THREE-DIMENSIONAL SIMULATIONS OF DUCTILE FRACTURE UNDER ARBITRARY LOADINGS

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Abstract
A complete constitutive theory is presented to enable ductile fracture simulations under complex loadings that may involve shear-dominated stress states or even negative triaxialities. The yield criteria accounting for various forms of anisotropy is supplemented with evolution equations to complete the constitutive theory formulation. State-of-the-art ductile fracture theory can only be fully exploited when a robust implementation enabling structural computations is available. This work set out to address the latter within a multisurface framework. A complete constitutive theory of plastic porous materials incorporating homogeneous (HY) and multiple (n) unhomogeneous yieldings (UY), named HUNnY is developed. The capabilities of the new formulation and its implementation are demonstrated by simulating fracture in tension, fracture in shear of top hat specimen and fracture by shear banding. The predictive theory promises to completely change our understanding of some of these most challenging problems that remained elusive for decades.

1. Introduction
The pioneer investigations, by Rogers (1960), on ductile fracture of solids revealed that voids nucleate at inclusions or coarse particles. Voids grow most rapidly at the center of the neck of a tensile rod because of enhanced triaxial tension, leading to central crack formation. Further, lateral crack growth is terminated by cup-cone or double-cup fracture. The earlier stage of stable and diffuse plastic flow in a porous matrix is called the homogeneous yielding (HY) mechanism. The stage of void impingement because of plastic flow localization in the inter-void matrix is called the unhomogeneous yielding (UY) mechanism.

We aim to formulate a complete constitutive theory in a multisurface representation, enabling ductile fracture simulations under complex loadings, such as torsion and compression. State-of-the-art theories that represent fracture mechanisms of homogeneous (HY) and unhomogeneous yielding (UY) are Morin et al. (2015) and Keralavarma and Chockalingam (2016), respectively. As a result, a complete constitutive theory of plastic porous materials incorporating homogeneous (HY) and multiple (n) unhomogeneous yieldings (UY), named HUNnY, is developed. The formulation includes poroelasticity (aimed at capturing stiffness degradation better from the first principles near the complete loss of stress carrying capacity) and, most importantly, a Koiter-like (Koiter (1953)) multisurface representation of yielding.

2. Methodology
The total rate of deformation is written as the additive decomposition of elastic and plastic parts: $\mathbf{D} = \mathbf{D}^e + \mathbf{D}^p$. The elastic part is given by poroelasticity $\mathbf{D}^e = \mathbb{M} : \overset{\triangledown}{\boldsymbol{\sigma}}$. The plastic deformation rate is written as additive decomposition of contribution from individual yielding mechanisms. The material undergoes homogeneous (HY) and multiple (n) unhomogeneous yieldings (UY) during the deformation.

$$\mathbf{D}^p = \dot{\gamma}^{\mathrm{H}} \frac{\partial \Phi^{\mathrm{H}}}{\partial \boldsymbol{\sigma}} + \sum_{\alpha=1}^{N} \dot{\gamma}^{\alpha} \frac{\partial \Phi^{\alpha}}{\partial \boldsymbol{\sigma}} \tag{1}$$

where Φ^{H} corresponds to homogeneous yielding, Φ^{α} corresponds to unhomogeneous yielding of α^{th} system, $\dot{\gamma}$'s are the plastic multiplier, N is the number of unhomogeneous yielding (UY) systems.

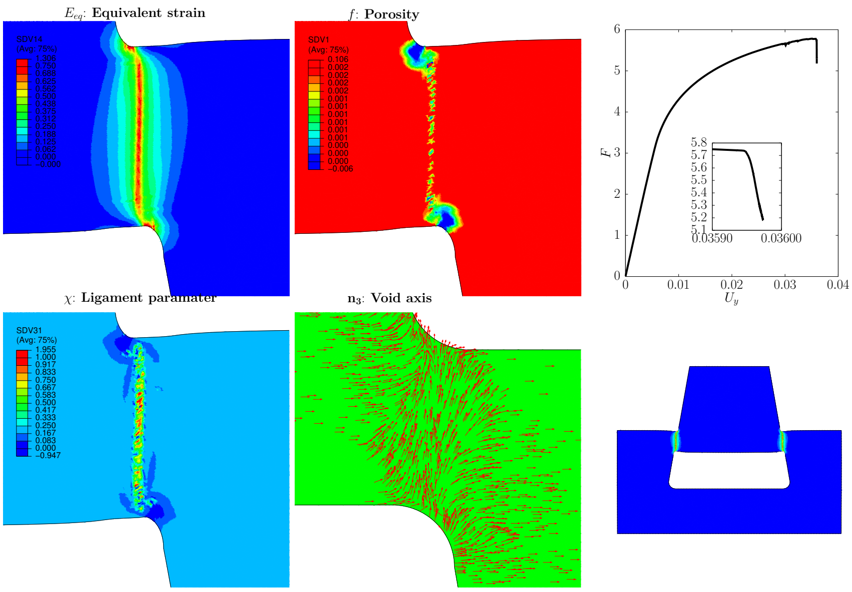
Homogeneous yielding (HY) For homogeneous yielding, the yield criterion of the form $\Phi^{\mathrm{H}}(\boldsymbol{\sigma}; f, \mathbf{W})$ depends on internal state variables (ISVs) such as porosity f, void shape and orientation (contained in $\mathbf{W}$), yield strength of the sound material σ_0.

Unhomogeneous yielding (UY) For unhomogeneous yielding, the yield citerion of the form $\Phi^{\alpha}(\boldsymbol{\sigma}; f, \mathbf{W}, \lambda^{\alpha}, \mathbf{n}^{\alpha})$ depends on ISVs such as porosity f, void shape and orientation (contained in $\mathbf{W}$), yield strength of the sound material σ_0, the plane of localization $\mathbf{n}^{\alpha}$ and void spacing ratio λ^{α}.

Evolution equations Since microstructure evolves with the deformation, equations describing such evolution are required to arrive at appropriate macroscopic estimates. There are five sets of evolution equations 1. The porosity (f) evolution is due to plastic incompressibility of the matrix, the plastic rate of deformation $\mathbf{D}^p$ carries contribution due to all yielding mechanisms. $\dot{f} = (1-f)tr\mathbf{D}^{\mathrm{p}}$ 2. The evolution of $\mathbf{W}$ is determined using the rate-of-deformation and rotation rate tensors associated with the void. 3. The void spacing ratio of every α'th UY system evolves according to the classical relations of change of area and volume due to deformation 4. As in crystal plasticity, where the normal to slip planes convects based on the lattice (or elastic) deformation gradient, here, normal to the UY plane ($\mathbf{n}^{\alpha}$) convects based on the total deformation gradient. 5. If the material is hardening, the evolution of average plastic strain in the matrix is obtained by the equivalence of plastic work.

2. Results

Finite element analysis is carried out on a top-hat shear specimen. The material has isotropic hardening in the form of a power law with initial yield stress of 420 MPa and a power law exponent of 0.1. The microstructure is characterized with initial porosity of 0.1% with initially spherical void. With deformation, the plastic flow localizes in two thin regions on either side of the "hat". However, because the stress triaxiality is close to zero in the zone (except near the edges) porosity growth is minimal in the entire band. On the other hand, significant void rotation takes place in the severely sheared areas, as indicated by the arrows. Each arrow represents the current orientation of the void at that location. Shear-induced rotation is accompanied with void elongation in the rotated state and, depending on the initial void spacing, leads to coalescence by impingement with no significant increase in porosity. As a result, the ligament parameter reaches the critical value of 1, as shown in the corresponding contour.The framework has the capability to sealessly describe degradation at the material point level, hence the loss of load bearing capacity at the structural level.



3. Conclusions

A complete theory of ductile fracture is presented which has the capability to represent failure under arbitrary loadings and its predictive capabilities are illustrated.

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