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A finite strain continuum damage model for simulating ductile fracture in steels

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ABSTRACT

A new coupled plasticity-damage model is proposed within a finite deformation framework for modeling ductile fracture in ASTM A36 structural steels. Damage mechanics principles of effective stress and strain equivalence are employed to formulate a new constitutive model for simulating damage due to the physical processes associated with microvoid nucleation, growth and coalescence. A scalar damage variable is used to track the micro-structural changes that occur during the ductile fracture process. The model is calibrated and validated by comparing its response to the results obtained from experimental testing of four symmetrically and asymmetrically notched ASTM A36 steel specimens. The proposed model is shown to successfully model failure due to ductile fracture under stress states typically observed in structural engineering applications.

1. Introduction

Ductile fracture in steel is a multistep process resulting from microvoid nucleation, growth and coalescence of microvoids in a plastically deforming material [1]. Microvoids typically nucleate at inclusions either by decohesion/debonding of the inclusion matrix interface or by fracture of the inclusion itself [2]. Void nucleation is followed by a void growth stage where microvoids grow under the applied stress state, and the final phase of ductile fracture occurs when adjacent microvoids coalesce together into a crack. The microvoid growth stage is highly influenced by the state of stress in the material, measured in terms of stress triaxiality ($T := \sigma_h/\sigma_m$) and defined as the ratio of the hydrostatic stress (σ_h) and Mises stress (σ_m). At high stress triaxiality ($T > \sim 1.0$), void growth is usually volumetric and microvoid coalescence is due to internal necking of the intervoid ligaments. However, at low stress triaxiality ($T < \sim 1.0$), microvoids may also elongate and final fracture initiation is by shear localization between the microvoids [3–5]. For instance, high triaxiality is observed in connection regions and shear links [6], while reduced beam sections are under low triaxiality [7]. This paper is concerned with constitutive modeling of damage attributed to microvoid growth in structural steels.

The ductile fracture process can be modeled using either uncoupled or coupled models. The constitutive relationship inherent to uncoupled models is assumed to be unaffected by material damage, such as that caused by nucleation and growth of microvoids and usually employ J_2 plasticity as a constitutive model. These models assume that fracture initiation occurs upon the onset of microvoid coalescence, detected by means of a fracture criterion in the post processing step [8–11]. Coupled models can be broadly classified into micromechanics and damage-mechanics based models. The former are derived by explicitly modeling the microstructure through unit cell simulations [12]. The latter simulate microvoid evolution

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Nomenclature

a_0, a_t, a_2, a_3 constitutive material parameters
α^d, α^p damage and plastic internal variables
$\boldsymbol{b}^e$ elastic Finger tensor
α_c^d critical damage parameter
$\boldsymbol{C}^p$ plastic Cauchy tensor
D_{int} internal energy dissipation rate
ε_n, ε_c nucleation and coalescence strains
$\Delta\varepsilon$ smoothening parameter
$\boldsymbol{F}$, $\boldsymbol{F}^e$, $\boldsymbol{F}^p$ total, elastic and plastic deformation gradient
γ plastic consistency parameter
J Jacobian determinant
k, μ bulk and shear modulus
$\lambda_a^e, \hat{\boldsymbol{n}}_a, a = 1, 2, 3$ Eigen values and Eigen vectors of elastic Finger tensor
Ψ, Ψ^e, Ψ^p total, elastic and plastic free energy functions
ϕ^p plastic potential
$\mathbb{P}_2, \mathbb{P}_2^{-1}$ pullback and pushforward operators
σ_h, σ_m hydrostatic and Mises stress
T stress triaxiality
$\boldsymbol{\tau}, \bar{\boldsymbol{\tau}}$ Kirchhoff and effective Kirchhoff stress tensor
$\boldsymbol{\tau}_{vol}, \boldsymbol{\tau}_{dev}$ volumetric and deviatoric component of Kirchhoff stress tensor
$\mathcal{T}_1 \mathcal{T}_2$ threshold functions
$\boldsymbol{\varepsilon}^e, \bar{\beta}, \bar{\boldsymbol{\eta}}, \tilde{\boldsymbol{\eta}}, \boldsymbol{a}, \bar{\boldsymbol{s}}, \bar{\boldsymbol{p}}$ model implementation parameters
$K^p, \sigma_{\max}, \sigma_Y, a$ saturation hardening parameters
ζ^p hardening function

by introducing damage internal variables into the constitutive relationship [13,14]. Irrespective of these differences, the constitutive equations in the case of coupled models have internal variables and evolution equations to simulate damage due to microvoid nucleation, growth and coalescence during the ductile fracture process.

The Gurson model [12] and its extensions [15–17] belong to the category of micromechanical models. Gurson [12] first proposed an approximate yield criterion and flow rules for rigid plastic porous material using an upper bound variational approach. Subsequently, Tvergaard [18] performed bifurcation studies on unit cells and modified the Gurson yield criterion to account for the void interaction effects. Tvergaard and Needleman [19] further modified the Gurson model to account for the rapid loss of load carrying capacity of the material at the onset of microvoid coalescence. This form of Gurson model, also referred to as Gurson–Tvergaard–Needleman (GTN) model, is popularly used to model ductile fracture in metals [20]. The relative success of the GTN model is primarily due to the incorporation of a sufficient number of adjustable parameters to enable curve fitting of the desired experimental results. However, the GTN model has nine material parameters and these parameters are difficult to calibrate [21]; improper choice of model parameters can easily lead to convergence issues [22]. Furthermore, its implementation is computationally expensive as four coupled nonlinear equations are needed to be solved at each integration point during finite element simulation, and without careful implementation to ameliorate numerical difficulties, convergence may be difficult to obtain [22]. The Gurson model has also been recently extended to account for the Lode parameter [23] and to account for damage due to shear [24], with a corresponding increase in the number of model parameters that are again difficult to calibrate.

GTN model parameters are dependent on the state of stress within the material [25]. Therefore, parameters calibrated to a particular experiment cannot be used to simulate fracture in situations which differ largely from the original experiment used for model calibration. Also, in the GTN model, the void nucleation strain is independent of hydrostatic stress. However, void nucleation models proposed by Argon et al. [26] and Goods and Brown [27], and metallurgical studies [28–30] have shown that void nucleation strain is sensitive to hydrostatic stress and that the nucleation strain decreases with increase in mean stress. Furthermore, the chosen parameters are sometimes found to be inconsistent with metallurgical results and may have no physical significance [31]. With the growing interest in the structural engineering community to model failure of steel structural systems, computationally efficient models are needed to simulate ductile fracture in structural steels [32].

In this paper a new continuum damage mechanics-based plasticity model is proposed within a finite deformation framework for modeling the micromechanical process of ductile fracture in ASTM A36 structural steels. Damage mechanics principles of effective stress [33] and strain equivalence [34] are employed to formulate a constitutive model for simulation of damage due to microvoids nucleation, growth and coalescence. The microscale response of the damage model arises from the addition of internal state variables known as damage variables that represent the change in microstructure of the material undergoing a deformation process.