International Journal of Solids and Structures 51 (2014) 2370–2381

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

Numerical simulation of 3D ductile cracks formation using recent improved Lode-dependent plasticity and damage models combined with remeshing

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ARTICLE INFO

Article history:
Received 24 October 2013
Received in revised form 28 January 2014
Available online 17 March 2014

Keywords:
Ductile damage
Lode parameter
Remeshing
Cup-cone fracture
Slant fracture

ABSTRACT

Damage to fracture transition has become a popular topic in the ductile fracture scientific community. Indeed, the transition from a damage continuous approach to a discontinuous fracture is not straightforward both from mechanical and numerical points of view. In the present study, a new improved Lode dependent phenomenological coupled damage model is used to investigate the ductile fracture in different mechanical tests. The remeshing and elements erosion techniques are employed to propagate the ductile cracks in 3D models using Forge® finite element code. This code is based on a mixed velocity–pressure formulation using the MINI element $P1+/P1$. In addition, the plasticity behavior is modeled by a Lode-dependent plasticity criterion. Applications to different mechanical tests at different loading configurations, using identified damage model parameters, show good agreement in terms of fracture prediction between experimental and numerical results.

1. Introduction

Damage to fracture transition has become a popular topic in the ductile fracture scientific community. Indeed, the transition from a damage continuous approach to a discontinuous fracture is not straightforward both from mechanical and numerical points of view. Tvergaard and Needleman (1984) first studied numerically the cup-cone fracture formation based on 2D axisymmetric finite element (FE) simulation, by using the GTN model (Gurson, 1977; Tvergaard and Needleman, 1984) and introducing an initial geometrical imperfection. These authors reproduced quite accurately the cup-cone fracture pattern but the use of an initial imperfection was the major limitation of this study. Besson and co-workers (Besson et al., 2001, 2003) used GTN and Rousselier models to study in details the formation of cup-cone and slant fractures as well as the influence of different factors (e.g. mesh design, symmetry, element aspect ratio, constitutive damage parameters etc.) on the numerical fracture surfaces. An indicator was defined by these authors (based on a bifurcation analysis) to detect the zone where strain and damage localization could occur. Based on 2D simulation of plane strain tensile test and 2D axisymmetric tensile test on round bar, the authors concluded that the formation of slant and cup-cone fracture surfaces depends on the constitutive model used as well as mesh size and mesh configuration. The authors showed that, a judicious choice of model constitutive parameters had to be made to obtain the cup-cone fracture (e.g. to obtain the cup-cone, the choice for the critical value of porosity f_c in the GTN model was not a realistic value of the micro-mechanical parameter). Based on experimental results of Bao and Wierzbicki (2004), Teng (2008) carried out the numerical simulation of cup-cone fracture obtained from tensile test on notched round bar and slant fracture obtained with plane strain tensile test. By using the Lemaitre coupled damage model (the 2 parameters version) and 2D FE models with element deletion technique, the author reproduced successfully the 2D slant fracture but the cup-cone fracture was not well captured. Also with the element removal technique, El Khaoulani and Bouchard (2012) used anisotropic mesh adaptation combined with error estimation based on the Lemaitre damage variable and its gradient, to obtain a cup-cone fracture in an axisymmetric tensile test. The main advantage of this method is, starting from a coarse mesh, automatic mesh adaptation and remeshing allow capturing the crack path with sufficient mesh refinement. The CPU time is thus significantly reduced.

Mediavilla and coworkers (Mediavilla et al., 2006a,b) used both coupled (with a regularization technique) and uncoupled damage models combined with a continuous-discontinuous approach as well as a remeshing technique to propagate a crack. More recently,

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http://dx.doi.org/10.1016/j.ijsolstr.2014.03.005
0020-7683/

Nomenclature

C_s, C_{ax}, C_t, C_c, k	material constants in the J_2-J_3 yield criterion
D	Xue damage parameter
E, ν	Young's modulus and Poisson's ratio
E_M, σ_M	Young's modulus and flow stress of undamaged material
J_2, J_3	second and third invariants of deviatoric stress tensor
$\dot{\bar{\epsilon}}_p$	equivalent plastic strain rate
ϵ_f	equivalent plastic strain at fracture
$\epsilon_{f0}, p_L, q, k, m, \beta, \gamma, \epsilon_{DX}, D_c$	material constants in the modified Xue damage model
η	stress triaxiality
$\bar{\epsilon}_p$	equivalent plastic strain
$\bar{\sigma}$, q	von Mises equivalent stress
σ_0	flow stress
$\sigma_1, \sigma_2, \sigma_3$	3 principal stresses, $\sigma_1 \geqslant \sigma_2 \geqslant \sigma_3$
$\theta_L, \bar{\theta}$	Lode angle and Lode parameter
$\underset{\sim}{\epsilon}, \underset{\sim}{\epsilon}^p, \underset{\sim}{\epsilon}^e$	total, plastic and elastic strain tensors
p	hydrostatic pressure
$w(D)$	weakening function (Xue model)

Feld-Payet et al. (2013) also employed this technique with a non-local formulation to model crack propagation. These studies required remeshing to insert new discrete crack growth. Cracks were inserted along lines where damage was maximum. Seabra and coworkers (Seabra et al., 2013) proposed a similar continuous-discontinuous approach as in Mediavilla et al. (2006a) and Feld-Payet et al. (2013) using the XFEM technique and the non local Lemaitre damage model to simulate cracks propagation without remeshing. Once again, only 2D applications were performed. In addition, many studies among the above-mentioned employed the Lemaitre and GTN damage models, which are stress triaxiality-based, to model damage accumulation process. Several recent studies have proved that the Lemaitre model fails to predict the maximum damage location in shear dominated loadings, for both simple torsion test (Cao et al., 2013b) and shear-dominated forming processes (Cao et al., 2013a). The GTN model is well-known not adapted to predict fracture for shear-dominated loading applications. Recent studies (Xue, 2008; Nahshon and Hutchinson, 2008) proposed different modifications for this model by accounting for the influence of the third deviatoric stress invariant in its formulation. However, these modifications are rather phenomenological, which are not based on micro-mechanical considerations. The use of a suitable damage model, which is capable of capturing the damage localization under different stress states, is essential to obtain an accurate fracture initiation location. In addition to the stress triaxiality, which is the ratio between the mean stress (σ_m) and the von Mises equivalent stress ($\bar{\sigma}$), the Lode parameter has been proved to have important influences on material ductility (e.g. Bai and Wierzbicki, 2008; Barsoum and Faleskog, 2007), thus on damage localization. This parameter is defined by a relation between the second and the third invariants of the deviatoric stress tensor, which helps distinguishing different stress states having a same stress triaxiality ratio. Damage models therefore must account for its influence.

Despite its simplicity, the element removal technique coupled with remeshing is a convenient way to model the damage to fracture transition for 3D configurations. Mesh dependency may deteriorate the stress field computation at the crack tip, which would be particularly problematic for brittle fracture when the crack path is computed based on stress intensity factor. For ductile fracture, the crack path is less sensitive to the local stress field at the crack tip. Fracture can be driven by ductile damage values and the use of the element erosion with a sufficiently fine mesh may conduct to good crack path prediction. In addition, for large strain applications (e.g. uniaxial compression test or metal forming processes) remeshing approach should be used to avoid extreme element distortions and guarantee well-shaped elements once crack is initiated.

In the present study, the formation of cup-cone fracture and slant fracture in tensile tests on notched round bar (NRB) and flat grooved (FG) specimens of a high carbon steel as well as diagonal crack in axisymmetric compression test on an aluminum 2024-T351 is studied. Damage accumulation is calculated using an enhanced Lode dependent damage model initially proposed by Xue (2007a). The remeshing and elements erosion techniques are used to propagate the ductile cracks in 2D axisymmetric and 3D models. With the present approach, neither initial crack (as in Tvergaard and Needleman (1984)) nor discrete crack growth (as in Mediavilla et al. (2006a)) needs to be defined. First, the enhanced Xue damage model is presented, followed by an application in fracture pattern prediction for a compression test on an aluminum, compared with experimental results of Bai and Wierzbicki (2008). In the second section, the tensile tests on NRB and FG specimens are addressed. The strain hardening and damage parameters for the high carbon steel studied were identified from different mechanical tests using J_2 plasticity (Cao et al., 2013a). However, the J_2 plasticity with the hardening law identified fails to describe the plastic behavior in tensile tests on FG specimens. A plasticity model that accounts for the influence of the second and third deviatoric stress invariants is thus employed. For the tensile test on round bar, due to the axisymmetric property of the specimen and loading, a 2D axisymmetric model is used. For the tensile test on flat grooved specimen, the ideal plane strain condition is not fulfilled and a 3D simulation is necessary to capture the crack propagation both through specimen's thickness and specimen's width. The fracture is triggered by critical values of the damage variable and the crack orientation follows the maximum direction of damage. These fracture surfaces are then compared with the experimental results.

2. Models and techniques

2.1. Enhanced Xue model

Xue (2007a) proposed a phenomenological damage model, which is based on the definition of the equivalent fracture strain ϵ_f as a function of hydrostatic pressure (p) and Lode angle (θ_L):

$$\epsilon_f = \epsilon_{f0}\mu_p(p)\mu_\theta(\theta_L), \tag{1}$$

where ϵ_{f0} is the reference fracture strain, which is determined from tension test at constant zero confinement pressure; $\mu_p(p)$ and $\mu_\theta(\theta_L)$ are the pressure-dependent function and the Lode angle-dependent function respectively. Eq. (1) defines a fracture envelope in three-dimensional space of pressure, Lode angle and equivalent strain. Since p and θ_L are orthogonal to each other, they can have separated forms:

$$\mu_p = 1 - q ln\left(1 - \frac{p}{p_L}\right), \quad \mu_\theta = \gamma + (1-\gamma)\left[\frac{6|\theta_L|}{\pi}\right]^k, \tag{2}$$

where p is the hydrostatic pressure, p_L is the limit pressure (above which damage does not occur), θ_L is the Lode angle, γ is the ratio between fracture strain under shear loading and fracture strain under