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Technical Note

Loading rate effects on parameters of the Weibull stress model for ferritic steels

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Abstract

This study investigates the effects of loading rate on parameters of the Weibull stress model for prediction of cleavage fracture in a low strength, strongly rate-sensitive A515-70 pressure vessel steel. Based on measured, dynamic fracture toughness data from deep- and shallow-cracked SE(B) specimens, the calibrated Weibull modulus (m) at $\dot{K}_I = 22.5\ \text{MPa}\sqrt{\text{m}}/\text{s}$ shows little difference from the value calibrated previously using static toughness data. This newly obtained result supports the hypothesis in an earlier study [Gao X, Dodds RH, Tregoning RL, Joyce JA. Weibull stress model for cleavage fracture under high-rate loading. Fatigue Fract Engng Mater Struct 2001;24:551–64] that the Weibull modulus likely remains rate independent for this material over the range of low-to-moderate loading rates. Additional experimental and computational results for higher rates show that a constant m-value remains applicable up to the maximum loading rate imposed in the testing program ($\dot{K}_I \approx 2200\ \text{MPa}\sqrt{\text{m}}/\text{s}$). Rate dependencies of the scale parameter (σ_u) and the threshold parameter ($\sigma_\text{w-min}$) are computed using the calibrated m, and the results indicate that σ_u decreases and $\sigma_\text{w-min}$ increases with higher loading rates. The predicted cumulative probability for cleavage fracture exhibits a strong sensitivity to small changes in σ_u. Consequently, σ_u must be calibrated using dynamic fracture toughness data at each loading rate of interest in an application or selected to make the Weibull stress model predict a dynamic master curve of macroscopic toughness for the material.

Keywords: Cleavage fracture; Fracture toughness; Failure probability; Weibull stress; Dynamic loading; Rate sensitivity

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1. Introduction

Defect assessments of structural components require accurate estimates of fracture toughness for engineering materials under various temperature and loading conditions. The empirically derived "master curve" [2], adopted in ASTM E1921 [3], describes the dependence of cleavage fracture toughness on temperature for ferritic steels in the ductile-to-brittle transition (DBT) region. The master curve shape and temperature dependence derives from extensive sets of static fracture toughness data measured using high-constraint, deep-cracked specimens. But defect assessments often must consider dynamic loading due to collision, sudden pressure rise, thermal shock, etc. Many low and medium strength steels exhibit strong, strain-rate sensitivity that leads to significantly reduced fracture toughness under dynamic loading. Recent studies by Joyce [4] and Wallin [5] accommodate this decrease in fracture toughness by shifting the (indexing) reference temperature (T_0) for the master curve to values greater than the value applicable for quasi-static loading.

The master curve defines the median fracture toughness for the high-constraint, small-scale yielding (SSY) configuration while in engineering applications the crack front often experiences constraint loss. This motivates development of micromechanics-based models to address the transferability of cleavage fracture toughness across varying levels of crack-front constraint. The Weibull stress model, proposed by the Beremin group [6], provides a basis to generalize the concept of a probabilistic fracture parameter and supports the development of procedures that adjust toughness values across different crack configurations and loading modes (tension and bending). Gao et al. [7] proposed a procedure to calibrate parameters of the Weibull stress model using fracture toughness data obtained from two sets of test specimens that exhibit different constraint levels at fracture. Using a three-parameter Weibull stress model with the parameters calibrated based on this new approach, Gao et al. [8] predicted accurately the distributions of measured cleavage fracture values in various specimens of an A515-70 steel under quasi-static loading—including surface crack specimens subject to different combinations of bending and tension.

The success of the Weibull stress model to "transfer" cleavage toughness values for static loading motivates our continuing studies to extend the applicability of the model to dynamic loading. Further progress requires a more complete understanding of the dependencies of the Weibull model parameters on loading rate. In an earlier study, Gao, et al. [1] assumed the Weibull modulus (m) remains independent of loading rate and obtained dependencies of the scale parameter (σ_u) and the threshold parameter ($\sigma_{\text{w-min}}$) on loading rate by matching the predicted and measured toughness distributions of the shallow-cracked SE(B) specimens of the A515-70 steel at several loading rates. More recently, Tregoning and Joyce [9] completed additional dynamic fracture tests of the same A515-70 steel using deep- and shallow-cracked SE(B) specimens. This makes it now possible to calibrate directly the Weibull modulus (m) using the dynamic fracture toughness data. In this short note, we examine the effects of loading rate on the Weibull stress parameters for the A515-70 steel using the newly obtained fracture toughness data for deep- and shallow-cracked SE(B) specimens obtained by Tregoning and Joyce.

2. The Weibull stress model

The Weibull stress model originally proposed by the Beremin group [6] derives from weakest link statistics and adopts a two-parameter Weibull distribution to describe the cumulative failure probability

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