ANALYSIS OF LOADING RATE EFFECTS ON CLEAVAGE FRACTURE TOUGHNESS OF FERRITIC STEELS

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ABSTRACT

The effects of loading rate on the Weibull stress model for prediction of cleavage fracture are examined in this paper for a low-strength pressure vessel steel (A515-70). We focus on low-to-moderate loading rates ($\dot{K}_I \leq 2{,}500$ MPa$\sqrt{\mathrm{m}}/\mathrm{s}$). Tregoning and Joyce [1] tested a large number of 1T SE(B) specimens for this material with different a/W ratios (0.15, 0.55) at several loading rates over this range. They also conducted comparative, quasi-static tests using 1T C(T) specimens and shallow-cracked SE(B) specimens ($a/W = 0.2$). We describe very detailed, 3-D finite element analyses of these specimens employing rate-sensitive material flow properties characterized by a viscoplastic constitutive model with uniaxial, tension stress-plastic strain curves specified at varying plastic strain rates. To quantify the probability of cleavage fracture, we adopt the three-parameter Weibull stress model as modified earlier by the authors to bring the microscopic model into better agreement with the macroscopic fracture toughness distribution adopted in ASTM E1921. The analyses described here examine dependencies of the Weibull stress parameters on $\dot{K}_I$. The study shows that the Weibull modulus (m) remains reasonably rate independent at constant temperature over the range of loading rates considered for this material. Rate dependencies of the scaling parameter (σ_u) and the threshold parameter (σ_{w-min}) can be computed using the calibrated m, and the results indicate these dependencies are not overly strong. However, the predicted cumulative probability for cleavage exhibits a strong sensitivity to the calibrated value of σ_u, analogous to the strong sensitivity of K_0 to loading rate. Consequently, use of a calibrated σ_u value based on static tests leads to significant errors in the predicted cumulative failure probabilities for dynamic loading.

1 INTRODUCTION

The potential for catastrophic failure initiated by cleavage fracture remains a key element in fitness-for-purpose assessments of high-performance structures constructed of ferritic steels. Cleavage fracture has been attributed primarily to slip-induced cracking of grain boundary carbides, followed by unstable propagation of the resulting microcracks into the surrounding ferritic matrix. Due to the highly localized character of the failure mechanism and the microstructural inhomogeneity of the material, fracture toughness data exhibit a large amount of scatter, a dependence on the crack front length and a strong sensitivity to the local stress and deformation fields (e.g., Wallin [2]; Sorem, et al. [3]). These observations motivate development of probabilistic models for cleavage fracture which couple macroscopic fracture behavior with microscale events. The Weibull stress model originally proposed by the Beremin group (Beremin [4]) based on weakest link statistics provides a framework to quantify the relationship between macro and microscale driving forces for cleavage fracture. The Beremin model [4] introduces a scalar Weibull stress (σ_w) as the probabilistic fracture parameter and adopts a two-parameter description for the cumulative failure probability. The two model parameters are m, the Weibull modulus (or shape parameter) which quantifies the statistical scatter, and σ_u, a scale parameter which sets the value of σ_w at 63.2% failure probability. The Weibull stress is computed by integrating a weighted value of the maximum principal (tensile) stress over the fracture process zone. The model assumes the parameters (m, σ_u) quantify inherent properties of the material that describe the formation of a certain distribution of metallurgical scale cracks once plastic deformation occurs as the precursor to cleavage. The Weibull stress thus emerges as a crack-front parameter to couple remote loading with a micromechanics model which incorporates the statistics of microcracks (weakest link philosophy) and enables construction of a toughness scaling model between crack configurations exhibiting different constraint levels by comparing *J*-values at equal values of σ_w and thus equal failure probabilities (Ruggieri and Dodds [5]; Gao, et al. [6]). Recently, Gao et al. [6] showed analytically and numerically that a non-uniqueness arises in the calibrated (m, σ_u) pair when the calibration process uses only fracture toughness data measured under conditions of small scale yielding (SSY, $T_\sigma = 0$). To resolve this issue, they proposed a new strategy to calibrate the Weibull stress parameters based on the scaling of measured fracture toughness between high- and low-constraint configurations. They also modified the expression for cumulative failure probability to include a threshold value (σ_{w-min}) for cleavage fracture which reflects an approximate model for the conditional failure probability.

Defect assessments of engineering structures often must consider events which impose low to intermediate loading rates. Such events raise crack-front strain rates sufficiently to increase the yield stress and alter the (plastic) hardening characteristics, but do not trigger significant inertia effects along the crack front. These loading rates decrease the (cleavage) fracture toughness and increase the ductile-to-brittle transition temperature, i.e., the reference temperature (ASTM E1921 [7]). Low-to-moderate strength structural steels exhibit a particularly strong strain rate sensitivity leading to significantly reduced fracture toughness. Tregoning and Joyce [1], for example, tested a large number of 1T SE(B) specimens of an A515-70 steel with different a/W ratios (0.14, 0.55) at several loading rates ($\dot{\Delta}_{LLD}$, load-line velocity). Their experimental results indicate a strong sensitivity of the fracture toughness on loading rate, e.g., the median fracture toughness for the SE(B) specimens with $a/W = 0.14$ decreases from 112 to 68 $\text{MPa}\sqrt{\text{m}}$ as $\dot{\Delta}_{LLD}$ increases from 0.25 to 6.35 mm/s. Such a large toughness shift for relatively small loading rate increases raises questions about potential dependencies of the Weibull stress parameters on loading rate. This issue is investigated in this paper.

2 THE WEIBULL STRESS MODEL

The Beremin model [4] adopts a two-parameter Weibull distribution to describe the cumulative failure probability

$$P_f(\sigma_w) = 1 - \exp\left[-\left(\frac{\sigma_w}{\sigma_u}\right)^m\right] \tag{1}$$

Here σ_w represents the Weibull stress defined as the integral of a weighted value of the maximum principal (tensile) stress (σ_1) over the process zone of cleavage fracture (i.e., the crack front plastic zone),

$$\sigma_w = \left[\frac{1}{V_0}\int_{V_p} \sigma_1^m \mathrm{d}V\right]^{1/m} \tag{2}$$

In Eq. (2), V_p represents the volume of the cleavage fracture process zone, V_0 is a reference volume and m denotes the Weibull modulus which defines the shape of the probability density function for microcrack size in the fracture process zone. Previous studies, e.g., Beremin [4], show that the probability density function for microcracks having size a has the form $f(a) = c/a^\gamma$ where c is a constant and γ defines the shape of the microcrack distribution. The relationship between m and γ follows $m = 2\gamma - 2$. In Eq. (1), σ_u represents the scale parameter of the Weibull distribution and defines the microscale material toughness when the cumulative failure probability is 63.2%.

The Weibull stress model enables scaling of fracture toughness values between crack configurations exhibiting different constraint levels based on equal probabilities of fracture. For fixed values of m and σ_u, the toughness scaling model requires the attainment of the same σ_w value for specimens with different sizes-types and loading conditions (tension *vs*. bending), even though the *J*-value may differ widely, Ruggieri and Dodds [5], Gao, et al. [6, 8].

The two-parameter model represents a pure weakest link description of the fracture event, which implies that a very small stress intensity factor due to applied load leads to a finite failure probability. However, newly formed microcracks cannot propagate in polycrystalline metals unless sufficient energy exists to break bonds, to drive the crack across grain boundaries and to perform plastic work. Consequently, there must exist a minimum toughness value (K_{min}) below which cracks arrest (ASTM [7]; Anderson, et al. [9]). A simplified, three-parameter Weibull distribution describing the macroscopic fracture toughness, proposed by Anderson et al. [9], has the form

$$P_f\left(K_I\right) = 1 - \exp\left[-\left(\frac{K_I - K_{min}}{K_0 - K_{min}}\right)^4\right] \tag{3}$$

Here K_0 represents the fracture toughness value at 63.2% failure probability and K_{min} represents the threshold toughness for the material. ASTM E1921 [7] adopts this form for the distribution of cleavage fracture toughness in SSY. This issue led Gao, et al. [6, 8, 10] to introduce a threshold σ_w value, σ_{w-min}, in the Weibull stress model for the cumulative failure probability. Cleavage fracture cannot occur if $\sigma_w \le \sigma_{w-min}$. Different forms of three-parameter expression for cumulative failure probability have been discussed by Gao and Dodds [10]. The expression which is consistent with (3) under SSY conditions has the form

$$P_f\left(\sigma_w\right) = 1 - \exp\left[-\left(\frac{\sigma_w^{m/4} - \sigma_{w-min}^{m/4}}{\sigma_u^{m/4} - \sigma_{w-min}^{m/4}}\right)^4\right] \tag{4}$$

In (4), σ_{w-min} is defined as the value of σ_w when $K_I = K_{min}$. Under SSY conditions, K_{min} has an experimentally estimated value of ~20 $\mathrm{MPa}\sqrt{\mathrm{m}}$ for common ferritic steels (ASTM [7]).

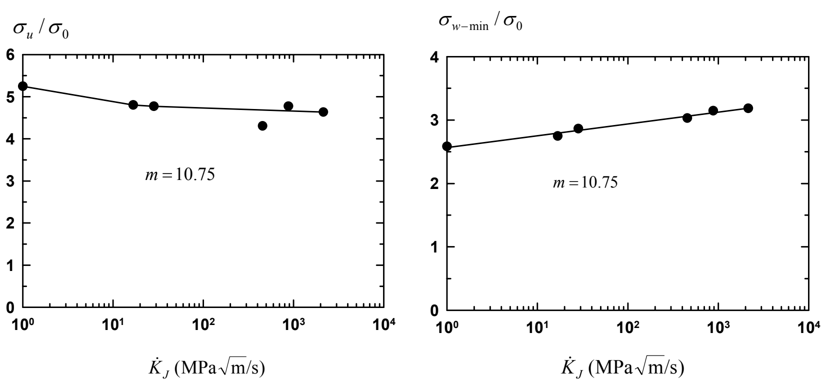

Figure 1: Calibrated variations of σ_u and σ_{w-min} with loading rate.

3 LOADING RATE EFFECTS ON WEIBULL STRESS MODEL

The calibration procedure proposed by Gao et al. [6] uses toughness values measured from two sets of fracture specimens exhibiting different constraint levels. This new procedure seeks an *m*-value that scales the two measured toughness distributions to the ones that have the same statistical descriptions in plane strain, SSY ($T_\sigma = 0$) conditions, i.e., the two constraint corrected, SSY toughness distributions have the same K_0 value. It eliminates the non-uniqueness that arises in previous approaches to calibrate values of the parameters (m, σ_u) using only fracture toughness data measured under high-constraint, SSY conditions where one parameter (*J*) describes the crack front fields. For fracture specimens, $\dot{K}_J$ provides a generalized parameter to describe the loading rate. Our numerical analyses show that $\dot{K}_J$ remains a constant value up to the highest K_{Jc} level for each specimen. Under the loading rate of $\dot{\Delta}_{LLD} = 0.25\,\text{mm}/s$, the $\dot{K}_J$ value is 17 $\text{MPa}\sqrt{\text{m}}/s$ for the $a/W = 0.14$ specimen and 28 $\text{MPa}\sqrt{\text{m}}/s$ for the $a/W = 0.55$ specimen. To accommodate the difference in $\dot{K}_J$, we use $\dot{K}_{SSY} = 22.5$ $\text{MPa}\sqrt{\text{m}}/s$ as the reference configuration to convert the test data to the plane strain, SSY ($T_\sigma = 0$) K_{Jc} values. At $m = 10.3$, the difference in K_0 for the two constraint corrected, SSY toughness distributions becomes zero, which suggests that the calibrated Weibull modulus is $m = 10.3$ for this loading rate. This m-value is very close to the value $m = 11.2$ calibrated using static toughness data.

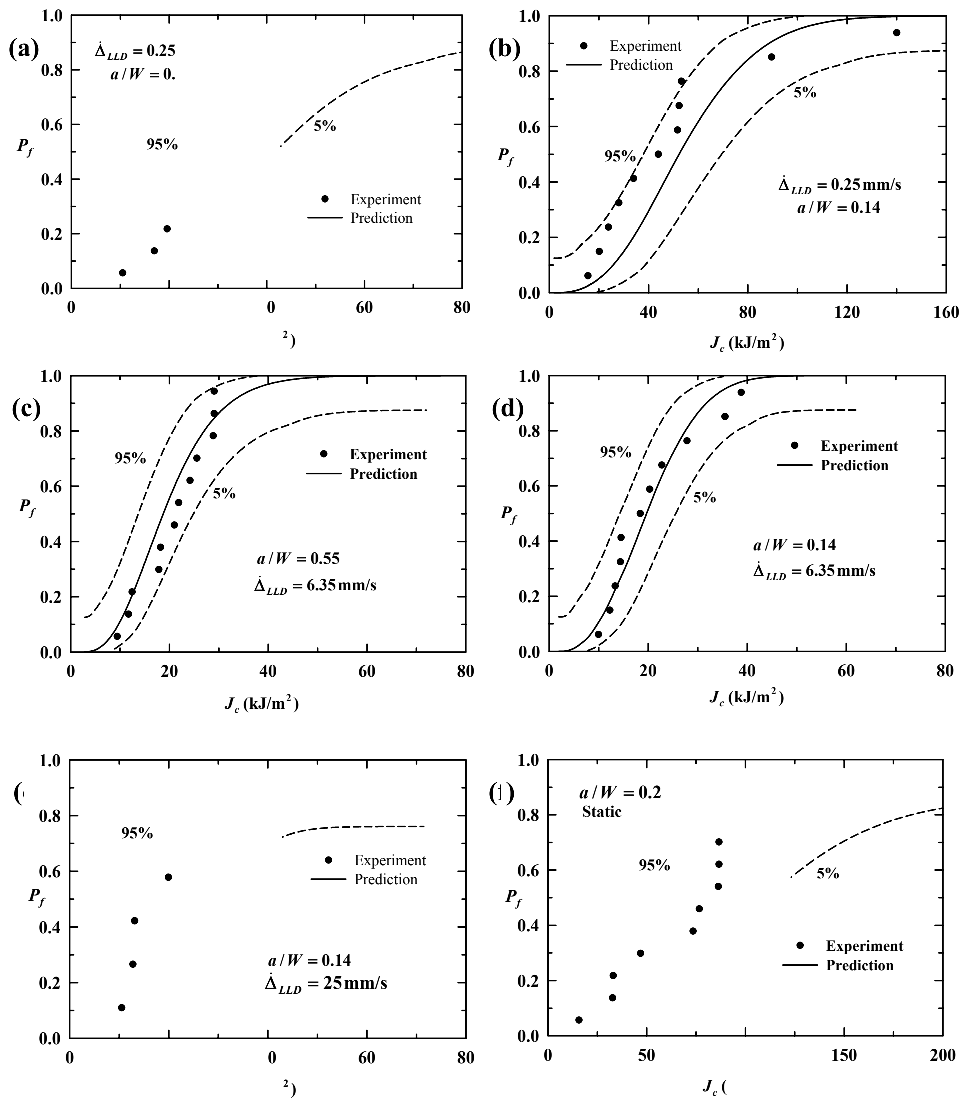

Figure 2: Comparison of predicted cleavage probabilities with rank probabilities for measured J_c-values.

Because of the strong rate sensitivity of the A515-70 steel considered in this study, the measured fracture toughness values quickly saturate to essentially the lower-shelf value as loading rate increases. At the loading rate of $\dot{\Delta}_{LLD} = 6.35$ mm/s, the K_{Jc-med} values for the deep and shallow cracked SE(B) specimens are very similar, which makes calibration of m using the measured fracture toughness data impossible at this loading rate. However, if we assume that the microcrack distribution remains unchanged in the low to moderate range, m should take the same value for different loading rates in this range. We take m as the average 10.3 and 11.2 and assume it remains fixed ($m = 10.75$) for dynamic loading over the range of rates considered ($\dot{K}_I \le 2{,}500$ $\mathrm{MPa}\sqrt{\mathrm{m}}/s$). The effects of dynamic loading then enter the Weibull stress model entirely through the rate-sensitive material flow properties. We obtain σ_{w-min} for each loading rate as the computed Weibull stress value at $K_I = K_{min}$ for the SSY configuration under the same $\dot{K}_I$ as the fracture specimen. Next, we scale each set of experimentally measured (dynamic) fracture toughness data to the SSY configuration corresponding to the same $\dot{K}_I$ and calibrate σ_u as the Weibull stress value at the fracture toughness corresponding to 63.2% failure probability of the constraint-corrected SSY distribution. For m=10.75, the dependencies of σ_u and σ_{w-min} on $\dot{K}_J$ are shown in Fig. 1 – these dependencies are not overly strong. In Fig. 1, the symbols indicate the $\dot{K}_J$ values of different specimens in the test program.

Figure 2 shows the evolution of cumulative probability for cleavage fracture with increased J for the deep and shallow cracked SE(B) specimens loaded with different load-line velocities. The solid lines represent the predictions of median fracture probabilities made using the three-parameter Weibull stress model, Eq. (4), with the above calibrated parameters. The symbols indicate the median rank probabilities for measured J_c-values computed as $P_i = (i - 0.3)/(N + 0.4)$, where i denotes the rank number and N defines the total number of fracture tests. The dashed lines represent the 90% confidence limits for the estimates of rank probability of the experimental data. Using m=10.75 and σ_u and σ_{w-min} values shown in Fig. 1, the Weibull stress model predicts very well the toughness distributions for both deep and shallow cracked SE(B) specimens at every applied loading rate.

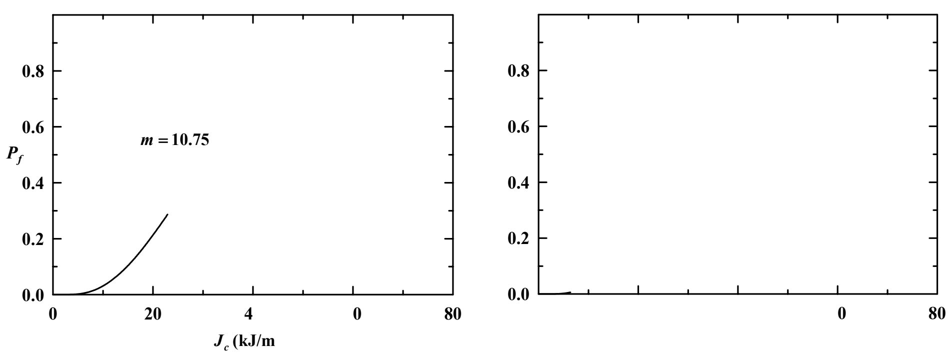

Figure 3: Sensitivity of the predicted P_f $vs.J$ relationship to the variation of m and σ_u.

Figure 3 examines the sensitivity of the predicted P_f *vs.* J relationship on the Weibull stress parameters. Consider for example the $a/W = 0.14$ specimen and the loading rate of $\dot{\Delta}_{LLD}$ $= 0.25\,\mathrm{mm}/s$. Figure 3(a) shows the difference in predicted P_f *vs.* J curve when σ_u is fixed while m varies from 10.75 to 12. Figure 3(b) shows the difference in predicted P_f *vs.* J curve when m is fixed at 10.75 while σ_u is reduced by 5%. Clearly, the predicted cumulative probability for cleavage exhibits a strong sensitivity to the value of σ_u. Consequently, the same value of σ_u cannot be used for different loading rates - specifically the static value of σ_u cannot be used for dynamic loading. The dynamically calibrated value of σ_u should be used to predict the dynamic fracture toughness at each loading rate.

4 CONCLUDING REMARKS

This work examines the effects of loading rate on the Weibull stress model for simulation of cleavage fracture in an A515-70 pressure vessel steel. The study shows that the Weibull modulus (m) remains reasonably rate independent over the range of loading rates considered for this material and the dependencies of σ_u and σ_{w-min} on loading rate are not overly strong. However, the predicted cumulative probability for cleavage exhibits a strong sensitivity to the calibrated value of σ_u. Consequently, use of a calibrated σ_u value based on static tests leads to significant errors in the predicted cumulative failure probabilities for dynamic loading.

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