Issues on Ductile Failure Modelling: Stress State Dependence, Non-Locality and Damage to Fracture Transition

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Ductile failure modelling

The recent investment on the research and improvement on ductile damage and fracture modelling may be explained by the necessity of exploiting and extending of traditional materials capacities, for different industrial applications, whilst maintaining safety rules and abiding to economic restrains. Another important factor has to do with the use of new materials with improved strength properties and the need of understanding their behaviour at severe stress/strain conditions. This is the case, in particular, in metal forming processes involved in the manufacture of a huge variety of structural parts in many industrial sectors, such as, for example, automotive, aeronautics or consumption goods in which materials are subject to significant changes in shape at the solid state that encompass large plastic strains.

Numerical modelling has become indispensable in the design, development and optimization of metal forming processes in the industry. The powerful commercial codes which are available nowadays allow for a reliable prediction of deformation, strain and stresses at critical points of industrial parts. One crucial issue is formability, i.e., the capability of produce a part without defects but within the material limits. The flow of the material, forced by contact with tools involve large plastic strains that, after a given threshold level, may trigger a ductile damage process occurring concomitantly with the plastic deformation due to the nucleation, growth and coalescence of micro-voids.

It is still common practice at the industrial level to use a posteriori fracture criteria, based on the computational evaluation of functions of some state variables that depend on the deformation story (e.g. [1]).These variables may be the total plastic work, the maximum plastic shear work or the equivalent plastic strain. Other criteria may be based on the growth of defects which include geometric aspects (e.g. [2, 3]), growth mechanisms, dependent on principal stresses or hydrostatic pressure or material behaviour coupling (e.g. [4, 5]).

Present production of many components in the industry require complex deformation paths and these criteria very often fail to give the appropriate information. Situations in which the damage localizes away from the sites where the maximum equivalent plastic deformation is concentrated or where damage evolves differently for different compression or traction stress states, different triaxialities or diverse shear stress states are hardly handled by these criteria.

Coupled models. Stress state dependence.

Models in which damage evolution is taken into account through the deformation process are for that purpose more reliable. Two major routes are often taken in building those models. One is based on Continuous Damage Mechanics (CDM) and the thermodynamics of irreversible processes. The most popular ones are based on Lemaitre's model which includes the evolution of internal damage, as well as non-linear isotropic and kinematic hardening in the description of the behavior of ductile materials [6].

Another route is grounded on micro mechanical considerations coupling damage and plasticity at the constitutive level [7, 8]. The Gurson-Tvergaard-Needleman (GTN) model , which is one of the most well-known extensions of Gurson's model, assumes both isotropic hardening and damage. This model includes strong coupling between plastic strain and damage variable, porosity or the void volume fraction, representing the presence of micro voids. More recently Xue [9] has proposed the introduction of a shear mechanism to improve the model performance at low levels of stress triaxialities.

Many researchers have shown that the third invariant of the deviatoric stress tensor, through the so-called the Lode angle, is an essential parameter in the characterization of the effect of the stress state on material yielding and on ductile fracture (e.g. [10, 11]). In particular, Bai and Wierzbicki have suggested a three dimensional fracture loci on the space of equivalent strain, stress triaxiality and Lode angle.

An assessment on the performance of some of the referred models will be carried out here at different stress states.

Non-local models

Nevertheless, most of those models are based on the assumption of the so-called local continuum in which the behaviour of the material is completely represented by a point-wise constitutive law, independently of the influence of surrounding material points. The material is assumed to be continuous at any scale and, therefore, size effects are inherently neglected. However, it is well known that the softening induced by the standard implementation of those models in finite element solutions may lead to mesh and orientation dependence. This fact is associated to the local change of the underlying type of differential equations representing the problem whenever a negative stiffness is locally included due to softening. As a consequence localization effects are not correctly dealt with by mesh refinement.

One of the solutions for this problem is the use non-local models (e.g. [12, 13, 14, 15, 16]). The non-local theory incorporates an intrinsic length, into the traditional continuum theory, trying to mimic those size effects at the constitutive level and, as a side effect, if conveniently formulated it alleviates or solves numerical problems associated with local models, either by means of gradient-enhanced or integral-type formulations.

The derivation of any non-local theory requires the choice of the variable or variables to be enhanced by non-locality. Typical choices are, amongst others, the regularization of variables related to kinematics (such as the strain tensor), regularisation of internal variables (e.g. scalar measurements of the amount of plastic strain or damage) or regularisation of thermodynamic forces power-conjugated with internal variables (for instance, the elastic energy release rate in damage models). In fact, the choice of the non-local variable depends on the kind of material to be modelled and on the nature of the problem to be solved. In the particular case of elasto-plastic damaging ductile solids, the internal degradation of the material, which in the CDM theory is usually treated by means of some damage measurement as an internal variable, is closely linked to the localisation phenomenon.

Different choices for non-local variables (damage, void volume fraction, hardening, elastic energy release rate, equivalent plastic strain) will be here numerically assessed for different combinations of stress triaxiality ratio and Lode angle.

Damage to fracture transition

Continuum models successfully describe most the stages of material behaviour. Nevertheless, when it comes to the final stages of failure, these models are not able to represent the initiation and propagation of macro-cracks within a structure. To correctly address surface decohesion and avoid spurious damage growth, the use of a discontinuous approach becomes imperative. One of the most successful simulations of ductile fracture processes, in a finite element method framework, lay in strategies that involve relatively fine meshes and continuous remeshing. Models based on the smeared crack model, more common in brittle failure applications, in which the effects of a discontinuity are incorporated in the stress field and not at the displacement or strain field level, avoid the need for remeshing.

A successful alternative approach is to locate displacement or strain discontinuities intra-element. A large number of intra-element discontinuity models falls within the embedded discontinuities class [17]. These models are in general characterized by the introduction of new deformation modes in the standard finite element. These deformation modes are able to represent discontinuities with an arbitrary orientation both at the strain level (weak discontinuity) or at the displacement level (strong discontinuity) (e.g [18, 19]).

Another powerful technique to represent discontinuities intra-element is the eXtended Finite Element Method (XFEM) [20] in which the standard displacement field approximation is enriched with functions able to capture the decohesion between two surfaces. Extra degrees of freedom are added to the nodes of the elements containing the discontinuity, allowing free propagation through the mesh. The XFEM possesses interesting characteristics to develop a successful simulation of ductile failure processes.

A simple strategy on how to apply it to ductile failure is briefly described here. When damage reaches a critical value a crack is included into the continuous and subsequently propagates following the damage pattern. To ensure thermodynamical consistency and to avoid a singularity in the continuum equations the transition is made by adding a cohesive law to the model built upon the underlying damage model.

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