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Computational Materials Science 32 (2005) 544–552
COMPUTATIONAL MATERIALS SCIENCE
www.elsevier.com/locate/commatsci

Identification of material parameters of the Gurson–Tvergaard–Needleman model by combined experimental and numerical techniques

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Abstract

To identify material parameters from suitable experiments it is prevalent to use global informations like force–displacement or force–necking curves. The quality of accordance between measured and calculated forces at given displacements can be expressed by a least-squares functional. In this contribution a non-linear optimization method will be presented, which minimizes the least-squares functional by use of a gradient based method. The gradient of this functional is calculated in a semi-analytical sensitivity analysis. To determine the derivatives of the force with respect to the material parameters, the local sensitivities on an intersection will be added together. On this intersection, the total nodal force and the external force have to be equal and the normal displacements have to be independent on the material parameters. The parameter identification is embedded in the finite element code SPC-PMHP for solving non-linear boundary and initial value problems on parallel computers. The Gurson–Tvergaard–Needleman model is used to describe the plastic deformation and damage behaviour of the ductile structural steel StE 690. The developed algorithm is applied to tensile tests with notched cylindrical bars.

PACS: 62.20.Fe; 81.40.Jj; 81.40.LM; 81.70.Bt
Keywords: Damage mechanics; Gurson model; Parameter identification; Non-linear optimization; Sensitivity analysis

1. Introduction

The practical applicability of a material model to structural analysis by the finite element method requires the knowledge of the actual material parameters. For the ductile damage model of Gurson–Tvergaard–Needleman (GTN), the para-

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0927-0256/$ - see front matter
doi:10.1016/j.commatsci.2004.09.010

meters are usually obtained from simple tensile tests via empirical (best fit) methods [2,3]. More advanced identification algorithms try to exploit informations from measured inhomogeneous deformation fields, see [1,5,11] and especially for the GTN-model [10] as well as for the Rousselier model [13,14]. In this paper an algorithm is developed which extracts the GTN parameters from measured force–displacement curves using gradient based methods. By means of this optimization method only a few calculations of the direct problem are required to identify the material parameters.

In the first part of this paper the basic equations of the GTN-model are resumed. The second part deals with the formulation of the objective function and the derivation of its gradients with respect to the material parameters. Furthermore, several numerical experiments are performed in order to check the efficiency of the identification algorithm. The last part presents the application of the algorithm to gain material parameters from tensile tests.

2. Gurson model

A widely-used model to describe the micromechanical effects of damage in ductile metals is the Gurson–Tvergaard–Needleman model. Gurson deduced in 1977 a flow potential for void growth in an ideal-plastic material [8], which was extended by Tvergaard and Needleman [15], who introduced additional parameters (q_1, q_2, q_3) and a modified damage variable f^*

$$Y = \left(\frac{\sigma_{\mathrm{eq}}}{\sigma_{\mathrm{YM}}}\right)^2 + 2q_1 f^* \cosh\left(-\frac{3}{2} q_2 \frac{\sigma_{\mathrm{m}}}{\sigma_{\mathrm{YM}}}\right) - \left(1 + q_3 f^{*^2}\right) = 0 \tag{1}$$

with the equivalent and the hydrostatic stress

$$\sigma_{\mathrm{eq}}(\boldsymbol{T}) = \sqrt{-3 II_{\boldsymbol{T}^{\mathrm{D}}}} \quad \text{and} \quad \sigma_{\mathrm{m}}(\boldsymbol{T}) = -\frac{1}{3} I_{\boldsymbol{T}}. \tag{2}$$

$\boldsymbol{T}$ denotes the 2nd Piola–Kirchhoff stress tensor and the superscript D signifies the deviatoric part. The material law and the following equations of the parameter identification are considered in the Lagrange description for large deformation analysis. The damage variable f^* is a function of the void volume fraction f

$$f^*(f) = \begin{cases} f & \forall\, f f_{\mathrm{c}} \\ f_{\mathrm{c}} + \frac{q_1^{-1} - f_{\mathrm{c}}}{f_{\mathrm{F}} - f_{\mathrm{c}}}(f - f_{\mathrm{c}}) & \forall\, f > f_{\mathrm{c}} \end{cases}. \tag{3}$$

The parameter f_{c} characterises the beginning of void nucleation and f_{F} denotes the final failure. The hardening of the matrix material depends on the equivalent plastic strain $\varepsilon_{\mathrm{vM}}^{\mathrm{p}}$ and is given by a power law including three material parameters

$$\sigma_{\mathrm{YM}}(\varepsilon_{\mathrm{vM}}^{\mathrm{p}}) = \sigma_0 \left(\frac{\varepsilon_{\mathrm{vM}}^{\mathrm{p}}}{\varepsilon_0} + 1\right)^n. \tag{4}$$

The initial yield stress σ_0 as well as ε_0 and n are hardening parameters. Using the equivalence of microscopic and macroscopic plastic work one receives an evolution equation for the internal hardening variable, where $\dot{\lambda}$ is the plastic multiplier

$$\dot{\varepsilon}_{\mathrm{vM}}^{\mathrm{p}} = \dot{\lambda} \frac{1}{\sigma_{\mathrm{YM}}(1-f)} \boldsymbol{T} : \frac{Y}{\boldsymbol{T}}. \tag{5}$$

The damage evolution in a ductile metal arises from growth and nucleation of voids. Consequently, the evolution equation for the damage variable is written

$$\dot{f} = \dot{f}_{\mathrm{growth}} + \dot{f}_{\mathrm{nucleation}}. \tag{6}$$

Assuming that the matrix material is plastically incompressible, the void growth is given by

$$\dot{f}_{\mathrm{growth}} = \dot{\lambda}(1-f)\,\mathrm{tr}\left(\frac{Y}{\boldsymbol{T}}\right). \tag{7}$$

The nucleation of voids is a very complex physical process depending on the microstructure of the material. Chu and Needleman [4] complemented the Gurson model by a statistical approach

$$\dot{f}_{\mathrm{nucleation}} = \frac{f_N}{s_N\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\varepsilon_{\mathrm{vM}}^{\mathrm{p}} - \varepsilon_N}{s_N}\right)^2\right] \dot{\varepsilon}_{\mathrm{vM}}^{\mathrm{p}}. \tag{8}$$

In the represented form the Gurson model contains 12 material parameters

$$\boldsymbol{p} = p_i = (\sigma_0 \;\; \varepsilon_0 \;\; n \;\; q_1 \;\; q_2 \;\; q_3 \;\; f_0 \;\; f_{\mathrm{c}} \;\; f_{\mathrm{F}} \;\; f_N \;\; \varepsilon_N \;\; s_N)^{\mathrm{T}}. \tag{9}$$