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On the extension of the Gurson-type porous plasticity models for prediction of ductile fracture under shear-dominated conditions

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ABSTRACT

One of the major drawbacks of the Gurson-type of porous plasticity models is the inability of these models to predict material failure under low stress triaxiality, shear dominated conditions. This study addresses this issue by combining the damage mechanics concept with the porous plasticity model that accounts for void nucleation, growth and coalescence. In particular, the widely adopted Gurson–Tvergaard–Needleman (GTN) model is extended by coupling two damage parameters, representing the volumetric damage (void volume fraction) and the shear damage, respectively, into the yield function and flow potential. The effectiveness of the new model is illustrated through a series of numerical tests comparing its performance with existing models. The current model not only is capable of predicting damage and fracture under low (even negative) triaxiality conditions but also suppresses spurious damage that has been shown to develop in earlier modifications of the GTN model for moderate to high triaxiality regimes. Finally the modified GTN model is applied to predict the ductile fracture behavior of a beta-treated Zircaloy-4 by coupling the proposed damage modeling framework with a recently developed J_2–J_3 plasticity model for the matrix material. Model parameters are calibrated using experimental data, and the calibrated model predicts failure initiation and propagation in various specimens experiencing a wide range of triaxiality and Lode parameter combinations.

1. Introduction

Microvoid nucleation, growth and coalescence, has been regarded as a common mechanism of ductile failure of metals and alloys. Early studies by McClintock (1968) and Rice and Tracey (1969) on growth of cylindrical and spherical voids in infinitely large, plastic solids showed the major parameters in this fracture process and suggested possible further developments towards mechanism-based, micromechanical models that describe the complex ductile failure process. Later Gurson (1977) proposed a homogenized yield surface for void-containing materials based on the maximum plastic work principle, and Rousselier (1987) described the mechanical behavior of voided materials using thermodynamic and plastic potentials. More recent efforts on this area have focused on extending/modifying these models to develop computational schemes that simulate the ductile fracture process under various circumstances. Tvergaard (1981, 1982) introduced two adjustment parameters into the Gurson model to account for the effect of void interaction and material strain hardening. Chu and Needleman (1980) proposed void nucleation models controlled by the local stress or plastic strain. Tvergaard and Needleman (1984) introduced a simplified method to provide for rapid deterioration of stiffness after localization has occurred in the material. Koplik and Needleman (1988) proposed a unit cell approach to calibrate the micromechanical parameters of the homogenized model. Gologanu et al. (1993, 1994) extended the Gurson model and derived a yield function for materials containing spheroidal voids. The Gurson model, with additional developments by Tvergaard and Needleman, is often referred as the GTN model. For the Gurson-type model, the prediction of ductile fracture comes out naturally through the progressive loss of load carrying capacity at the material level. With the existence of a critical porosity to predict ductile fracture, the porosity serves not only as an internal variable, but also as a “failure indicator”. To address the mesh sensitivity issue inherited from the lack of a length scale in the material model, Xia et al. (1995) and Gao et al. (1998) presented a computational cell approach based on the GTN model and predicted the constraint effect on ductile fracture. This idea of representing material in the fracture process zone as cell elements governed by the GTN model has been widely employed by the computational fracture mechanics community in recent years.

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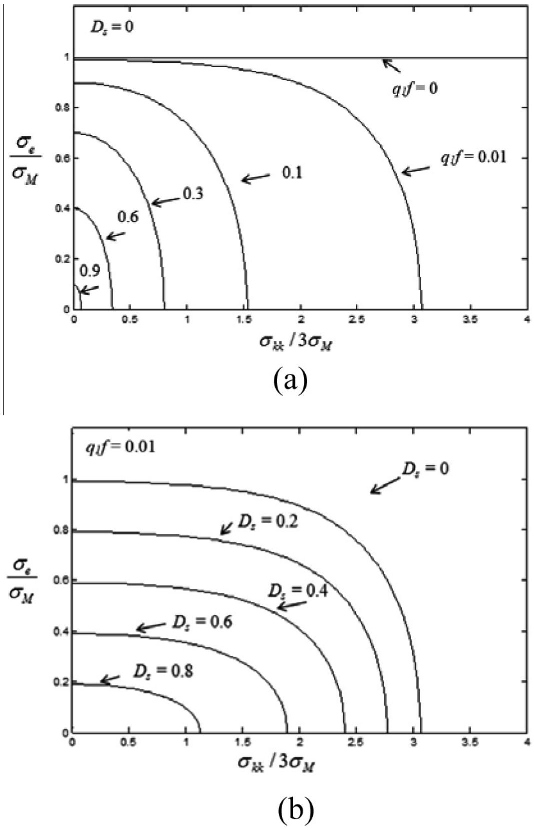

Fig. 1. Effect of volumetric damage and shear damage on the yield surface: (a) $D_s = 0$, (b) $q_1 f = 0.01$.

Despite the apparent success and wide popularity of the GTN model in predicting ductile fracture, it still suffers from several limitations (Benzerga and Leblond, 2010). A major drawback of the GTN model is its inapplicability to model localization and ductile fracture under low stress triaxiality, shear dominated deformations, since it does not predict void growth and damage under shear loading. Recent modifications have been motivated by this limitation to include shear-induced damage in the GTN model, among which the work by Xue (2008) and Nahshon and Hutchinson (2008) have received the most attention. These modifications preserve the original form of the GTN model while treating the void volume fraction in the model as a generalized damage parameter driven by a volumetric contribution that represents the traditional void nucleation, growth and coalescence processes *and* a deviatoric contribution that incorporates void shearing mechanisms. These modifications show improvement in predicting ductile damage under low triaxiality conditions but indicate excessive and spurious damage in the cases of moderate to high triaxiality. Nielsen and Tvergaard (2010) recognized this problem and introduced an ad hoc modification to the shear damage evolution law to reduce shear damage under high triaxiality. Moreover, these modified GTN models are shown to over-predict the volume change and thus result in unreasonable numerical results under shear-dominated conditions.

To resolve the problems faced by the existing models, a new extended GTN model is proposed in this study by combining the damage mechanics concept of Lemaitre (Lemaitre, 1985; Lemaitre and Lippmann 1996) with the GTN void growth model. Lemaitre's continuum damage mechanics (CDM) model treats the effect of damage in a purely phenomenological way and does not explicitly describe the details in the microstructure. It is based on the idea that the actual sustainable stress level in the material increases due to the reduction of the effective load bearing area resulted from defects such as micro-cracks or micro-voids. In this framework, a damage variable is introduced as the internal variable to the plasticity model without the details of the micro features being defined. Similar to using the porosity in a GTN model as a "failure indicator", the damage variable in CDM is also used as a "failure indicator". The CDM model is widely used in literature with various damage definitions, e.g., Chaboche (1988) and Xue (2007). By combining the GTN model with the CDM concept, two damage parameters, the volumetric damage (effective void volume fraction) and the shear damage, are coupled into the yield function and flow potential. The evolution law for void volume fraction remains the same as in the original GTN model and a new shear damage evolution law is proposed. Separate critical damage condition is used for volumetric damage and shear damage and complete material failure is said to have occurred if the total damage parameter (a combination of volumetric damage and shear damage) reaches unity. By doing this, the proposed model can no longer be regarded as a micromechanical model but a phenomenological one.

Table 1
Model parameters for extended GTN model used in the single material point analyses.

q_1	q_2	f_0	f_c	f_f	ε_f^s	n	k
1.5	1	0.005	0.1	0.25	1.4	5	0.7

This paper is organized as follows. In Section 2 we first briefly review the GTN model and the recent modifications by Xue (2008) and Nahshon and Hutchinson (2008). A new model is presented after the discussions of the drawbacks of the existing models. The effectiveness of the new model is illustrated through a series of numerical tests that compare its performance with existing models in the literature. In Section 3 we apply the new model to predict the ductile fracture behavior of a beta-treated Zircaloy-4, where the elastic–plastic response of the undamaged material exhibits tension–compression asymmetry and is described by a recently developed J_2–J_3 model (Zhai et al., 2014). The material constants involved in the model are determined based on the experimental observations reported by Cockeram and Chan (2009, 2012) as well as model calibrations using experimental data reported in Zhai et al. (2014). The predicted failure initiation and propagation behavior and load–displacement response of specimens experiencing a wide range of stress states are compared with experiments. Finally some concluding remarks are made in Section 4.

2. The ductile failure model

In this section, we first briefly describe the GTN model as well as recent modifications by Xue (2008) and Nahshon and Hutchinson (2008). After discussing the drawbacks of these existing models, we present a new, modified model by combining the damage mechanics concept and the void growth model.

2.1. The original GTN model

To date, the most widely used micromechanical model for ductile fracture descends from Gurson with extensions by Tvergaard and Needleman (Gurson, 1977; Tvergaard, 1981, 1982; Tvergaard and Needleman, 1984). The yield function of the GTN model takes the following form

$$\Phi = \left(\frac{\sigma_e}{\sigma_M}\right)^2 + 2q_1 f \cosh\left(\frac{q_2}{2}\frac{\sigma_{kk}}{\sigma_M}\right) - 1 - (q_1 f)^2 = 0, \qquad (1)$$

where: f is the current void volume fraction; σ_e is the macroscopic effective stress; σ_{kk} is the hydrostatic stress; and σ_M is the current