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A porous-based discontinuous model for ductile fracture in metals

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ABSTRACT

A discontinuous model aimed at modeling ductile fracture for metals is presented. The effect of microvoid nucleation, growth and coalescence on the inelastic response of structural metals is modeled through a suitable interface proposal for cracking analysis. The discontinuos proposal is completely conceived within the general framework of fracture mechanics and porous plasticity concepts. The porosity affects the strength parameters and softening rules defining the failure initiation and post-cracking response of the interface. To demonstrate the soundness and capability of the proposed formulation, a comparative study against numerical simulations obtainable from a classical well-known continuous approach for capturing ductile fracture, based on finite element analysis, is presented.

1. Introduction

Ductile fracture in metals usually follows a multi-step inelastic process involving several concurrent mechanisms, which, at microscopic level, can be subdivided into (a) nucleation of microscopic voids (mostly at second phase particles and inclusions), (b) growth of fine microscopic voids due to localized inelastic deformation and eventual coalescence, (c) localization of plastic flow (the crack initiation) and (d) final failure and crack growing [1,2].

Void nucleation, growth and coalescence and the subsequent crack initiation deal with two distinct mechanisms of ductile fracture [3]: (i) the first mechanism is represented by a crack growth initiation as a consequence of a single void and interacting with the crack tip along the fracture front, while (ii) the second failure considers the simultaneous growth and interaction of multiple voids on the plane ahead of the crack tip.

Moreover, failure under intense shearing at close to zero hydrostatic stress (the mean stress is zero or even negative) is widely observed for ductile metallic materials [4]. Experimental studies [5] and numerical formulations by Barsoum and Faleskog [6,7] aimed at investigating ductile failure under such conditions. Furthermore, the progressive reduction of material ductility with increasing triaxial stress was investigated by Bonora et al. [8] and Benzerga et al. [9], while the temperature effect on the ductile fracture of metal was considered in several works [10,11].

Ductile failure mechanisms and simulations of crack growth in metals are classically analyzed through several of constitutive formulations which mainly represent modified versions or extensions of the model originally developed by Gurson [12]. His study dealt with the growth of a single spherical void which produces the development of ductile fracture.

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Nomenclature

A	nucleation parameter of the continuous model
A_{IE}	nucleation parameter of the interface model
$\mathbf{C}$	elastic stiffness matrix
$\mathbf{C}^{ep}$	tangential interface stiffness matrix for elasto-plastic degradation
E	Young's modulus
f	void volume fraction (porosity)
f_C	void volume fraction value at the beginning of the coalescence
f_F	void volume fraction value corresponding to a total failure
f_0	initial void volume fraction
f^*	modified void volume fraction function
f_{gro}	void volume fraction due to growth of existing voids
f_{nuc}	void volume fraction due to nucleation of new voids
f_N	volume fraction of the nucleated voids for the normal distribution
G	shear modulus
H^α	set of scalar state variables
$\bar{H}$	softening parameter
k_N	normal elastic stiffness
k_T	tangential elastic stiffness
l	thickness of the joint
$\mathbf{n}$	vector outlining the direction of the interface fracture displacements
N	hardening exponent of the power hardening law
q_β	internal parameters of the yield function
s_N	standard deviation value for the nucleation normal distribution of the GTN model
$s_{N_{IE}}$	standard deviation value for the nucleation normal distribution of the interface model
$\mathbf{t}$	interface contact stress vector
$\mathbf{u}$	relative interface displacement vector
$\mathbf{u}^{el}$	elastic part of the relative interface displacement vector
$\mathbf{u}^{p}$	plastic part of the relative interface displacement vector
u	relative interface normal displacement
$\bar{u}$	equivalent plastic interface displacement
$\dot{\bar{u}}$	equivalent plastic interface displacement rate
u_0	elastic limit relative displacement for the interface hardening law
u_N	model parameter to be calibrated for the nucleation description
v	relative interface transversal displacement
$\bar{\varepsilon}$	equivalent plastic strain
ε_N	mean strain value for the nucleation normal distribution
ε_0	elastic strain limit
ϕ	yield function equation
$\dot{\lambda}$	non-negative plastic multiplier
ν	Poisson's coefficient
θ	mixed mode load angle
σ	normal interface contact stress
σ_0	yield stress of the interface fully dense matrix material
σ_e	von Mises stress
σ_m	hydrostatic pressure
σ_y	initial matrix yield strength
$\bar{\sigma}$	yield stress of the continuous fully dense matrix material
τ	shear interface contact stress

Enakoutsa [13] developed a nonlocal methodology to delocalize the damage in Gurson model for porous ductile materials. An original way to account for the surface/interface stresses effect at micro-scale, between the nano-inclusion and the surrounding matrix, was extended for the classical Gurson model for ductile porous media by Dormieux and Kondo [14]. A modified Gurson model was also developed by Jackiewicz [15] for the simulation of damage growth and ductile fracture under low, medium and high triaxial stresses. A phenomenological modification to the Gurson model that incorporates damage accumulation under shearing was proposed by Nahshon and Xue [16]. Furthermore, Nahshon and Hutchinson [17]