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Final Technical Report

Contract Number: N00014-86-K-0235

Title: Advanced Modelling of Failure Modes in Metals

Principal Investigator: C.F. Shih (with R.J. Asaro and A. Needleman)

Research Summary

Three studies have been carried out under this contract: (i) A numerical study of the effects of material rate sensitivity and void nucleation on fracture initiation [1]; (ii) An analysis of the temperature and rate dependence of Charpy V-notch energies for a high nitrogen steel [2]; and (iii) a study of material rate dependence and mesh sensitivity in localization problems [3]. The first two of these studies clearly illustrate that analyses of failure processes based on non-classical constitutive models exhibit phenomenologies that do not emerge from calculations based on classical plasticity theories and that these phenomenologies are consistent with experimental observations. The third study shows how accounting for the rate dependence of plastic flow can eliminate a pathological mesh sensitivity associated with rate independent material models. The mesh sensitivity of solutions to localization problems is a key issue that must be addressed to obtain reliable failure predictions for ductile solids.

Effects of Material Rate Sensitivity and Void Nucleation on Fracture Initiation

Couque *et al.* (*Metall. Trans.*, 19A, 1988, p. 2179) have conducted quasi-static and dynamic fracture toughness experiments using circumferentially cracked round bars. They have correlated fracture toughness measured at loading rates that differ by six orders of magnitude by

$$\frac{K_{Ic}}{K_{Id}} = \sqrt{\frac{\tau_y(\text{at quasi-static rate})}{\tau_y(\text{at dynamic rate})}}$$

Studies of the micrographs of the fracture surfaces indicate that the kinematics of ductile rupture at the level of microvoid nucleation and growth were very similar for the quasi-static and dynamic tests. This suggests that strain-controlled void nucleation is the mechanism controlling the fracture processes.

This numerical study was aimed at providing an understanding of the nature of crack tip stress and deformation fields in an axisymmetric fracture specimen and to explore the basis for the fracture toughness correlation with yield strength proposed by Couque *et al.* The effect of material rate sensitivity and void nucleation and growth on fracture initiation was included in our analysis. Finite element analyses were carried out for two very different rates which correspond to the quasi-static ($\dot{K}_I = 1 \text{ Mpa s}^{-1}$) and high rate ($\dot{K}_I = 10^6 \text{ Mpa s}^{-1}$) tests on a 1020 plain carbon steel of Couque *et al.* A strain rate-dependent version of Gurson's (*J. Eng. Mater. Tech.*, 99, 1977, p. 2) porous-plastic constitutive theory is used, which allows for progressive microrupture through void nucleation and growth, Pan *et al.* (*Int. J. Fract.*, 21, 1983, p. 261). The nucleation of voids is taken to be strain controlled. The material parameters were chosen to be representative of mild structural steel.

A quasi-static analysis was undertaken. This can be justified by the actual experimental conditions; the applied pulse is long compared to the specimen geometry so that the fields that develop at the uncracked ligament can be captured by a quasi-static analysis. However, rate effects



are investigated by imposing strain rates which are 10^6 times the reference quasi-static strain rate. Our analysis of the experiment, based on *strain-controlled* void nucleation, supported Couque *et al.*'s correlation of toughness with yield strength.

An Analysis of the Temperature and Rate Dependence of Charpy V-Notch Energies for a High Nitrogen Steel

The brittle-ductile transition for a high nitrogen steel was investigated in a numerical analyses of the Charpy impact test. This test is of interest because the absorbed energy versus temperature curve for the Charpy V-notch test is frequently used to characterize the brittle-ductile transition in steels. The material was described in terms of an elastic-viscoplastic constitutive model that accounts for the nucleation and growth of micro-voids, leading to ductile fracture, as well as for cleavage failure by micro-crack nucleation. The temperature dependence of flow strength and strain hardening is included in the model, and this leads to the prediction of a transition from cleavage fracture to predominantly ductile fracture as the temperature increases. For the particular steel considered it was found that the variation of strain hardening with temperature had a strong effect on the failure mode transition. Both slow loading and impact loading of the Charpy specimen were analyzed. Most of the computations were based on a quasi-static formulation since, even at the strain rates encountered in the Charpy impact test, material strain rate sensitivity is the main time effect. The influence of material inertia was investigated in a few transient analyses.

The temperature dependence of the absorbed energy results from the variation with temperature of the material parameters; in particular, from the fact that the initial yield stress tends to decrease for increasing temperature, while the critical stress for cleavage is approximately constant over a wide range of temperatures. Additionally, the degree of strain hardening can vary with temperature in our calculations this is found to have a significant effect on the failure mode transition. The temperature dependence of the flow strength and the strain hardening exponent are based on data in Ritchie *et al.* (*J. Mech. Phys. Solids*, 21, 1973, p. 395). At temperatures above $+80^\circ$ Ritchie *et al.* observed serrations on the stress-strain curves and ductility decreased indicating 'blue brittleness'. Some calculations were carried out for a 'comparison' material in order to illustrate what the behavior would be in the absence of 'blue brittleness.' At low temperatures, the high flow strength leads to early cleavage while at higher temperatures, the flow strength varies little with temperature. The decrease in energy absorption with increasing temperature is not typical of structural steels and is a consequence of the rapid increase in work hardening rate with temperature for the particular steel considered. The comparison material exhibits the more expected type of brittle-ductile transition with increasing temperature. The dynamic analyses give predictions of failure initiation that differ little from the corresponding quasi-static predictions because, in the circumstances analyzed, failure initiates after extensive plasticity and dynamic stress oscillations are largely damped out. The dynamic analyses indicate that, at least when fracture initiates after general yielding, there is little effect of material inertia on the energy absorbed to the initiation of cleavage cracking.

Material Rate Dependence and Mesh Sensitivity in Localization Problems

The role of material rate dependence in setting the character of governing equations was illustrated in the context of a simple one dimensional problem. For rate dependent solids, the incremental equilibrium equations for quasi-static problems remain elliptic and wave speeds for dynamic problems remain real, even in the presence of strain-softening. The pathological mesh sensitivity associated with numerical solutions of localization problems for rate independent solids

is eliminated. In effect, material rate dependence implicitly introduces a length scale into the governing equations, although the constitutive description does not contain a parameter with the dimensions of length. Numerical results were presented that illustrate the localization behavior of slightly rate dependent solids under both quasi-static and dynamic loading conditions.

When a solid can be modelled as rate and time independent, a theoretical framework that goes back to Hadamard in 1903 is available in which shear band formation coincides with a change of type (typically from elliptic to hyperbolic) of the equations governing continuing quasi-static deformations. When inertia is accounted for, the change in the character of the momentum balance equation is from hyperbolic to elliptic, i.e. wave speeds become imaginary. Unfortunately the change of type of the governing equations leads to ill-posed problems so that solutions to post-localization boundary value problems exhibit pathological behavior. The pathology can be viewed in terms of the governing equations admitting arbitrarily narrow shear bands, with nothing in the formulation to set the shear band width. Physically then the task is to introduce appropriate characteristic lengths. There are a number of ways to do this. Perhaps a surprising one is by accounting for the rate dependence of inelastic material response. A simple one dimensional problem was used to illustrate how accounting for material rate dependence regularizes the problem by implicitly introducing a characteristic length.

In quasi-static problems, material rate sensitivity renders the band solution unique and the imperfection sets the width of the band. Localization can still occur in the sense that the ratio of the strain rate in the band to that outside the band may become arbitrarily large. It is worth noting that material rate dependence does not smooth out the strain discontinuity across the band. The solution is sensitive to initial conditions; for example, in the simple shear problem, the band width is set by the initial inhomogeneity thickness. By rendering the solution unique, material rate dependence makes the initial inhomogeneity width the relevant length scale. The simple shear problem is highly degenerate, but the conclusion holds in a more general context.

Under dynamic loading conditions, rate sensitive material behavior leads to a wave equation, with plasticity entering terms with lower order derivatives. This is consistent with the experimental observation that incremental disturbances in plastically deformed solids propagate at the elastic wave speed. Hence, the character of the governing equation, as determined from the highest order derivative terms, is independent of whether the material is hardening or softening, which contrasts with the situation for rate independent solids. In the rate independent limit, only the lower order derivative terms remain. As can be anticipated from the character of the governing equation, numerical solutions exhibit a boundary layer behavior. The strain localizes into a continually narrowing boundary layer. For a continually softening solid, the possibilities include: (i) the shear stress vanishes with the strain rate remaining finite and (ii) the strain rate becomes unbounded before the shear stress vanishes. In the former case, fracture precedes instability while in the latter case instability precedes fracture.

List of Publications

- [1] B. Moran, R.J. Asaro, and C.F. Shih, "Effects of Material Rate Sensitivity and Void Nucleation on Fracture Initiation," *Metallurgical Transactions*, **22A**, 161-170 (1991).
- [2] V. Tvergaard and A. Needleman, "An Analysis of the Temperature and Rate Dependence of Charpy V-Notch Energies for a High Nitrogen Steel," *International Journal of Fracture*, **37**, 197-215 (1988).

- [3] A. Needleman, "Material Rate Dependence and Mesh Sensitivity in Localization Problems," *Computer Methods in Applied Mechanics and Engineering*, **67**, 69-85 (1988).