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Effects of loading path on the fracture loci in a 3D space

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ABSTRACT

Axi-symmetric and 3D unit cell analyses with continuous non-proportional loading paths are performed to investigate the path dependence of the fracture loci in a 3D space. The loading pattern utilized is the generalization of a number of non-proportional paths recorded in real tests. Failure of the unit cell is predicted when localization of plastic flow occurs, and the failure strains are plotted against the strain history averaged stress triaxiality and Lode parameter to construct fracture loci in a 3D space. The fracture locus with a non-proportional loading path deviates from that with a proportional loading path along the axis of stress triaxiality and becomes non-monotonic in high triaxiality regime. Meanwhile, such deviation occurs only when a certain level of triaxiality is reached. Agreement with the proportional locus as well as monotonicity maintains over a large range of stress triaxiality that covers most cases in reality, as long as the non-proportionality of the loading path is sufficiently low. This provides the rationale for utilizing the average triaxiality based fracture locus as an acceptable approximation in practice. Deviations of the non-proportional loci along the axis of Lode parameter are also observed. Further study on the Lode history dependence suggests using the final value of Lode parameter instead of the averaged one as the Lode axis in the fracture loci, which can alleviate the severity of path dependence for the loading patterns concerned. Based on these results, the effectiveness of the average stress state based fracture loci reported in the literature is discussed.

1. Introduction

The ductile fracture mechanism of many structural materials is most often characterized by void nucleation, growth and coalescence [1–4]. Based on this mechanism, a series of ductile fracture models has been proposed, among which the most popular is the one originally proposed by Gurson [5] and later modified by Tvergaard [6] and Tvergaard and Needleman [7]. The Gurson–Tvergaard–Needleman model, however, is lamed by the lack of a physical mechanism-based void coalescence criterion. Zhang and Niemi [8,9] and Zhang et al. [10] proposed a so-called complete Gurson model incorporating Thomason's plastic limit load model [11] for void coalescence. Thomason's model has been further modified by Pardoen and Hutchinson [12], considering hardening materials and void shape effects. Most recently, an extension of the Gurson model was proposed that incorporated damage growth under low triaxiality straining for shear-dominated states [13,14].

In Gurson-like fracture model, the void volume fraction is essentially a damage parameter employed in the constitutive equation interacting with other state variables. Such model allows the yield surface of the materials to be modified by the damage evolution and is classified as a coupled approach. Another example of such approach is the continuum damage

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Nomenclature

$\bar{\eta}$	the strain history averaged stress triaxiality
$\bar{\theta}$	Lode angle parameter
$\bar{L}$	the strain history averaged Lode parameter
ϵ^*	effective strain at the end of stage *I*
ϵ_f	failure strain
ϵ_p	plastic strain
η	stress triaxiality
η^*	the final value of stress triaxiality
v	Poisson's ratio
σ_0	yield stress
$\sigma_1, \sigma_2, \sigma_3$	three principal stresses
σ_f	flow stress
θ, θ'	Lode angle due to different definitions
ζ	normalized third deviatoric stress invariant
k_1^η	rate of variation of stress triaxiality in loading stage *I*
k_1^L	rate of variation of Lode parameter in loading stage *I*
k_2^η	rate of variation of stress triaxiality in loading stage *II*
k_2^L	rate of variation of Lode parameter in loading stage *II*
L	Lode parameter
L^*	the final value of Lode parameter
n	strain hardening exponent
p	hydrostatic pressure
q	equivalent stress

mechanics-based criterion [15] which is formulated in a phenomenological manner within the framework of thermodynamics [16]. In this approach, damage is not related to any specific micro-mechanism of fracture but it accounts for the damage evolution and progressive degradation of materials at macro-scale [17]. Apparently, the coupled approaches have an intrinsic ability to account for the effect of loading history in plastic deformation.

In contrast, the uncoupled approaches are formulated empirically or semi-empirically with the general form [18–20]

$$\int_0^{\epsilon_f} g(\eta(\epsilon), L(\epsilon))d\epsilon = C \tag{1}$$

where C is a material constant and ϵ_f the failure strain. g is an uncoupled damage indicator that is a function of the current stress state or effectively, the current effective strain ϵ. $\eta(\epsilon)$ and $L(\epsilon)$ are the stress triaxiality and Lode parameter respectively, which will be elaborated later. Failure is predicted when Eq. (1) is fulfilled. This criterion is, however, path dependent. Consider two general categories of loading paths here, the proportional loading where the principle stresses maintain constant directions as well as constant ratios and the non-proportional loading which violates this condition. Specifically, only varying stress ratios are considered in the present work for the non-proportional loading. For more detailed description, the reader is referred to [21]. In the limiting case of proportional loading, the equation reduces to a 3D fracture locus in the $\langle \epsilon_f, \eta, L \rangle$ space. Apparently, the loci in non-proportional loading conditions differ from the proportional one, that is, a unique fracture locus does not exist [18]. There are two possible ways to calibrate parameters in this kind of model: utilizing optimization techniques or finding an alternative fracture locus, and the latter is generally more preferable according to Bai and Wierzbicki [22]. To calibrate the model parameters, Bai and Wierzbicki [18], Bai et al. [23], Lou et al. [20], and Lou and Huh [24] constructed the fracture loci based on the average values of the stress state parameters $(\bar{\eta}, \bar{L})$ in the loading process. This locus is then utilized as a reference surface for more complicated loading paths. Similar practices are seen in Bao and Wierzbicki [25], Bao [26], Oh et al. [27,28], Choung et al. [29], where fracture loci based on average stress triaxiality are proposed empirically, without an explicit interpretation of damage accumulation as in Eq. (1).

The problem with these methodologies is that they artificially removed the path-dependence of the fracture locus. This issue has been discussed in depth by Benzerga et al. [21] from both micro-mechanical and analytical perspectives. Unit cell analysis was performed in the micro-mechanical simulation part. The unit cell method pioneered by Koplik and Needleman [1] is an enabling technique to study the micro-mechanisms behind the ductile failure behavior. In this method, a single void-containing representative material volume (RMV) with periodic boundary conditions is loaded up to void coalescence [2], yielding detailed information on void growth and coalescence. For more detailed information on the history of unit cell analyses with proportional loading paths, the reader is referred to [30,31]. Only a limited number of unit cell studies have