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Gurson-based modelling of ductile damage and failure during cyclic loading processes at large deformation

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ABSTRACT

Purpose is the formulation, numerical implementation, identification and application of a material model for ductile damage and failure during cyclic and non-proportional loading. The authors combined a hyperelasticity-based elasto-plastic model for non-linear isotropic as well as kinematic hardening with a modified Gurson model. Evolution strategy helped identify the model parameters for the high-strength steel 10MnMoNi5-5. The simulation of ductile failure in fracture mechanics specimens verified the model with respect to cyclic loading at two temperatures. The simulation of additional fracture mechanics applications validated the model as to the development of residual stresses at the crack tip under cyclic loads.

1. Introduction

The modelling of inelastic material behaviour at geometric imperfections such as cracks or notches requires in general the consideration of loading paths which may be locally non-proportional or cyclic even when the global loading is monotonic. Indeed, deformation localisation in tensile specimens, as well as crack tip blunting in fracture specimens, can cause a loading path change or reversal at a material point. As such, modelling of ductile damage and failure of fracture mechanics specimens and engineering structures should incorporate kinematic hardening effects. In the current work, the authors carried this out in the context of a modification of the Gurson–Tvergaard–Needleman (GTN) model [1–4].

Extensions of the original Gurson model [5] to the case of combined hardening have been proposed by [6], and to the case of non-spherical voids and combined hardening, by [7]. Lievers et al. [8] presented a formulation of kinematic hardening following [9] involving a modified GTN yield function. Likewise, [10] formulated an extension of the Gurson model to cyclic loading conditions based on the Chaboche–Lemaitre thermodynamical approach. Recently, a review about techniques of modelling ductile damage [11] stated the lack of a combination between ductile damage and kinematic hardening and its application to fracture mechanics specimens. The current work introduces a model that represents such an extension to the GTN model for void nucleation, growth and coalescence to the case of non-monotonic and non-proportional loading at large deformation [12,13]. It follows the approach of [7] and for simplicity, only the matrix material undergoes kinematic hardening. For monotonic and proportional loading, the model reduces to the original GTN formulation.

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Nomenclature

c	hardening parameter, kinematic hardening
b	saturation parameter, kinematic hardening
f	void volume fraction
f_0	initial void volume fraction
f_n	volume fraction of void-nucleating inclusions
f^*	effective void volume fraction, GTN yield function
f_c	critical value of f for void coalescence
f_f	critical value of f for material failure
f^*_u	critical value of f^* for material failure
h	hardening modulus, linear isotropic hardening, unit cell modelling
q_1, q_2	Tvergaard parameters, GTN yield function
r	hardening parameter, isotropic hardening
k	saturation parameter, isotropic hardening
z	accumulated magnitude of the inelastic rate of deformation
A	strain-controlled void nucleation strength
$\boldsymbol{X}$	back stress tensor
$\boldsymbol{I}$	identity tensor
$\boldsymbol{D}_\mathrm{P}$	local inelastic rate of deformation tensor
$\boldsymbol{E}$	small strain tensor
$\boldsymbol{F}_\mathrm{E}$	local elastic deformation tensor
$\boldsymbol{F}_\mathrm{P}$	local inelastic deformation tensor
$\boldsymbol{M}$	Mandel stress tensor
$\boldsymbol{R}_\mathrm{E}$	elastic polar rotation tensor
$\boldsymbol{T}$	small stress tensor, Cauchy stress tensor
$\boldsymbol{U}_\mathrm{E}$	elastic right stretch tensor
$\ln \boldsymbol{U}_\mathrm{E}$	elastic right logarithmic stretch tensor
ε_n	mean accumulated equivalent plastic strain for void nucleation
s_n	standard deviation of distribution about ε_n
ε_M	accumulated equivalent plastic strain in the matrix
γ	plastic multiplier
ϕ	Gurson yield function
λ, μ	Lamé constants
σ_M	matrix yield stress
σ_vM	von Mises equivalent stress
σ_H	hydrostatic stress
σ_A	yield stress for hydrostatic part of current yield condition
χ	triaxiality

As in any model identification, it is reasonable to (i) minimise the number of parameters, and (ii) identify as many parameters as possible independently of each other. The procedure described in the current work firstly identifies the hardening parameters (*i.e.*, before damage begins), followed by the identification of the damage parameters at fixed hardening parameters. The two selected temperatures for testing were room temperature 25 °C (RT) and 300 °C. The use of a number of different experimental data sets minimises the non-unicity of the parameter identification. Therefore, the current work used the evolution strategy [14]. In the rear part of the present work, the model simulates the development of residual stresses at the crack tip during cyclic thermomechanical loading. In the case of the warm-pre-stress (WPS) effect for example, the thermomechanical loading history of a component influences the associated fracture behaviour significantly [15–17]. Such components often do not exhibit brittle fracture after cooling because the fracture toughness K_IC (*e.g.* [18]) is larger than the crack resistance determined for this temperature by following the specified standard procedures [19]. This is due to the development of residual stresses at the crack tip. In turn, they come from significant plastic deformation at the crack tip and cause blunting of the initially sharp crack. The current analysis yields information about the plastic deformation and the ductile damage that occurs during the loading process and – after unloading – about the residual stress. The results from simulations are validated by comparison with measurements of residual and crack-opening stresses around the crack tip of a $C(T)$25 fracture mechanics specimen [15].