ASSESSMENTS OF CRACKS UNDER TRANSIENT THERMAL-MECHANICAL LOADING CONDITIONS IN DUCTILE ENGINEERING MATERIALS

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Abstract

Under pressurized thermal shocks based on the postulated loss of coolant accident conditions the conventional fracture mechanics concepts may become invalid due to elastic unloading and plastic reloading. In frame of this work we have studied specimens with different crack lengths under two different transient loading conditions. To examine feasibility of the two-parameter concept, $J-Q$, we have performed very detailed finite element computations under both deformation and incremental theory of plasticity. Our results for the shorter cracks confirm that the J-integral gives a reliable estimate of the stress intensity. Although at the assumed higher cooling velocity the Q values deviate from the deformation theory results significantly, $J-Q$ under the incremental theory provides a good description of the crack state. It has been shown that the time behavior of the stress intensity is independent of the crack length. One may find out the critical time point for different crack lengths based on a single computation.

INTRODUCTION

In recent years extensive experimental and computational research projects have been performed worldwide [1, 2]. In nuclear power plant industry one of keen topics in component safety is to assess the reactor pressure vessel integrity under pressurized thermal shock conditions. Due to time-dependent temperature distributions a crack postulated in the component may be temporarily elastically unloaded and plastically reloaded. It is important to know how the crack is affected by the complicated time-dependent loading history.

In the present work we discuss effects of transient thermal-mechanical loading on crack descriptions. The mechanical properties of the investigated material and loading conditions are related to those introduced in an international round-robin study [1]. All computations reported in this paper have been performed under plane strain conditions with infinitesimal strain J_2 flow theory. To check effects of the elastic unloading and plastic reloading, we summarize some results under the known deformation theory.

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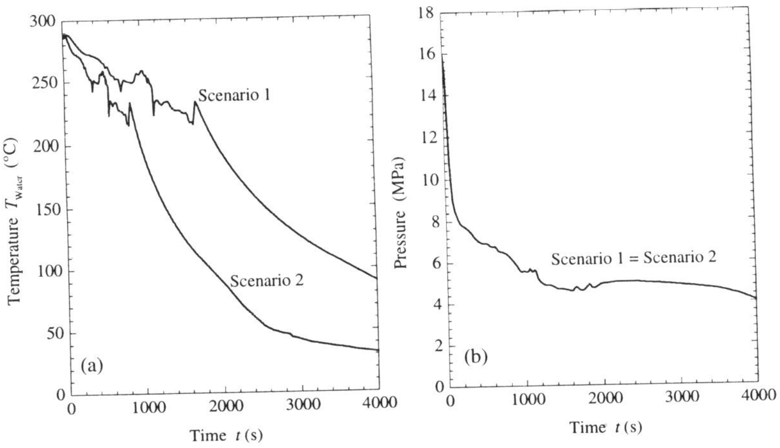

Figure 1: Loading conditions for transient thermal-mechanically loaded crack analyses. (a) Temperature variations in water. Scenario 1 is experimentally measured for an international round-robin study [1]; temperature of Scenario 2 changes twice as quickly as Scenario 1. The initial temperature in cracked specimen is $288°C$. (b) The internal pressure in the reactor pressure vessel [1] is used for all computations.

COMPUTATIONAL MODELING

In order to quantify the effects of transient temperature fields we use the small scale yielding (SSY) field as our reference solution. We denote the temperature at the crack tip as our reference temperature, T_0, and the corresponding yield stress as σ_0. Furthermore, we assume that plastic strain hardening exponent $n = 10$ and Poisson's ratio $\nu = 0.3$ in the Ramberg-Osgood model for both incremental theory and deformation theory of plasticity are temperature-independent.

Cracks are modeled under plane strain conditions, which provides us an upper bound of characteristic crack parameters for three dimensional components. In the pressurized pressure vessel a crack is loaded essentially by the tension loads, which is modeled using a single edge cracked tensile bar with uniformly constrained tension edges. The mechanical pressure shown in Fig. 1(b) is converted into tension load on the edges. The thermal loads are added by given time-dependent ambient temperature in water for convection on specimen surfaces. The temperature-dependent convection coefficient is in accordance with the round-robin study [1]. The specimens computed in this paper are 1000 mm long, L, and 249 mm wide, W. The crack lengths, a, are assumed to 16 mm ($a/W = 0.064$), 37 mm ($a/W = 0.15$) and 124 mm ($a/W = 0.5$), respectively, in order to quantify effects of the crack length. Note the crack length termed in this report includes the cladding sheet [1].

The radial length of the smallest elements is less than 10^{-5} of the crack length. The mesh is scaled exponentially in the radial direction. There are 36 sectors of elements within the angular region from 0 to π in the crack-tip region. 4-node

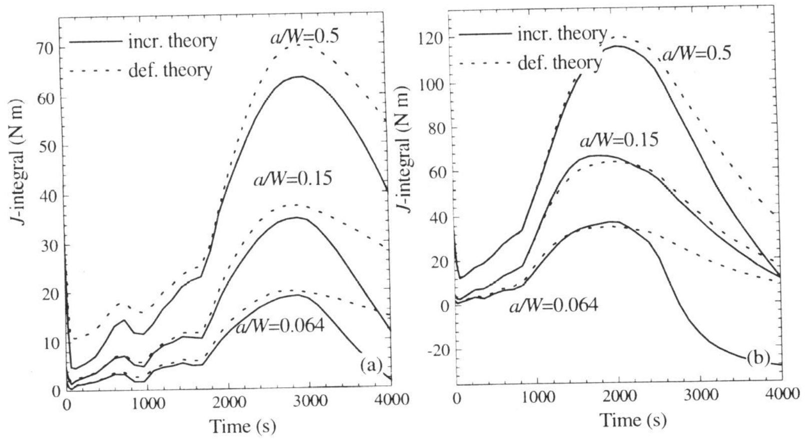

Figure 2: Development of the J-integral as a function of time under different computations and transient cooling conditions. The solid and dotted curves denote results under incremental theory and deformation theory of plasticity, respectively. J under incremental theory is evaluated in the far-field, J_{ff}, due to its path-dependence. (a) Scenario 1; (b) Scenario 2.

isoparametric elements are applied. Because of symmetry we only have to model the upper plane. We use meshes with more than 2600 nodes and 2500 elements for all computations presented in the present paper.

RESULTS

Prior to thermal loading the plastic zone around the crack tip is very small for all crack lengths, in comparison with a and $W - a$, and all calculated J values are path-independent. As soon as the temperature shock starts, the pressure in the vessel sinks and the crack is less loaded. At this stage the estimated values of the J-integral as well as stress fields under deformation theory give us a conservative assessment since J under incremental theory of plasticity drops more rapidly and becomes strong path-dependent.

With cooling around the crack tip, the crack is gradually reloaded by the thermal contraction. The J-integral grows consequently (Fig. 2), which implies that the stress intensity increases regardless of path-dependency of J. The so-called far-field J-integral, J_{ff}, at reloading is generally smaller than the corresponding J value of deformation theory. Our extensive numerical computations confirm that the J-integral is path-dependent in a rather large domain at the reloading stage, which is numerically scalable by J_{ff} [3]. The path-dependency under transient thermal loading seems to be a monotonic function of the integration contour size, as observed in crack propagation analyses [9]. Hence, deformation theory provides a more conservative estimate of the stress intensity at the crack tip.

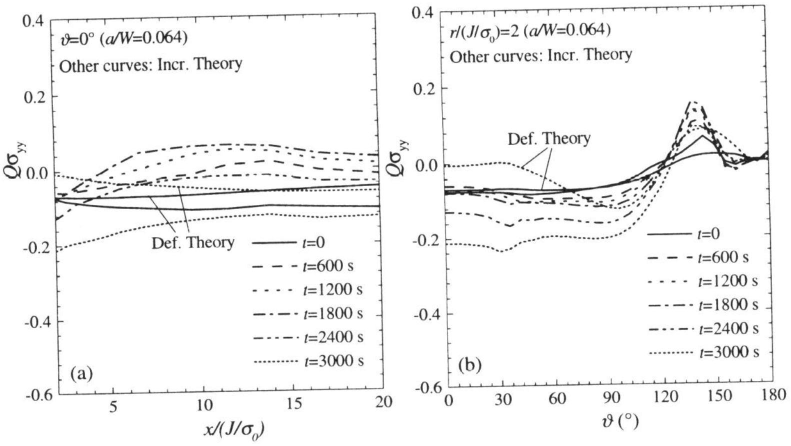

Figure 3: Development of the second term of a normal stress component for Scenario 1 for $a/W = 0.064$. (a) $Q\hat{\sigma}_{yy}$ at $\vartheta = 0^\circ$; (b) $Q\hat{\sigma}_{yy}$ at $r/(J/\sigma_0) = 2$.

Due to different plastic zone sizes, deviations between the deformation and incremental theory solution are proportional to the crack length. It is most interesting that all cracks are plastically reloaded and then elastically unloaded at the same times point, independently of the crack lengths. It implies that variations of the J-integral is determined by the cooling velocity alone. Should the cooling water temperature be known, the time behavior of the J variations can be predicted based on a single calculation with a given crack length. The crack length can only change the amplitude of the stress intensity, but not its time behavior.

Figures 3 and 4 display radial and polar distributions of the second term of a normal stress component, σ_{yy}, for loading and reloading steps obtained at $\theta = 0^\circ$ and $r/(J/\sigma_0) = 2$, respectively. The stresses are extrapolated based on the results on the Gaussian integration points of the surrounded elements. The second term is evaluated according to the definition of O'Dowd and Shih [7]. The radial distribution of the second stress term shows that the stress fields at all loading and reloading steps are only slightly dependent on $r/(J/\sigma_0)$. Deviations of the stress values in the radial direction $2 \leq r/(J/\sigma_0) \leq 20$ are less than 10% [3]. It implies that stress fields at the loading steps are hardly affected by the complicated loading history. Under J_2 plasticity theory the loading history effects fade in crack tip fields rather quickly. However, deviations between deformation and incremental theory of plasticity grow with time and crack length, due to increasing plastic zone sizes. It implies that the constraint around the tip is more sensitive to the transient loading process.

In fact the Q values are affected by the cooling temperature more substantially. It becomes interesting to know how the $J - Q$ description is affected by the cooling velocity. Actually the cooling temperature in pressurized thermal shock process has been assumed based on some local loss of coolant accident postulation. Should the

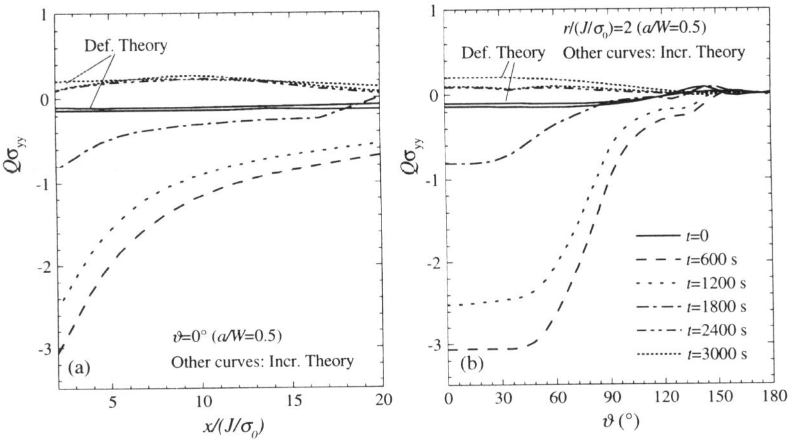

Figure 4: Development of the second term of a normal stress component for Scenario 1 for $a/W = 0.5$. (c) $Q\hat{\sigma}_{yy}$ at $\vartheta = 0°$; (d) $Q\hat{\sigma}_{yy}$ at $r/(J/\sigma_0) = 2$.

cooling water injection be larger, the water temperature will change more quickly as considered in the other international round-robin study [2], in which the temperature sinks almost ten times quicker than that in [1]. In Fig. 5 we summarize some results which have been obtained under stronger thermal shock loading condition (Scenario 2) with ambient temperature changes twice as quickly as in the project [1]. Based on the such computations we see that, with increasing of cooling velocity, the crack tip fields are more strongly unloaded and the J-integral is more path-dependent (Fig. 2(b)). Fig. 5 shows that even for $a/W = 0.064$ the second terms of σ_{yy} under incremental theory deviate from deformation theory more significantly and the constraint effects become much stronger, in comparing with Fig. 3. It is necessary to use the two-parameter description to control the transient crack tip fields with very different constraint values.

CONCLUDING REMARKS

For the Scenario 1 based on the postulated loss of coolant accident conditions [1] we have confirmed that the J-integral provides a reliable prediction about structural integrity. Differences between the deformation and incremental theory of plasticity are negligible (less than 10%) for the shorter cracks, whereas for the longer cracks this deviation increases.

Under quicker cooling conditions (Scenario 2) the crack fields can be no longer described by the J-integral alone. Effects of the transient loading can be quantified by the second crack parameter, Q. The deformation theory does not give accurate results of time-dependent crack states. It becomes necessary to perform full scale computations under incremental plasticity theory in order to know the constraint

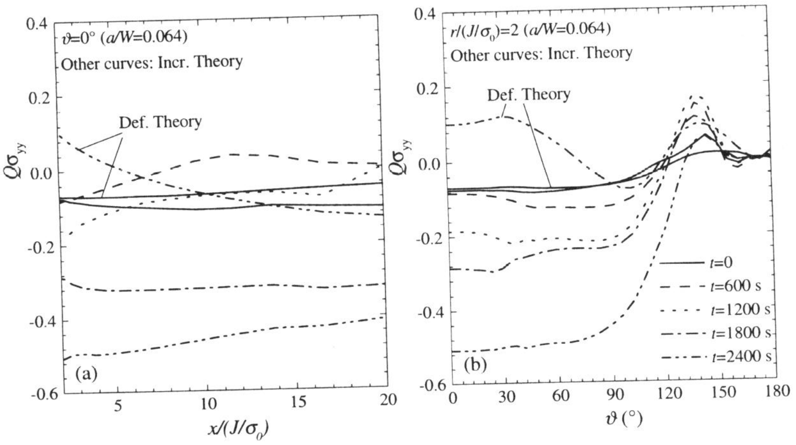

Figure 5: Variations of the second terms of σ_{yy} at different loading steps ($a/W = 0.064$) for Scenario 2. (a) $Q\hat{\sigma}_{yy}$ at $\vartheta = 0°$; (b) $Q\hat{\sigma}_{yy}$ at $r/(J/\sigma_0) = 2$.

effects around the crack tip.

In both investigated transient scenarios the time behavior of the stress intensities for all crack lengths is similar. It implies that the maximum J values appear at the same time point which is determined by the cooling temperature alone. Therefore, it is possible to predict the time behavior of the stress intensity for different crack lengths, based on a single calculation.

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