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Robust modelling and simulation of ductile damage

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Most structures exposed to severe loadings may suffer damage, possibly resulting in safety risk or economic loss. In complement to experimental studies and design codes and standards, advanced numerical simulation of damage appears as a promising approach to describe such critical regimes. However, damage modelling still faces several difficulties. In the case of ductile damage, characterized by a large amount of plastic strain, spurious strain localization and plastic volumetric locking are observed and should be dealt with.

Ductile damage is one of the most difficult phenomena to be modeled because of its significant level of plastic strain. The literature on the topic of finite strain is particularly abundant. It may be noted that logarithmic formalism [1] seems particularly interesting since it maintains a similar structure in finite strain and small perturbations framework.

Volumetric locking is a well-known numerical issue in finite strain simulations. It is characterized by spatial stress oscillations which disrupt the convergence of the computation. Its origin lies in the fact that classical finite element cannot restrain the displacement **u** to be consistent with quasi-incompressible behavior at every integration point. It can be circumvent by mixed finite elements which introduce not only the displacement but also the pressure P and the volume change θ as unknown variables. In our work, the two polynomial interpolations of $(\mathbf{u}, \theta, P)$ have been considered: P2P1P1 and P2P1P2, where P1 and P2 respectively stand for linear and quadratic interpolation. Both of them avoid the volumetric locking successfully. But we found out that the P2P1P2 element results in strong unacceptable oscillations of the pressure field. Unfortunately, the P2P1P1 mixed finite element also encounters numerical issues: spurious and unexpected localization of plastics strain occurs. This appears to be specific of finite strain: it is observed as well with the finite strain formulation introduced in [2] as with the appealing logarithmic one [1] which retains a close relation with the infinitesimal strain implementation. The same kind of instability has been encountered and analyzed in [3], without immediate solution. Even though the origin of this localization is not clearly understood, it seems to be related to a loss of ellipticity amplifying prematurely the geometrical softening. Therefore, the treatment of strain localization resulting from damage softening may also control the plastic spurious localization, a conjecture that has

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been confirmed in our work, as will be observed hereafter.

In order to control the localization, we propose to combine the mixed finite element with a non-local model based on the gradient of internal variables. It has proved efficient in some fracture models [4]. Here, the gradient of the cumulated plastic strain is introduced in the free Helmholtz energy: a quadratic term is added, weighted by a scalar parameter which reflects the range of the nonlocal interactions. Using a decomposition-coordination method for the numerical solution, two additional degrees of freedom are introduced: the cumulated plastic strain a and a Lagrange multiplier λ. It results eventually in five nodal variables with P2P1P1P1P1 interpolation for $(\mathbf{u}, \theta, P, a, \lambda)$.

Several preliminary test simulations on different geometries both in 2D and 3D show that the volumetric locking and the plastic strain localization are avoided, hence confirming our conjecture. Besides, note that the formulation proved compatible with remeshing [5], thanks to the retrieved smoothness of the different fields.

At this moment, we have successfully combined plastic finite strain formalism, mixed finite element and nonlocal regularization. Additional results will be presented illustrating the ability of the formulation to deal successfully with ductile constitutive laws such as the Gurson model.

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