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APPLICATIONS OF ELASTIC-VISCOPLASTIC CONSTITUTIVE MODELS IN DYNAMIC ANALYSES OF CRACK RUN-ARREST EVENTS*

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Unified constitutive theories attempt to treat different manifestations of time-dependent inelastic behavior, such as creep, stress relaxation, and plastic flow, by a single kinematic equation and a discrete set of state variables. The motivation for developing such theories has, over the last fifteen years, come mostly from interest in high-temperature applications. High temperature refers to the range where observable creep deformations occur over long periods of time when the stress levels are near the engineering yield stress. There are, however, rapid loading situations at lower temperatures where rate effects can become equally important. One such situation is the representation of rapid crack propagation events in ductile structural alloys. Ductile here means that the material is at a temperature above that where cleavage (brittle) fracture characteristics cease to be

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present. The temperature for transition from brittle to ductile fracture may be well below the classical creep regime, for example, about 50 to 100°C for some nuclear grade structural steels. This paper examines the role that viscoplasticity may play in the prediction of crack run/arrest behavior in such ductile steels.

The growing interest in the viscoplastic aspect of fracture behavior is reflected by several recent studies[1,2] in the literature which emphasize the importance of including combined plastic and strain-rate effects in constitutive relations. Accordingly, in concert with subcontracting groups, the Heavy-Section Steel Technology (HSST) Program at the Oak Ridge National Laboratory (ORNL) is supporting research efforts to develop viscoplastic-dynamic finite element analysis techniques for high strain-rate fracture analyses and to validate their utility through the analysis of carefully performed crack-arrest experiments. In particular, these analysis capabilities are expected to give an improved basis for assessing the dynamic fracture behavior of large (1 × 1 × 0.1 m) plate crack-arrest specimens currently being tested by the National Bureau of Standards as part of the HSST program.

In the studies being conducted at ORNL, various viscoplastic constitutive models and several nonlinear fracture criteria are being installed in the ADINA general purpose finite element computer program, and the combined predictive capabilities are being evaluated through applications to the HSST wide-plate experiments. The first two constitutive models selected for installation in ADINA were a variation of the Perzyna[3] elastic-viscoplastic model with linear strain hardening and the Bodner-Partom[4] viscoplastic model with strain hardening. Other models being examined include those due to Robinson-Pugh[5], and Hart.[6] The fracture criteria being examined for use with nonlinear analyses include several path-independent integrals that were formulated by different researchers (e.g., Atluri,[7] Kishimoto[8]) to remove limitations on the original J-integral of Rice. Some of these integrals represent slight modifications of the J-integral, while others have a different theoretical basis.

This paper describes applications of these nonlinear techniques to the first series of six HSST wide-plate crack-arrest tests that have been performed. These experiments include crack initiations at low temperatures and relatively long (20 cm) cleavage propagation phases which are terminated by arrest in high-temperature regions. Crack arrests are then followed by ductile tearing events. Consequently, the crack-front regions in these tests are exposed to wide ranges of strain rates and temperatures.

The viscoplastic formulations installed in ADINA at ORNL can be expressed in vector form at time t as

$$ {}^{t}\dot{\varepsilon}^{vp} = {}^{t}\Phi \, D \, {}^{t}\sigma \qquad (1) $$

where $\dot{e}^{vp}$ is the viscoplastic strain rate, σ is the stress tensor, and D is the deviatoric stress operator matrix. The implementation of the Bodner-Partom[4] model in ADINA is based on the formulation described by Kanninen, et al.[9] for which Φ is defined by

$$ \Phi = \frac{D_o}{(J_2)^{1/2}} \exp\left[-\left(\frac{1}{2}\right)\left(\frac{Z^2}{3\,J_2}\right)^n\right] \qquad (2) $$

where the hardening parameter Z has the form

$$Z = Z_1 + (Z_0 - Z_1) \exp(-m W_p) \qquad (3)$$

and where Z_0, Z_1, n, m, D_0 = prescribed material constants,

W_p = accumulated plastic work, and

J_2 = second invariant of deviatoric stress.

In Ref. 9, temperature dependence of the material properties is taken into account primarily through the relations

$$n = \frac{175}{T} + 1.35 \quad \text{and} \quad Z_0 = \frac{2.44 \times 10^4}{T} + 1084 \text{ (MPa)} , \qquad (4)$$

where temperature T is in deg K. Values for the remaining material constants are given by m = .061 (1/MPa), $D_o = 10^6$, and Z_1 = 1550 MPa.

The Bodner-Partom model described above has been applied to the analysis of the fifth HSST wide-plate crack-arrest test, WP-1.5. Figure 1 shows the single-edge-notched plate specimen (1 × 1 × 0.1 m) that was cooled on the notched edge and heated on the other edge to give a linear temperature gradient (T_{min} = -83.3°C, T_{max} = 183.3°C) along the plane of crack propagation. Upon initiating propagation of the crack in cleavage, arrest was intended to occur in the higher-temperature ductile region of the specimen. The specimen had an initial crack depth-to-plate width ratio (a/w) of 0.2. Each surface was side-grooved to a depth equal to 12.5% of the plate thickness. The specimen was welded to pull-plates which have a pin-to-pin length of 9.6 m to minimize stress wave effects. Drop weight and Charpy test data indicate that RT_{NDT} = -23°C for this material. Information on material properties of the wide-plate material are described in Ref. 10.

The specimen was instrumented with thermocouples, strain gages, and crack-opening-displacement gages. A series of eleven thermocouples and sixteen strain gages were located about 65 mm above the crack plane across the plate to record temperature and strain as functions of time and crack position.

The two-dimensional (2-D) finite element model used in the analysis consisted of 1833 nodes and 567 eight-noded isoparametric elements. The measured fracture load of F_{in} = 11.03 MN was applied at the top of the load-pin hole to determine the load point displacement. For the dynamic analysis, the load point was fixed at the displacement value of the initiation load and the time step was set at Δt = 1 μs in the implicit Newmark scheme for the time integration. The estimate of crack position vs. time in Fig. 2 was constructed from strain-gage data and was used as input for a generation mode dynamic analysis. Figure 2 shows the measured first crack arrest at a_{fm_1} = 0.52 m which occurred at time t = 0.723 ms after crack initiation. Figure 3 shows contour plots of the effective viscoplastic strain at times t = 0.7 ms and t = 2.9 ms, respectively. The time histories of the Atluri and the Kishimoto path-independent integrals are depicted in Fig. 4. The results are expressed in terms of a pseudo-K_I value for purposes of comparison with elastodynamic values. The values at crack arrest were determined to be K_I = 208 MPa$\sqrt{m}$ (Atluri) and K_I = 174 MPa$\sqrt{m}$ (Kishimoto).

Computed results from the viscoplastic analysis are compared with measured data for crack-line strain-time response and with elastodynamic analyses of the same crack run-arrest event. Work is currently under way to determine material constants for the Perzyna model that can be applied to wide-plate analysis. Results of this effort will permit comparisons between the Perzyna and the Bodner-Partom models for the wide-plate material in the temperature and strain-rate regions of interest to the HSST program.

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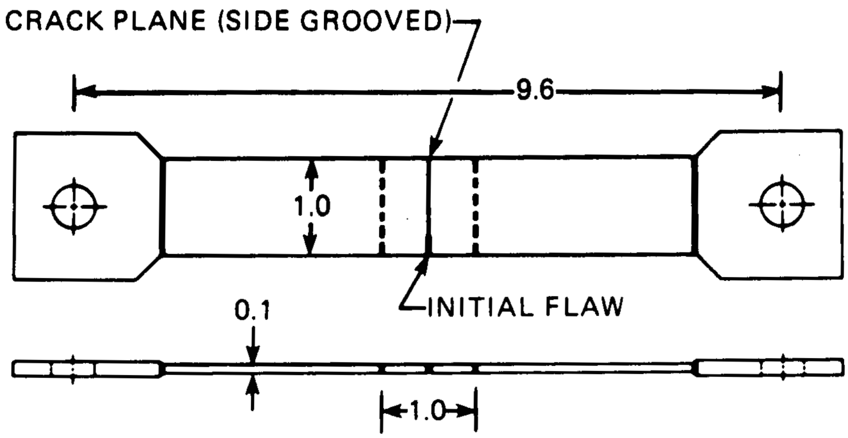

Fig. 1. Wide-plate crack-arrest specimen and pull-plate assembly.

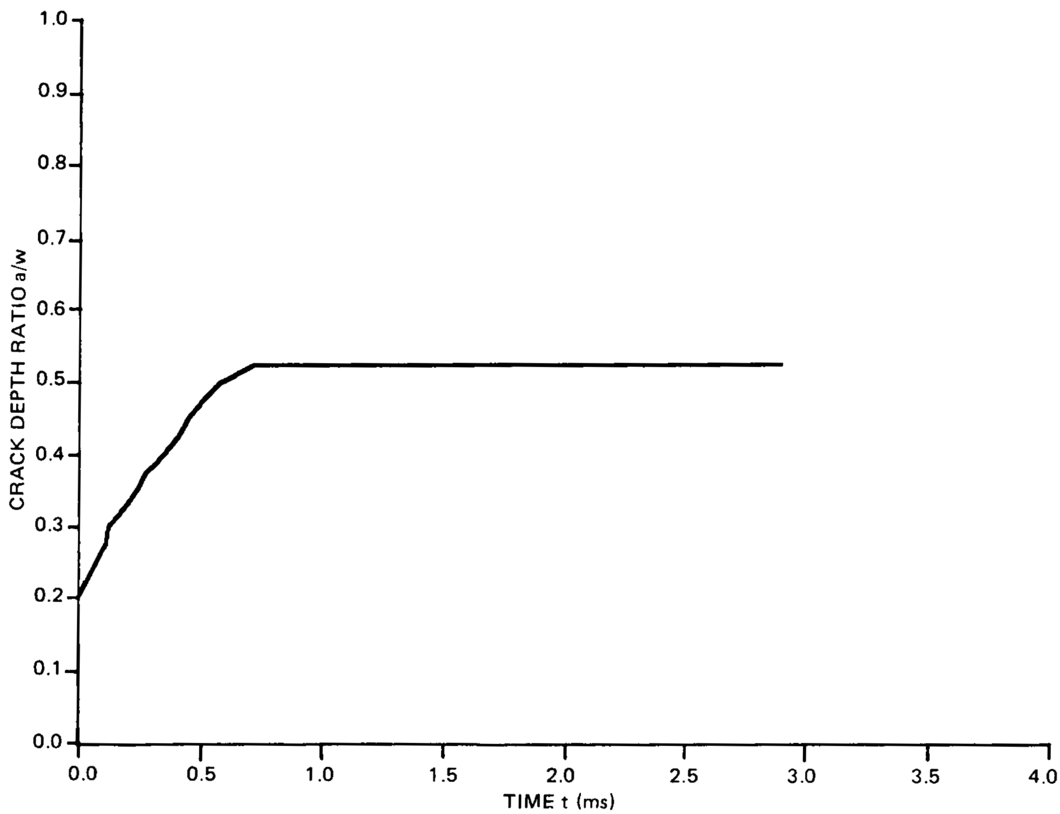

Fig. 2. Crack depth history derived from strain gage data for wide-plate test WP-1.5.

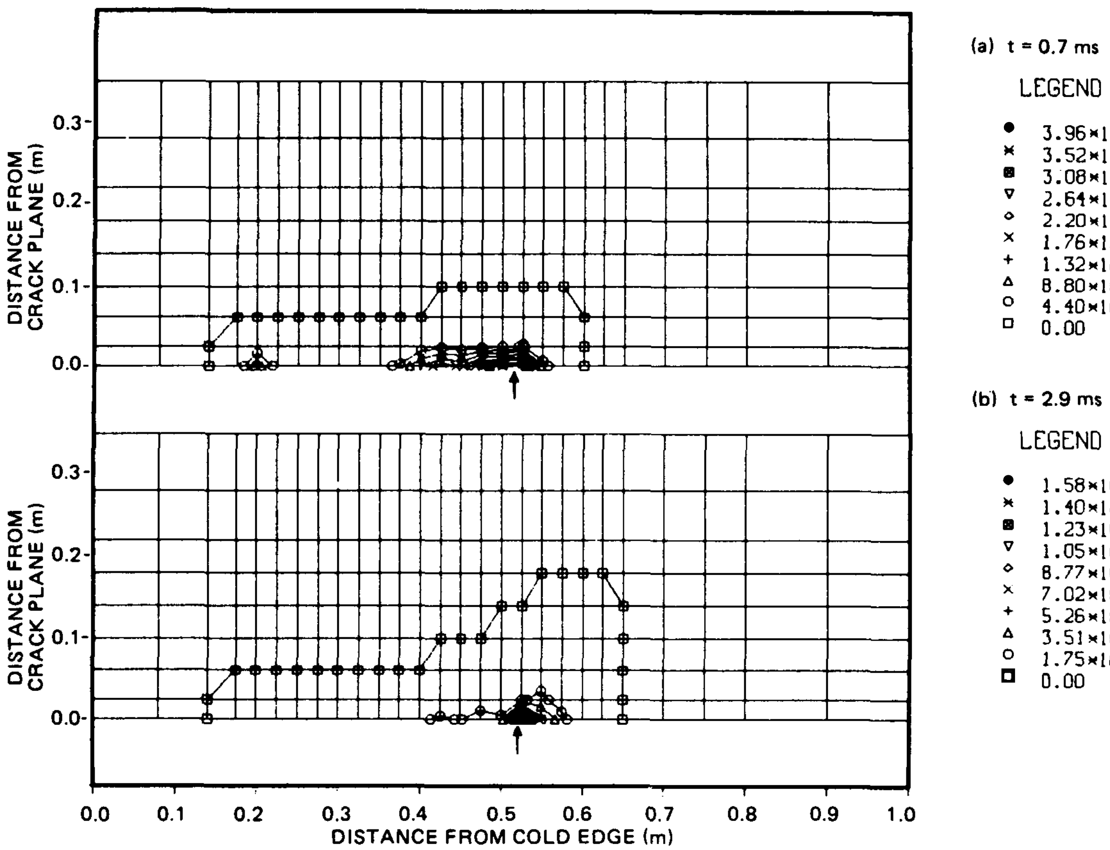

Fig. 3. Contour plots of effective viscoplastic strain at times t = 0.7 ms and t = 2.9 ms from generation mode analysis of wide-plate test WP-1.5.

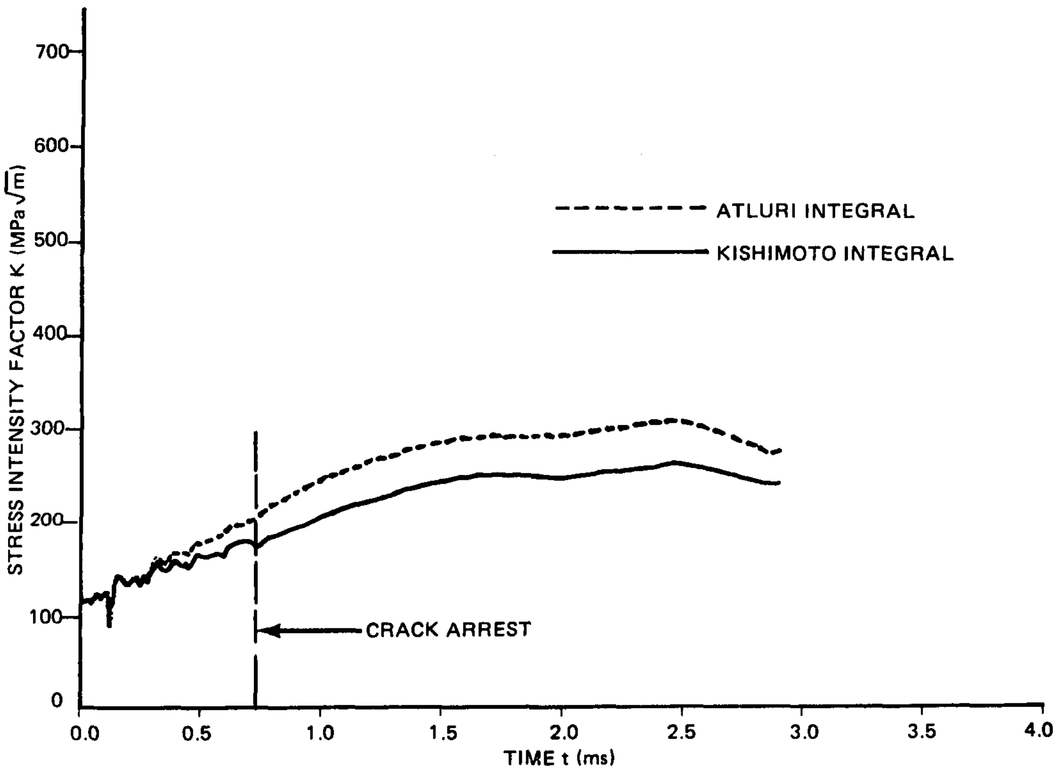

Fig. 4. Amplitude of pseudo-stress-intensity-factor versus time from two path-independent integrals for wide-plate test WP-1.5.