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A nonlocal coupled damage-plasticity model for the analysis of ductile failure

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ABSTRACT

This paper presents a nonlocal coupled damage-plasticity model for the analysis of ductile fracture. The proposed model makes use of both damage mechanics and plasticity theories and hence is able to capture the pre-peak hardening and post-peak softening responses as well as the stiffness reduction of the material during the deformation and fracture processes. Nonlocal regularisation technique is used as an enhancement to the proposed damage-plasticity model to deal with softening related problems in the constitutive modelling and the failure analysis. Emphasis is put on the determination of model parameters with a novel calibration procedure, based on the experimental technique (Korsunsky and Kim, 2005) on the measurement of essential and non-essential works of fracture, proposed and effectively used for the model calibration. It is shown that all model parameters can be properly calibrated based on the proposed method, and experimental results, making the model attractive for practical applications. The proposed nonlocal model enables the stress update to be carried out pointwise, and hence facilitates the implementation of the model in existing finite element codes. Numerical examples are used to demonstrate the capability of the proposed model.

1. Introduction

The approaches to the issue of structural analysis in the aeronautical industry have evolved over the decades. Original approaches relied on the principle of avoiding crack initiation in order to ensure fatigue resistance and durability. Later, damage tolerant design principles were introduced, in which the presence of small defects (cracks) was accepted as unavoidable, and emphasis was placed on ensuring that they do not grow to critical lengths within exploitation intervals between inspections. In the current view, not only crack initiation, but also crack propagation and trajectory analysis are very important for ensuring safe design and operation. Aeroengine components are subjected to complex loading induced by the combination of mechanical loading, changing temperatures and thermal gradients, inducing plastic deformation and creep that ultimately may lead to crack initiation and propagation. High temperature components are mostly made from ductile materials such as nickel-base superalloys. In these materials rupture (material separation) is preceded by damage that finds its physical representation in void nucleation, growth and coalescence. Development of populations of these defects in ductile materials is responsible for material softening that is played out in competition with the common strain hardening behaviour observed

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when ductile metal alloys are subjected to (tensile) loading. Modelling the behaviour of these materials in the post-peak softening regime and the correct and reliable prediction of crack propagation even today represent a serious challenge.

In the early 1960s, the development of the finite element method (FEM) brought about a major improvement in the tools available for the study and understanding of deformation in structural components subjected to arbitrary thermo-mechanical loading. However, despite the methods of crack propagation modelling being intensively debated in the scientific community ever since, performing it efficiently and reliably remains nowadays challenging even for simple loading cases, such as pure tensile loading. Considerable effort has been expended by the scientific community in order to solve crack propagation problems in a manner that is computationally as light as possible and that gives the same results for the crack path and propagation rate whichever (suitably refined) mesh is used. For that purpose, two radically different approaches have been thought and developed throughout the years.

The discrete crack approach is performed by introducing the separation of surfaces within the original structural body. Cracks within the original structures can be modelled either through the insertion of special types elements whose boundaries lie along the faces of the advancing crack (e.g. cohesive zone element method (Barenblatt, 1962) or by the introduction of elements with enriched nodal degree of freedom. This later method, known as extended finite element method (X-FEM) (e.g. Moes et al., 1999; Sukumar et al., 2000), allows crack propagation without remeshing. The newly introduced degree of freedom accounts for the displacement jump along the crack and the singular stress field at the tip of the propagating crack.

The second approach is derived from continuum mechanics principles. It considers fracture as the natural ultimate consequence of material degradation (Lemaitre, 1984). It is more realistic than the discrete crack approach in the sense that it accounts for the degradation of the material in the area surrounding the crack and can capture phenomena such as strain localisation. The load-bearing properties of the material (stiffness and strength) are modified through a special state variable referred to as damage. Damage is typically represented by a scalar or a higher dimension object (such as vector or tensor) with values between zero for virgin material and unity for the material that lost all its bearing capacity. Considered in this way, damage becomes an additional field quantity that needs to be considered along with strain and stress, and can be computed either incrementally, or as a certain function of a suitable physical parameter such as inelastic strain. The advantage of enriching the formulation of a continuum deformation problem with the damage parameter is that it allows considering the material post-critical behaviour, i.e. its response under deformations exceeding those when the maximum load-bearing capacity has been reached. Typically, this is associated with strain localisation, formation of discontinuities and fracture. Within a Continuum Damage Mechanics (CDM) framework (Kachanov, 1958; Lemaitre, 1992), cracks are represented by diffuse regions of material damaged so that it lost all its strength in at least one direction. Complete or partial loss of stress-carrying capacity of the material belonging to the ‘‘cracked’’ region provokes stresses redistribution and results in deformation and crack growth concentration in a relatively small region ahead of the crack tip. The rate and direction of the crack propagation are thus determined directly by the damage growth in the process zone. As opposed to the discrete crack approach, no separate fracture criteria are needed. Crack initiation and propagation follow directly from continuum mechanics theory. CDM approach allows treating cracks problems in any nonlinear FE code by simply implementing a routine for a new material constitutive behaviour. Therefore, the method is particularly attractive. In contrast to the discrete crack approach, it allows to take into consideration the material degradation in the vicinity of the crack and strain localisation phenomena. Moreover, in theory, no re-meshing techniques are needed.

However, soon after the introduction of CDM models based on the local formulation (i.e. such that the damage state at a point within the continuum only depends on the stress–strain state and history of that point), it was shown (Bazant et al., 1984) that these finite elements solutions do not converge upon mesh refinement. Due to the stress singularity at the crack tip, the damage field obtained from a local CDM model tends to localise on a plane, even though CDM assumes an homogeneous (or, at least smooth) damage distribution. The total energy dissipated during the cracking process is found to be proportional to the element size, and when the mesh size becomes infinitesimally small the dissipated energy vanishes. This physically unrealistic phenomenon is at the origin of strong mesh-dependency (as for the discrete crack approach). Moreover, strong damage localisation also leads, in some cases, to numerical instabilities (Benallal et al., 1989). Strain softening associated with the material degradation results in the loss of positive definiteness of the tangent material stiffness and ill-posedness of the boundary value problems. This phenomenon is more commonly described as the loss of ellipticity of the governing equation.

Over the years it has become clear that extensions of CDM models incorporating spatial interaction terms (whether they are gradient-based models (Peerlings et al., 1996) or models based on the spatial integral of one of the internal variables (Pijaudier-Cabot and Bažant, 1987) are the best way to overcome the above-listed difficulties. Nonlocal models make use of a material characteristic length to smooth the deformation and/or damage fields and thus prevent localisation of strain and damage within a plane. The newly introduced material characteristic length is particularly interesting because it also turns out to be related to a particular manifestation of the strain localisation phenomenon that accompanies fracture in materials: the so-called size effects, i.e. dependence of material mechanical properties (notably, its strength) on the structure size.

The majority of nonlocal models proposed up to now were intended to describe the behaviour of brittle and quasi-brittle materials (e.g. Pijaudier-Cabot and Bažant, 1987; Jirásek and Rolshoven, 2003; Grassl and Jirásek, 2006; Nguyen and Korsunsky, 2008; Peerlings et al., 1996) whereas ductile rupture was primarily addressed using micro-mechanically based models formulated using the considerations of void growth within a perfectly plastic matrix. A very detailed review of the subject can be found in Besson (2009) and recent contributions to the field include Dunand and Mohr (2011), Lecarme et al. (2011), Malcher et al. (2013), Scheyvaerts et al. (2011), Tekoglu et al. (2012). Like all local or discrete