A CDM APPROACH OF DUCTILE DAMAGE WITH PLASTIC VOLUME CHANGES

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Abstract Continuum Damage Mechanics approaches for ductile damage are revisited in order to incorporate plastic volume changes in conformation with micromechanics based approaches. The theory is still consistent with a general thermodynamic framework and allows the possibility for damage anisotropy as well as damage deactivation effects. Systematic comparisons are made for various multiaxial loading conditions and some applications are shown in the context of metal forming simulation.

GENERAL CONTEXT

Since a long time Continuum Damage Mechanics (CDM) concepts have been developed that obey a general thermodynamic framework. The theories proposed in the past by one of the authors, mainly for creep damage in metals and for the brittle and inelastic behaviour of composite systems, show several interesting capabilities such as the damage anisotropy [1-2] (by second or fourth rank tensors) and the damage deactivation effects [3], both in terms of the actual mechanical behaviour of the damaged material and for the subsequent damage evolutions under complex non proportional loadings.

However, in the context of ductile damage of metals, the corresponding developments were not made inside the same modelling framework. The nearest approaches are made by Lemaître's school [4], mainly within isotropic damage variables. Similar theories based on the energy equivalence principle were also developed by Saanouni and co-workers, extensively applied for the simulation of metal forming processes [5]. Though expressed in a general thermodynamic framework, one of the limitations of the above theories is to not consider properly the possibility for a volumetric plastic strain associated with the volumic damage development.

This is the main objective of the present paper to review some possibilities and to show how the standard thermodynamic framework can be extended in order to include such volumetric plastic strains that play important roles in the ductile fracture under high triaxialities, and are well incorporated into micromechanics based Gurson like approaches [6].

MODEL DEVELOPMENT

The concept of an effective stress based on a strain equivalence assumption is still used throughout the present theoretical development. It allows the consistent mechanical coupling between damage and both the elastic and plastic behaviours. Limiting here to the isothermal, small strain, rate independent framework, and to isotropic hardening and isotropic damage, we propose several coupled yield functions for the modelling of plastic flow. The two first ones are written in the context of a macroscopic CDM approach, incorporating the first stress invariant in various ways :

Parabolic model : $$f_p = \tilde{\sigma}_{eq} + \alpha^* D \frac{(Tr\tilde{\sigma})^2}{\tilde{R}+k} - \tilde{R} - k \le 0 \qquad (1)$$

Elliptic model : $$f_p = \sqrt{\tilde{\sigma}_{eq} + \alpha^* D (Tr\tilde{\sigma})^2} - \tilde{R} - k \le 0 \qquad (2)$$

In which $\tilde{\sigma}$ denotes the effective stress tensor, $\tilde{\sigma} = \sigma/(1-D)$ in the isotropic damage case, and $\tilde{R}$ is the corresponding isotropic hardening effect. K is the initial plastic threshold and $\alpha^* = \alpha + \beta \; Sgn(Tr\sigma)$ a material dependent parameter, depending on the sign of the first stress invariant, in order to adjust plastic volume changes under negative triaxialities. The damage growth obeys a pseudo standard format [2], with an independent dissipation potential that can be chosen Lemaître's form or any other.

A third model is developed in a micromechanics approach of polycrystals, through a scale change based on a self-consistent rule), in which the crystal plasticity is coupled to the slip damage evolutions through a Non Schmid la written at the level of each slip system.

SYSTEMATIC COMPARISONS

The developed models have been compared with classical ones, including the well known Gurson model, and the Rousselier model [7] (also incorporated in a consistent thermodynamic framework). Figure 1 illustrates the corresponding yield criteria at two stages of damage development (or volume fraction of cavities). The models have been implemented in the Z-Set platform (ZéBuLoN finite element code), and used systematically for convergence studies. In the case of the elliptic model (2), very near from Gurson's, figure 2 illustrates the evolutions of the equivalent stress / hydrostatic stress, as well as the corresponding yield surfaces, during an elastoplastic -damage loading under strain control in which the total shear strain ε_{12} and the $Tr\varepsilon = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}$ are increasing proportionally. It has been shown that a limit point may exist, when changing the ratio between shear and hydrostatic strain controls, for which the damage cannot attain its critical value ($D=1$) and the stress cannot vanish continuously, even in the case of a representative volume element (the Gauss point level).

Compared to other approaches, the present one is thought to offer more capabilities and flexibilities. Thanks to previous works in other contexts, its generalization to the anisotropic damage evolutions, including non-proportional paths, seems to be straightforward, at least from a theoretical standpoint.

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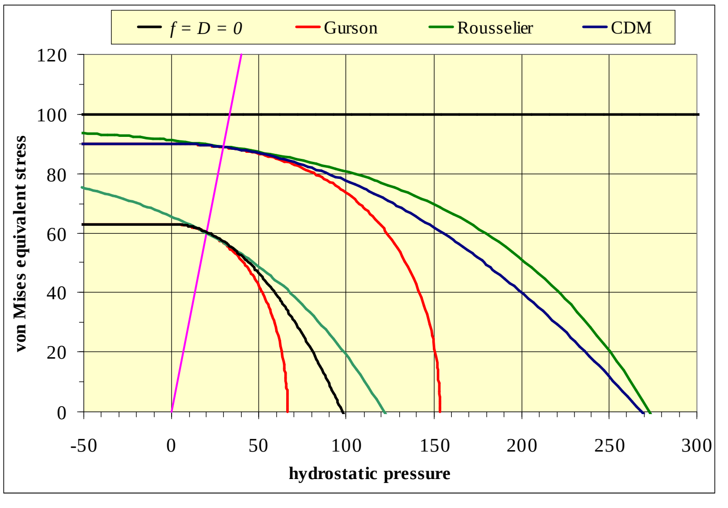

Fig. 1 : yield surfaces with the 3 models at two stages of damage development

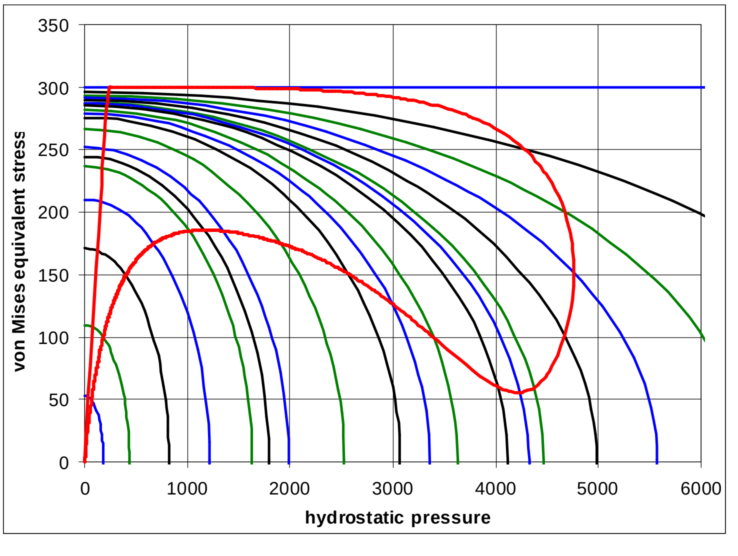

Fig. 2 : evolution of the yield surfaces with the CDM elliptical model for a proportional shear/hydrostatic stra in evolution