NONLOCAL CONSTITUTIVE MODEL FOR IMPACT DAMAGE IN METALS

George Z. Voyiadjis*, Rashid K. Abu Al-Rub*, Anthony N. Palazotto**
*Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, USA
**Department of Aeronautics and Astronautics, Air Force Institute of Technology, WPAFB, USA

Summary As soon as material failure dominates a deformation process, the material increasingly displays strain softening and the finite element computation is mesh dependent with non-physical description in the localized regions. Gradient-enhanced constitutive equations with length scale measures are presented to alleviate these inconsistencies. Numerical simulations are performed to study the effect of including length scale parameters on the dynamic localization of plastic flow in shear bands for impact-damage related problems.

INTRODUCTION

The motivation for this study stems out from the experimental tests of specimens made of ductile and heterogeneous materials loaded at low- and high-speed impacts. In many of these tests the intensive nonlinearity induced in the material is attributed to the viscoplasticity and viscodamage morphologies. These experiments indicate that the failure mechanisms occur at localized zones of viscoplasticity and viscodamage where numerous interactions of defects take place. Finite element codes that implement classical plasticity and damage theories also indicate that in problems involving shear localization the simulations are sensitive to the mesh size and alignment [1]. Although it has been shown that the viscoplasticity theory regularizes the solution by introducing implicitly length-scale through the viscous parameter, the numerical results still show mesh dependence for large deformations. In order to be able to capture such localized deformation zones using computational models, we aim here to introduce explicit and implicit length-scale measures in plasticity and damage governing equations through the use of the gradient-dependent theory and viscoplasticity theory coupled to the rate-dependent damage theory.

GRADIENT INELASTICITY THEORY

The model is based on the gradient plasticity and gradient damage theories. The theory of a thermodynamically consistent formulation of a finite deformation gradient inelasticity is presented in [2]. The nonlocal generalized yield condition in the spatial configuration is given by

$$f=\sqrt{3\boldsymbol{s}:\boldsymbol{s}/2}-[1-\hat{\phi}][\sigma_{yp}+\hat{R}][1+(\eta\dot{\hat{p}})^{1/m}][1-(T/T_m)^n]\equiv 0 \tag{1}$$

where $\boldsymbol{s}$ is the deviatoric part of the Cauchy stress tensor $\boldsymbol{\sigma}$, $\hat{\phi}$ is a gradient-dependent damage variable, σ_{yp} is the initial yield strength, $\hat{R}$ is the gradient-dependent isotropic hardening stress, $\hat{p}$ is the gradient-dependent effective viscoplastic strain, m and n are material constants, η is the viscosity relaxation time, T is the absolute temperature, and T_m is the melting temperature. The nonlocal evolution equations of $\hat{p}$ and $\hat{\phi}$ are given by

$$\dot{\hat{p}}=\dot{p}+\ell_1^2\nabla^2\dot{p} \quad \text{and} \quad \dot{\hat{\phi}}=\dot{\phi}+\ell_2^2\nabla^2\dot{\phi} \tag{2}$$

where ℓ_1 and ℓ_2 are the plasticity and damage material length scale parameters, respectively, and ∇^2 designates the Laplacian operator. The nonlocal evolution equation for the isotropic hardening, $\hat{R}=R+R^g$, is given by

$$\dot{R}=b(Q-R)\dot{p} \quad \text{and} \quad \dot{R}^g=b\ell_1^2\left(Q-R^g\right)\nabla^2\dot{p} \tag{3}$$

where b and Q are material constants. The evolution laws for the local damage variable ($\dot{\phi}$) and the viscoplastic rate-of-deformation ($\boldsymbol{d}^{vp}$) are given by

$$\boldsymbol{d}^{vp}=\dot{\Lambda}^{vp}\frac{\partial f}{\partial\boldsymbol{\sigma}} \quad \text{and} \quad \dot{\phi}=\dot{\Lambda}^{vd}\frac{\partial g}{\partial Y} \tag{4}$$

where $\dot{\Lambda}^{vp}$ and $\dot{\Lambda}^{vd}$ are the viscoplasticity and viscodamage multipliers, respectively, and g is the viscodamage growth surface and is assumed in the spirit of viscoplasticity to be as follows

$$g=\hat{Y}-Y_o[1+(\eta\dot{\hat{\phi}})^{1/m}][1-(T/T_m)^n]=0 \tag{5}$$

where Y_o is the initial damage threshold and $\widehat{Y}$ is the nonlocal viscodamage force and is given by

$$Y = \sigma^{*\,2} \Big/ E\left(1-\widehat{\phi}\right) \quad \text{with} \quad \sigma^{*} = \sigma_{eq}[\tfrac{2}{3}(1+\nu)+3(1-2\nu)(P/\sigma_{eq})^{2}]^{1/2} \tag{6}$$

where E is the Young's modulus and ν is the Poisson's ration and $\sigma_{eq} = \sqrt{3\mathbf{s}:\mathbf{s}/2}$. P is the thermodynamic pressure stress for a shock compressed solid and is given by

$$P = \left(1-\gamma\right) c_v T^{ig} \varepsilon \tag{7}$$

where $\gamma = c_p \big/ c_v$ is the ratio of the specific heats, where c_p and c_v are the specific heats at constant pressure and constant volume, respectively, T^{ig} is the ideal gas temperature, and ε is the nominal volumetric strain .

NUMERICAL EXAMPLE

The following example demonstrates the performance of the proposed gradient theory in solving the mesh size dependency. A two-dimensional initial boundary value problem is considered here for a specimen of length 100 *mm* and width 20 *mm*. The bottom side of the specimen is fixed and the topside is movable. The loading is enforced by a velocity of $30 m/s$ that acts at the free end of the specimen for a period of $t_f = 700\ \mu s$. The constitutive parameters used in computation are: $\rho = 7850\ kg/m^3$, $E = 185 GPa$, $\nu = 0.3$, $\sigma_{yp} = 122.5 MPa$, $c_p =$ 460 *J/kgK*, $\Upsilon = 0.9$, $\eta = 0.01\text{s}$, $n = 1$, $m = 2$, $T_r = 300K$, $T_m = 1500K$, $Y_o = 0$, $l_1 = 5\mu m$, $Q = 400MPa$, $b = 8$, $l_2 = 7\mu m$. The numerical analysis is performed by implementing a material subroutine VUMAT in the explicit finite element program ABAQUS. Fig. 1 shows the effective viscoplastic strain distribution at the end of localization for two meshes (left mesh: 15 x 50, right mesh: 25 x 70). One can easily observe the intense equivalent plastic strain distribution that shows the width and the location of the shear band development. Moreover, it can be seen that the thickness of the shear band and the magnitude of the effective plastic strain are the same for the two meshes.

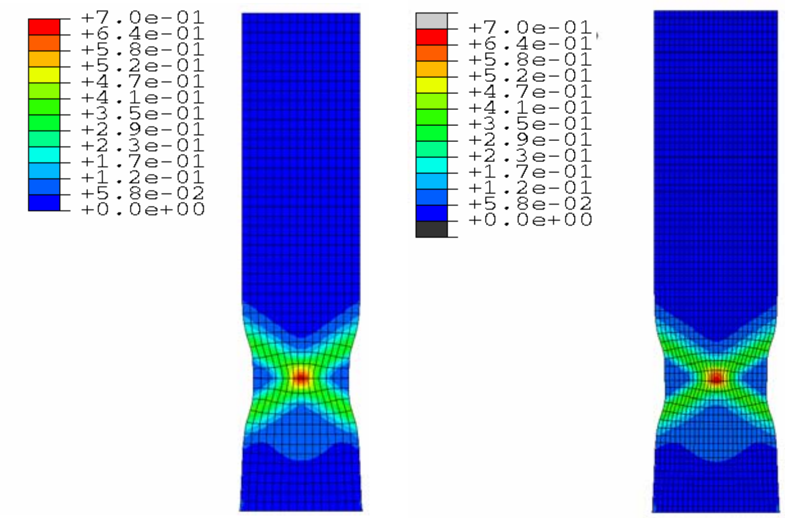

Fig.1. Effective viscoplastic strain distribution.

CONCLUSIONS

The inclusion of higher-order gradient terms with explicit length scales can solve the mesh sensitivity problem and gives physically meaningful results within the impact damage computations.

References

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