G_c$ which can be read as

$$\dot{\ell} = \frac{\pi}{8(1-\nu^2)} \frac{E}{\sigma_c} \mathsf{f}\left(\frac{G}{G_c}\right)\delta_c. \tag{5}$$

Moreover, when G/G_c is small, the relation between $\dot{\ell}$ and G is approximately a power law with the exponent 2 (and hence with the exponent 4 in terms of K_I). In other words, we have obtained a propagation law which contains both Griffith and Paris laws. Griffith's law in the supercritical case where $G \geq G_c$ and Paris' law in the subcritical case where $G < G_c$. These results can be extended to the case of a general surface energy of Barenblatt type.

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Ductile damage in metals studied by X ray tomography.

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ABSTRACT

Rupture of materials is a main concern for the engineers today. Most of the structural and safety parts in the devices that we all use are made of ductile metals so the understanding of the rupture process in these materials is a key issue. Experimental studies allow to determine the damage process which leads to the rupture of a particular kind of material in given loading conditions. X ray tomography has been used by our team for about 15 years at the ESRF. These studies have shown that 3D imaging is a very powerful tool for performing this kind of damage qualification and quantification. The talk will explain the basis of the method we use, which combines high resolution X-Ray tomography and in situ mechanical tests on smooth or notched samples. It will be shown that in model and industrial materials (steels and Al alloys), the three phases composing damage (initiation, growth and coalescence), can be easily imaged and then quantified. The results obtained are completely different from what was measured before, using conventional microscopy techniques. Models allowing to predict the evolution of damage based on the observation, will also be presented and compared with the experimental measurements.

A Multiscale Cohesive Zone Model for Quasi-continua

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Abstract

An atomistic based multiscale cohesive zone model has been proposed for a quasi-continuum (QC) medium. In this approach, coarse grain models for both the bulk medium and the material interfaces, or defects are considered. The material interfaces are considered as the weakest link in the model, the cohesive zone between two bulk media is remodeled as a different lattice strip regions whose lattice constants and atomistic potential are different from those of the bulk medium. Then the local version of QC method is applied to obtain coarse grain models for both the bulk region and the cohesive zone region. The constitutive relations for both bulk region and cohesive element are obtained by employing the local version of QC method. To obtain the atomistic potential in the cohesive zone, we assume that the cohesive zone is a kind of compliance interface that is much weaker than the two adjacent bulk elements. The cohesive strength of the cohesive zone is determined by the van der Waals force or interactions between the cohesive zone and the bulk medium. Since we know the atomistic potential inside the bulk medium, we can obtain the atomistic potential of the cohesive zone by integrate the bulk potential over the rigid bulk medium half space under assumption that the bulk medium is rigid with almost no deformation comparing to cohesive zone region. As we know, the local QC method only provides the coarse gaining model for bulk materials; it prevents us to simulate material failures such as fracture and dislocation motions because of the assumption of uniform deformation in an element. From this perspective, the model we constructed is a multiscale cohesive zone model, which is embed into the QC bulk medium, and it is an atomistically enriched cohesive zone that is compatible with the bulk (local) QC model. This multiscale cohesive zone model has been applied to simulate crack propagation. Crack branching and void formation are all possible for certain parameters and lattice orientations. High speed impact-induced spall fracture has been simulated.
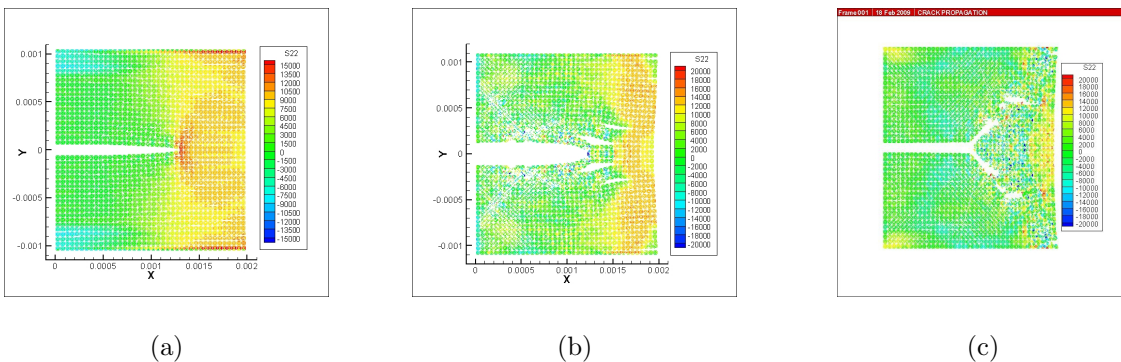
| (a) | (b) | (c) |

Figure 1: Different types of fractures based on different lattice orientations inside the cohesive zone.

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THEORETICAL AND NUMERICAL MODELING OF NON LINEAR BEHAVIOR OF PLASTIC MEDIA CONTAINING MICROCRACKS

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Summary We propose a 3D model of the non linear behaviour of materials made up of a perfectly plastic matrix containing prolate or oblate microcavities (including microcracks). The macroscopic yield function of this class of materials is derived by using a limit analysis approach in which an Eshelby solution-based trial velocity field is considered. Closed form expressions of the anisotropic pressure-sensitive yield function are provided, in the case of parallel oblate cavities (including penny-shaped cracks) and for arbitrary 3D loadings. The approach is then extended to the case of arbitrarily oriented oblate cavities (including cracks). Finally, in order to show the capabilities of the ductile damage model, we present a numerical study (by means of a finite element code (Abaqus)) of a notched specimen. Comparisons of the obtained results to those given by existing models are shown.

POSITION OF THE PROBLEM AND METHODOLOGY

The modeling of the behavior of ductile porous media has been the subject of important researches extending the pioneer work of Gurson [3] in order to take into account voids shape effects (see for instance review by Gologanu et al. [2]). Several applications on structural components has shown the great interest of such extensions [8], [9]. However, as for the Gurson model, there is still need for improving the considered constitutive micromechanical model, in particular for a certain range of loading. This has recently motivated recent studies performed in [5] by developing a limit analysis approach based on the use of Eshelby-like trial velocity fields. The calculations have been be performed in the general case of prolate and oblate voids. The determination of the macroscopic criterion is done by considering a spheroidal unit cell containing a (confocal) spheroidal void, as in [2] or [1]. More precisely, the velocity field in the matrix, $\underline{v}$, is, as classically, decomposed into a first field, $\mathbf{A}.\underline{x}$, corresponding to uniform strain rate $\mathbf{A}$, and an heterogeneous field, denoted $\underline{v}^E$, which describes void expansion and shape changes. It is for $\underline{v}^E$ that it is proposed to consider the exterior point Eshelby solution (see [6]) adapted to an incompressible viscous matrix containing a spheroidal void. By the consideration of these new fields, a suitable approximate expression of the macroscopic dissipation is obtained (see [5]), leading after a minimization procedure to the macroscopic dissipation $\Pi(\mathbf{D})$, $\mathbf{D}$ being the macroscopic strain rate tensor.

GENERAL RESULTS

From the new expressions of the macroscopic criteria of the porous media, derived from $\Pi(\mathbf{D})$, it is shown that the obtained results significantly improve existing criteria for ductile porous media. Moreover, for "low stress triaxialities", these new results agree with the (non linear) Hashin-Shtrikhman bound (see [10]). Moreover, the existence of an effective stress is noted.

For illustration purpose, consider here the particularly simple case of a porous medium with spherical cavities. In this particular case, f being the porosity and σ_0 the yield stress of the solid matrix, the obtained macroscopic criterion takes the form :

$$\frac{\Sigma_{eq}^2}{\sigma_0^2} + 2f \cosh\left\{\frac{1}{\sigma_0}\sqrt{\frac{9}{4}\Sigma_h^2 + \frac{2}{3}\Sigma_{eq}^2}\right\} - 1 - f^2 = 0 \tag{1}$$

Σ_{eq} is the von Mises equivalent stress and Σ_h the hydrostatic part of the macroscopic stress tensor.

In addition to an improvement of the Gurson criterion, expression (1) provides also the remarkable property that the deviatoric equivalent stress Σ_{eq} enters with the hydrostatic stress Σ_h in the *cosh* term. For low values of $\frac{\Sigma_h}{\Sigma_{eq}}$, the nonlinear Hashin-Shtrikman bound is recovered.

It is also shown that in the general case of a spheroidal oblate cavitiy, the developed approach leads to some improvements of existing models [4]. As an example of illustration, consider a porous medium with an oblate
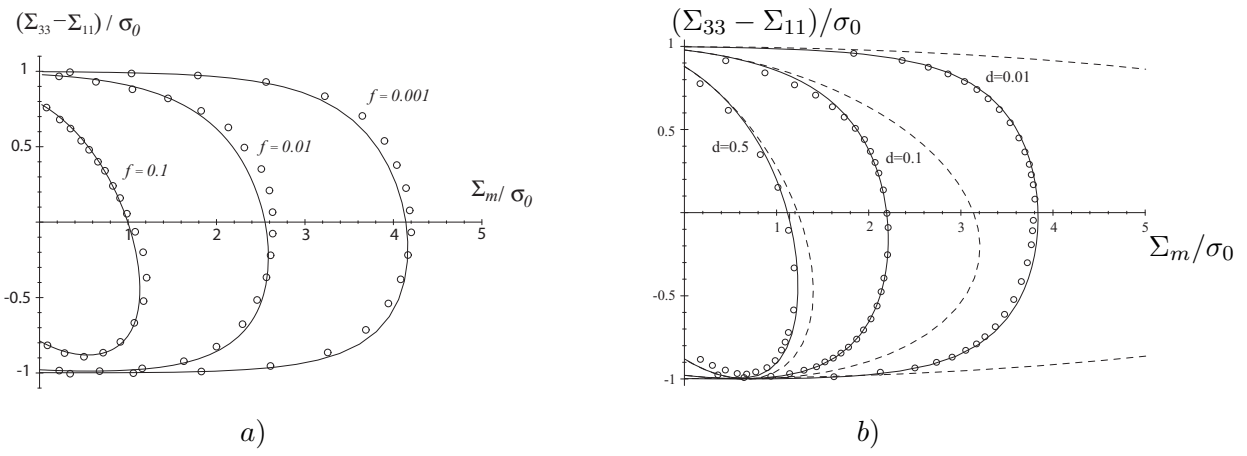
Figure 1. Yield surface of the porous material : a - case of an oblate void with an aspect ratio of $a_1/b_1 = 1/5$. Comparison of the obtained results with "numerical" ones. b- case of penny-shaped cracks. Comparison between the obtained criterion (full line) the Hashin-Shtrikman upper bound (dashed line) and the exact solution, obtained numerically (circles)

void subjected to an axisymetic load. The results in this case are shown on figure 1a and are compared to numerical ones.

THE CASE OF PLASTIC CRACKED MEDIA

We have also examined the case of a plastic solid matrix weakened by a penny-shaped crack which represents in fact a family of parallel cracks (oblate voids with an aspect ratio tending to zero). In this case, the macroscopic yield function, in the frame associated to the void, takes the form :

$$\frac{\Sigma_C^2}{\sigma_0^2} + \frac{1}{2}(2+d)d\cosh\left\{\frac{\Sigma_B}{\sigma_0}\right\} - \frac{1}{2}(2+d)d = 0 \tag{2}$$

Σ_C and Σ_B depends not only on the macroscopic stress, but also on cracks geometry and porosity. The quantity d is the the crack density parameter introduced by Budiansky and O'Connel (1976). On figure 1b is represented the yield locus for different values of the crack density parameter d: $d = 0.008$, $d = 0.14$ and $d = 1.67$. The obtained criterion, the Hashin-Shtrikman upper bound [10] and the exact yield criterion obtained by numerical resolution of the limit analysis problem using the considered Eshelby-type velocity fields are plotted. A very good agreement of the proposed criterion with numerical resultts is observed.
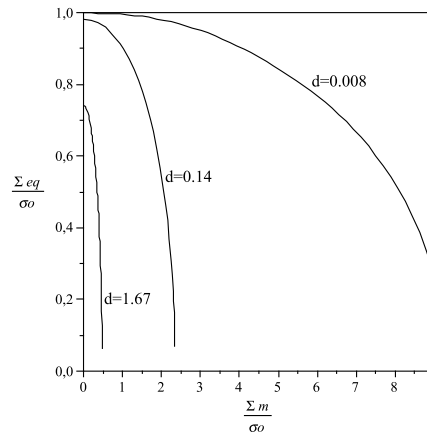

Figure 2. Yield locus for a plastic solid matrix with randomly oriented penny-shaped cracks.

Examples of results, in the case of randomly oriented cracks system are illustrated on figure 2.
Finally, finite element computations (by means of a commercial software (Abaqus)), based on a model constructed from the above criteria, are performed and will be illustrated on a on a notched sample.

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A micromechanical model coupling damage and strain gradient effect

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Standard continuum-mechanics theories cannot describe various situations which are dominated by microstructural effects. In many problems, the load or the geometry of the mechanical structure induce strain or stress singularities and concentrations for which standard models cannot take into account properly the influence of the effects. Generalized continuum theories, on the other hand, such as higher-order gradient theories or couple-stress theories are often considered as describing more adequately the effect of the microstructure at the macroscale. There are many ways to generalize the classical continuum elasticity framework, the main principle of these approaches being to consider additional kinematical variables in order to refine the modeling. In this context a variety of models has been proposed and developed since more than forty years, (see for instance by Toupin et al. 1962, Mindlin et al. 1964, among many other works).

The gradient elasticity theory generalizes the usual linear elasticity theory and includes gradients of the displacement field which have an order higher than the one introduced by the strain tensor. Gradient models are used in the study of special mechanical problem such as localization phenomena and fracture. In the gradient theory, the introduction of strain gradient into the potential introduces supplementary parameters which include a characteristic length of the microstructure. However, in many studies the introduction of this characteristic length into the modeling is made from an empirical point of view but not within a micromechanical framework.

The aim of the present study is to provide the effective properties of a voided elastic material, which incorporate the effect of the gradient of strain, by using a homogenization technic. The material is made up of an elastic matrix and ellipsoidal voids. The incorporation of the effect of the higher order strain gradient effect is made by replacing the classical linear boundary conditions by boundary conditions related to non-homogeneous strains. Following Gologanu and Leblond (1997), those nonlinear boundary conditions are taken on the form of a polynomial function which explicitly depends on the strain and the gradient of strain. The gradient elastic properties are determined by the use of an Eshelby's type dilute scheme, generalized here to the consideration of this new kind of boundary conditions.

Influence of Anisotropy (Crystallographic and Microstructural) on Spallation in Zr, Ta, HY-100 Steel, and 1080 Eutectoid Steel

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Abstract

While the influence of crystallographic texture on elastic and plastic constitutive response has seen extensive investigation in recent years, the influence of texture on the dynamic fracture of engineering materials remains less extensively explored. In particular, the influence of anisotropy, both textural and morphological, on the spallation behavior of materials remains poorly quantified. In this study, experiments have been conducted to quantify the influence of textural and microstructural anisotropy. This includes anisotropically-oriented MnS inclusion stringers in the HY-100 and 1080 steels on spallation, within two crystallographically isotropic steels, and also the influence of crystallographic texture in high-purity polycrystalline Ta and Zr materials possessing strong textures to also assess the role of texture on damage evolution and spallation responses. The effect of crystallographic (texture) on the spallation response of Ta and Zr is shown to play a minimal role in the spallation response of each material compared to the effect of texture on the shock arrival time and the Hugoniot elastic limit that reflects strength in these two high-purity materals. Correlation of the rear-surface pull-back signals with post-mortem metallographic quantification of the damage evolution in the incipiently spalled Ta and Zr samples is presented and contrasted with the role of microstructural morphological anisotropy on the spallation responses of 1080 eutectoid steel and HY-100 steel. In the case of both the 1080 and HY-100 steels the influence of elongated MnS stringers, resident within the essentially crystallographically isotropic steels, on the spallation responses in each steel were investigated. The spallation response of both steels is dominated by the heterogeneous nucleation of damage orthogonal to the MnS stringers. Delamination between the matrix pearlitic microstructure and the MnS stringers in the 1080 steel and the inclusions and the matrix in the HY-100 steel was seen to correlate to a lower pull-back signal during transverse loading than to that parallel to the stringer axis in each steel. The "pull-back" signals and post-spallation metallographic observations for the incipient spallation in Zr, Ta, 1080 steel, and HY-100 steel are discussed with reference to the influence of crystallographic and microstructural anisotropy on damage evolution.

Plastic Instabilities in Polycrystalline Metals Under Strain Reversal at Large Strains

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Abstract

The mechanical behavior under reversed strain has been studied for a broad variety of f.c.c. and b.c.c. metals and alloys with a particular attention for the observed decrease of the yield stress at reloading known as the Bauschinger effect. The material formability, that is the main subject of concern for the present work, is essentially controlled by the subsequent hardening rate. It has been repeatedly noticed that, for moderate to large prestrains, a low or even negative work-hardening behaviour may be recorded. A softening will undoubtedly promote failure. However even in these cases, the hardening may eventually resume, at least if the loading mode does not favour premature flow localisation as in tension. Consequently, a more or less pronounced plateau is noticed on the stress-strain curves when the samples are deformed in compression, torsion, or planar simple shear. This transient behavior, that extends over a strain range that is around one to two times the prestrain, suggests an adjustment of the inner substructure to the new deformation conditions. Several physically based models have been proposed to describe the strain-hardening under strain reversal or, more generally, for loading path changes. The driving force for these developments is the need for robust and versatile flow laws to be implemented in finite element simulations of forming processes. Deep drawing, for example, induces abrupt changes of strain path for rather high levels of prestrain. For such kind of processes, the anisotropy of the plastic response is of primary importance. It is now recognized that the plastic anisotropy is not only due to the crystallographic texture but also to the intragranular microstructure. The latter may be successfully represented by a single dislocation density and its evolution as long as the deformation remains monotonic. By contrast, it is obvious that the transient hardening noted for cross loading or strain reversal tests required additional parameters. The current trend is to extract these parameters from the TEM observations and consequently entities like the cell size, the dislocation wall thickness, the wall orientation with respect to the active slip systems or the dislocation densities within the cells or the walls are regularly considered. The point is that, the dislocation patterns and their evolutions may reflect the existence of some physical processes but the latter may be activated without obvious structural signature. The objective of the present work is (i) to review some specific characteristics associated to strain reversal tests and (ii) to propose a simple approach to describe the observed transient hardening rates.

Integrated Multiscale Characterization-Analysis Methodology for Ductile Fracture in Heterogeneous Metallic Materials

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ABSTRACT

Heterogeneous metallic materials e.g. cast aluminum alloys or metal matrix composites are widely used in automotive, aerospace, nuclear and other engineering systems. The presence of precipitates and particulates in the microstructure often affect their failure properties like fracture toughness or ductility in an adverse manner. Important micromechanical damage modes that are responsible for deterring the overall properties include particulate fragmentation, debonding at interfaces and ductile matrix failure due to void initiation, growth and coalescence, culminating in local ductile failure. The complex interaction between competing damage modes in the presence of multiple phases makes failure and ductility prediction for these materials can be quite challenging. While phenomenological and straightforward micromechanics models have predicted stress-strain behavior and strength of multi-phase materials with reasonable accuracy, their competence in predicting ductility and strain-to-failure, which depends on the extreme values of distribution, is far from mature. To address the needs of a robust methodology for ductility, the work will discuss a comprehensive multi-scale characterization based domain decomposition method followed by a multi-scale model for deformation and ductile failure. Adaptive multi-scale models are developed for quantitative predictions at critical length scales, establishing functional links between microstructure and response, and following the path of failure from initiation to rupture. The work is divided into three modules. (i) Multi-scale morphology based domain partitioning to develop a pre-processor for multiscale modeling, (ii) Enriched Voronoi Cell FEM for particle and matrix cracking leading to ductile fracture and (iii) Macroscopic homogenization continuum damage model for ductile fracture. Finally a robust framework for two-way multi-scale analysis module is the coupling of different with different inter-scale transfer operators and interfaces is developed.

MEASUREMENT OF CRACK OPENINGS IN THE 2D CASE
COMPARISON BETWEEN EXPERIMENTAL AND NUMERICAL RESULTS

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This contribution deals with the measurement of crack opening of a 2D concrete structure to assess the durability of the structure through the transfer properties of the material. Although a discontinuous approach (fracture mechanics, cohesive crack model, X-FEM) of the material failure is able to give straithforward the quantity of interest (i.e. the crack opening through the displacement discontinuity), this kind of approach is not able to estimate the onset of the cracking. Consequently, we use a continuous approach (regularyzed damage mechanics) and estimate afterwards the discontinuous displacement across the crack. In this method, the crack position is first found using a heat conduction-like problem developped by Oliver and Huespe [1]. Once the position and consequently the normal direction to the crack are known, one can use the 1D procedure developped by Dufour et al. [2] to estimate the crack opening at any point of the crack. This method is based on the comparison between the regularized variable driving the damage parameter in the numerical FE computations with its analytical counterpart derived from the strong discontinuity approach.

Experimentally the image correlation technique has been used on 3-point bending and splitting (Brazilian) tests on plain concrete specimens to measure the displacement field. From these fields, the displacment jump (i.e. the crack opening) is evaluated along the crack. Comparison between these experimental measurements and the numerical estimation are made. The error stands within few tens of percents and allows us to estimate quite accurately the tightness of a concrete structure. The error has two origins. The first one is the comparison with the strong discontinuity approach that is not so valid right after the peak load. The second one, that remains even when the crack is widely opened and the strong discontinuity approach is verified, comes from the limited capability of a damage continuum approach to represent the discontinuous failure of the material.

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Discrete modeling applied to the characterization of cracking in brittle materials

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ABSTRACT

Fine description of cracking in civil engineering structures is today a main concern, in particular when dealing with the durability of civil nuclear installations. Furthermore, the current engineering rules, like EuroCode 2 for designing civil engineering structures, are now based on an explicit description of cracking (crack opening and spacing). Discrete modeling is an efficient approach to represent cracking in brittle heterogeneous materials, due to its natural representation of the material heterogeneity and an explicit description of cracking. This work focuses on the description of cracking by such discrete approach.

We present in a first part the used discrete model, based on a representation of the material by an assembly of Voronoi particles, linked together with brittle beams. The simpleness of the links behavior ensures the robustness of the model and a computational efficiency. Details are given on the numerical solver and on the post treatment of the data at the macroscopic scale. The second part focuses on the description of cracking. We show that the discrete model represents in a fine way the crack roughness, the crack opening and the crack length. Different examples, from laboratory samples to reinforced structural elements, illustrate the applicability of the model.

Failure Mechanisms in Geomaterials

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ABSTRACT

Because of the non-associativity of plastic and damage strains, the elasto-plastic operator is not symmetric. As a consequence the main features of rate-independent failure must be reconsidered. The limit surface corresponding classically to all the limit stress states has to be replaced by a bifurcation domain with various geometric or material instabilities and generalised limit states. The usual plasticity criterion and the flow rule have also to be generalised respectively into bifurcation criteria and mixed failure rules.

These questions are considered first according to experimental results (isochoric –undrained-compressions and q constant drained tests on Hostun sand). The complex link between failure, bifurcation, instability and loss of uniqueness is discussed. Then the second order work criterion is introduced, its link with bursts of kinetic energy is established and this criterion is investigated with incrementally piece wise and non linear constitutive relations. Cones of unstable directions are given and plotted in axisymmetric, plane strain and general 3D conditions.

Finally the question of failure in granular materials is investigated by a micromechanical analysis and failure is also simulated and analysed by a discrete element model. The main features of non associated failure shown from the theory are obtained through these direct numerical simulations.

Recent related papers :
- F. Nicot, F. Darve, H.D.V.Khoa, "Bifurcation and second-order work in geomaterials", Int. J. Num. Anal. Methods in Geomechanics, vol.31, n°8, pp 1007-1032, 2007
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Numerical exploration of a high cycle fatigue criterion using a polycrystalline analysis

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A large number of engineering structures are constructed from metals and are subject to repetitive loadings conducting to failure through fatigue. The method developped for lifing do focus generally either on a phenomenological modelling of the fatigue observations at the macroscopic scale of the structure or on a precise material description at the mescopic crystalline scale.

The Dang Van criterion is one of the high cycle fatigue criteria proposed in the '70ies, which combines succesfully an analysis at both the macroscopic and the mesoscopic scale. The main idea is that elastic shakedown should be reached in each grain in order to assure an infinite lifetime. In order to obtain the closed-form formula of the criterion the initial proposoal was based on (i) an elastoplastic Eshelby inclusion (ii) Kroener homogenisation scheme using (iii) simple localisation tensor (equal to the identity).

In the last decades important advances have been reached in the fine description of crystalline plasticity and the computational power enables us to run modells covering several hundreds of grains. Recently several analysis of fatigue phenomena have been realised using polycrystalline plasticity. Manonukul and Dunne [6] used a polycrystal plasticity finite-element model for a nickel-base alloy C263. They were able to precisly reproduce a wide range of cyclic plasticity behaviour in face-centred cubic nickel alloy C263 and proposed a simple fatigue crack initiation criterion based on a critical accumulated slip.

Goh et al.[3] employed crystallographic plasticity in two-dimensional fretting analyses of Ti6Al4V and discuused deformation maps, fretting maps, and shakedown maps are constructed on application of J2 plasticity theory suggesting that plastic ratchetting plays a signifcant role in the fretting fatigue process.

In this presentation we propose to reanalyse the Dang Van high cycle fatigue criterion replacing the initial homogenisation scheme with a numerical multigrain model similar with the ones presented in [6, 3]. The novelty lies in the fatigue criterion which uses directly the mechanical fields at the grain level. The proposed analysis will permit to highlight a series of aspects related to the Dang Van fatigue criterion:

- (i) verify the consistency of the initial assumptions of the criterion [4]

- (ii) explain and estimate the "stress gradient effect" for the criterion [1]

- (iii) observe and estimate the correllation between fatigue, plastic dissipation and thermography observations [2]

- (iv) explain and propose solutions for lifing in the finite life regime [5]

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Theoritical and experimental framework for the multiscale study of fatigue

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Polycrystalline metallic materials are made of an aggregate of grains more or less well-oriented, with respect to the loading axis, for plastic gliding. Under mechanical loading, this diversity of crystalline orientations leads to a heterogeneous deformation state at the microstructure scale: local plastic strains can arise within some grains whereas the sample is under macroscopic elastic loading. Under cyclic loadings, such heterogeneities conduct to crack initiation at the grain scale followed by a growth process until the failure of the specimen or the structure. Besides, local plasticity triggers the appearance of slip marks at the surface of the material along with a thermal dissipation linked to mechanical irreversibilities. Therefore, an exact description of these mechanical and energy phenomena, at the scale where plasticity and damage take place, bring forth the outlook for identification of mechanically admissible models in good agreement with energy considerations.

Some years ago, Luong [5, 6] proposed a thermodynamical framework which allows to establish a link between the observed dissipative regime and the fatigue limit of many materials. Some recent works extend Luong's observations and underline the links between the fatigue phenomenon, the thermoplasticity and the dissipation [2, 3]. This dissipative framework seems to allow the construction of a unified approach in fatigue. However, a purely thermoplastic dissipative framework stumbles on the mean stress effect in fatigue. Indeed, the application of a mean stress under cyclic loading leads generally to a variation of the S-N curve and, consequently, of the macroscopic fatigue limit. In the same way, the observed macroscopic cyclic temperature variations depend also on mean stress. Mean stress is generally taken into account in the multiaxial fatigue criteria with a postulated linear dependence of the shear component on the hydrostatic pressure; this is the case of the Dang Van criterion [4]. As classical purely plastic models depends generally only on deviatoric part of stress tensor, dissipation is however independent on the hydrostatic part.

In a first part, in order to represent all these experimental observations, a new plasticity-damage approach in fatigue, provided by the recent work of Monchiet et al. [7, 8] has been proposed. The main feature consists in the incorporation of some observed damage mechanisms (reported in literature for materials involving faced-centered-cubic structures) in the multiscale framework proposed initially by Dang Van. Here, this approach is derived in the Thermomechanics of Irreversible Processes framework in order to define dissipative terms associated to damage and plasticity and to study the effect of mean stress on dissipation and temperature evolution.

In a second part, an original experimental set-up [1], necessary to realize such mechanical and energy analyses at the microstructure scale, is presented. In order to get simultaneous kinematic and thermal data at the finest scale reachable nowadays, the polycristal grains scale, temperature fields are grabbed by infrared thermography and strain fields by digital image correlation within an original experimental coupling device. Thanks to this experimental set-up, temperature and strain fields have been studied simultaneously during monotonic and cyclic uniaxial loadings on a 316L austenitic stainless steel.

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A homogenization-based constitutive model for viscoplastic porous media with evolving microstructure

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This paper deals with a constitutive theory for porous viscoplastic composites under general three-dimensional finite deformation loading conditions. The proposed model is based on the "second-order" nonlinear homogenization theory of Ponte Castaneda (2002), which makes use of a linear comparison porous material to provide estimates for the nonlinear porous material. In addition, the new model is constructed in such a way that it reproduces exactly the behavior of a "composite-sphere assemblage" in the limit of hydrostatic loadings, and therefore coincides with the hydrostatic limit of Gurson's criterion in the special case of ideal plasticity. As a consequence, the new model improves on earlier homogenization estimates, which have been found to be quite accurate for low triaxialities but overly stiff for sufficiently high triaxialities and nonlinearities. Comparisons are made with FEM calculations and the model is found to give fairly accurate predictions for the evolution of the microstructure, including the dilatation, average shape and orientation of the voids. In addition, the model predictions for the evolution of the dilatation rate in dilute porous media are in good agreement with numerical results by Budiansky et al. (1982) and Lee and Mear (1992, 1994) for spherical and spheroidal voids subjected to axisymmetric loading conditions (aligned with the pore symmetry axis), as well as by Fleck and Hutchinson (1986) and Lee and Mear (1992, 1999) for cylindrical voids with elliptical cross-sections. However, it should be emphasized that the new "second-order" model is based on a rigorous variational principle and is capable of handling arbitrary (ellipsoidal) shapes and orientations of the pores, as well as general, three-dimensional loadings, in contrast to earlier Gurson-type models (Gologanu et al., 1997; Garajeu et al., 2000; Flandi and Leblond, 2005), which are valid only for axisymmetric loading conditions that are aligned with the pore symmetry axis.

Grain scale mechanisms of deformation during strain localization in a granular material

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ABSTRACT

Deformation in geomaterials (soils, rocks, concrete, etc.) is often localised, e.g., in the form of shear bands or fractures. In experimental analysis of materials exhibiting such behaviour standard laboratory methods are insufficient as the majority of measurements are made at the sample scale and rarely at a "local" scale, and almost never at the grain scale. X-ray tomography monitoring during triaxial compression tests allows high resolution full-field observation of the development of deformation, down to the grain scale. However, such images only indicate clearly the deformation when there are significant changes in material density that produce a change in x-ray absorption. 3D Volumetric Digital Image Correlation (V-DIC) approaches have been developed that allow quantification of the full strain tensor field throughout the imaged volume, even when changes in x-ray absorption values are negligible. Moreover, with accurate enough images, the individual grain displacements and rotations might be analysed, using a special implementation of V-DIC.

This paper presents results from a triaxial compression test on a granular material (Hostun sand) recently performed at the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, using an original experimental set-up developed at Laboratoire 3S-R, Grenoble. Complete 3D images of the specimens were recorded at several stages throughout each test using x-ray micro tomography. The images were subsequently analysed using in-house V-DIC codes. Initially we adopted a relatively classical 3D-volumetric DIC procedure, which yields continuum fields of displacements and strain. Subsequently we use an original discrete version of V-DIC, developed at LMS and applied at the grain-scale, with which we are able to follow the individual particle kinematics. Full-field incremental displacement and strain measurements (continuous and discrete) have thus been obtained, which allowed the detection of the onset of strain localisation and its timing relative to the load peak. Furthermore different features of localised deformation are identified and their spatial and temporal development characterised.

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