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Fracture assessment of ferritic steel components under dynamic loading

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ABSTRACT

This paper summarizes recent studies on application of the Weibull stress model to predict cleavage fracture of structural components under dynamic loading. Two pressure vessel steels, the strongly rate-sensitive A515-70 steel and the moderately rate-sensitive Euro material (22NiMoCr37), are considered in the investigation. The results, based on independent calibrations at different loading rates, demonstrate that the Weibull modulus (m) is invariant of loading rate for both materials. While m remains a constant for each material, σ_u decreases and σ_{w-min} increases with higher loading rates. The studies also show that dynamic loading reduces constraint loss, i.e., it drives the response towards the small-scale yielding configuration, and this rate effect tends to saturate at higher loading rate. The demonstrated loading rate invariance of m, when combined with the Master Curve for dynamic loading, can provide a practical approach which simplifies the process to estimate σ_u as a function of loading rate.

1. Introduction

Ferritic steel pressure vessels, piping and other components have a critical role in current commercial nuclear power plants and will have in future designs as well. These materials and their welds undergo a ductile-to-brittle transition (DBT) in fracture behaviour with decreasing temperature, increased loading rates, embrittlement by radiation, and most generally by complex combinations of these effects. The brittle (cleavage) mechanism raises the most concern for structural integrity as effectively uncontrolled and dynamic crack propagation may lead to macro-scale component failure. The sharp variations of pressure–thermal loadings that occur during a pressurized thermal shock (PTS) event can lead to a complex set of cleavage crack initiation – fast propagation – crack arrest – dynamic re-initiation processes such as observed in the scale-model vessel tests performed by the Oak Ridge National Laboratory in the early 1980s [1,2]. Reliable, quantitative predictions of the observed fracture processes in such tests continue to pose substantial challenges for current modeling capabilities.

Two major obstacles arise in application of elastic-plastic fracture mechanics principles to assess the integrity of structural components in the DBT region: the scatter of measured fracture toughness data and the transferability of toughness values between crack configurations with different levels of constraints [3,4]. These are results of the strongly stochastic effects of metallurgical scale inhomogeneities and the nonlinear mechanical response from plastic deformation. To add more complexities to an already very complex problem, temperature effects, strain-rate effects, irradiation effects, welding inhomogeneities, etc., must be considered in prediction of cleavage fracture in pressure vessel components. These have stimulated an increasing amount of research in the past two decades, leading to a quantitative understanding of the scatter and temperature dependence of macroscopic fracture toughness (in terms of J_c or K_{Jc}) under high constraint, small-scale yielding (SSY) conditions. Scatter of the SSY toughness data can be described by a three-parameter Weibull distribution, where the Weibull modulus for the K_{Jc} distribution is 4 and the minimum fracture toughness for common ferritic steels is $K_{min} \approx 20\ \mathrm{MPa}\sqrt{\mathrm{m}}$ [3,5]. This three-parameter Weibull distribution has been adopted in ASTM standard E1921 [6]. E1921 also adopts a so-called "Master Curve", empirically derived by Wallin and others [7,8], to describe the dependence of the median fracture toughness on temperature for ferritic steels in the DBT region. E1921 and the Master Curve approach have gained widespread acceptance to describe the transition fracture toughness and the scatter of toughness values in recent years. Recent studies by Joyce [9] and Wallin [10] accommodate the decrease in fracture toughness with increasing loading rate by shifting the (indexing) reference temperature (T_0) for the Master Curve to values greater than the value applicable for quasi-static loading. Lucon et al. [11] performed fracture toughness tests of an European reduced activation ferritic/martensitic steel in the unirradiated condition and after irradiation using precracked

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Charpy specimens and found the effects of irradiation embrittlement can also be characterized by a shift in T_0.

The Master Curve defines the median fracture toughness under high constraint, SSY conditions while in engineering applications the crack front often experiences constraint loss. For examples, defect assessment of pressure vessels often deals with shallow surface cracks; fracture tests of irradiated materials have to use Charpy or sub-Charpy size specimens due to material availability (from surveillance capsules), etc. This motivates the development of micromechanics-based models to address the transferability of cleavage fracture toughness across varying levels of crack-front constraint. The Weibull stress model, originally proposed by the Beremin group [12], provides a framework for quantifying the relationship between macro-scale and micro-scale driving forces for cleavage fracture. The introduction of the so-called Weibull stress (σ_w) provides the basis for generalizing 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 vs. bending). The Beremin model has two material parameters, the Weibull modulus (m) and the scale parameter (σ_u). Gao et al. [13] introduced a threshold parameter ($\sigma_{w\text{-}min}$) into the Weibull stress model and proposed a procedure to calibrate the model parameters using fracture toughness data obtained from two sets of fracture specimens that exhibit different constraint levels at failure. Using the three-parameter Weibull stress model with parameters calibrated according to the proposed procedure, Gao et al. [14] predicted the distributions of measured fracture toughness values in various specimens of an A515-70 pressure vessel steel, including surface crack specimens subject to different combinations of bending and tension.

A very important consideration in developing predictive models for engineering applications is to involve a minimum number of model parameters which can be determined according to a rational calibration procedure. The Weibull stress model contains only two or three material parameters and provides a very attractive tool to predict structural component failure by cleavage fracture in the DBT region. The model applies equally to initiation of a propagating cleavage crack triggered by quasi-static or by dynamic loading representative of motions possible in a large-scale component. The model supports the "adjustment" of static and dynamic fracture toughness values to accommodate different crack-front constraint conditions that develop in simple laboratory test specimens and in full-scale components. Recently Petti and Dodds [15] argued that the Weibull modulus (m) is independent of temperature and the scale parameter (σ_u) increases with temperature to reflect the increase of micro-scale toughness of ferritic steels. They proposed a procedure to calibrate the variation of σ_u with temperature using the Master Curve. Wasiluk et al. [16] calibrated the Weibull stress parameters for a $22NiMoCr_{37}$ pressure vessel steel at different temperatures using the fracture toughness data generated in a fracture research project sponsored by the European Union [17], and demonstrated the temperature invariance of m. Gao et al. [18, 19] studied the effects of loading rate on the Weibull stress model for the A515-70 steel and found a loading rate-independent m can be employed in the range of low-to-moderate loading rates. A more recent experimental-numerical study presented by Gao et al. [20] demonstrated m is also invariant of loading rate for the 22NiMoCr37 pressure vessel steel. With m being demonstrated invariant of temperature and loading rate, the Petti and Dodds approach [15] provides a simple and practical method to estimate σ_u as a function of temperature and loading rate. This significantly reduces the number of fracture tests required for defect assessment at dynamic loading rates.

This paper summarizes recent studies on application of the Weibull stress model to predict cleavage fracture in pressure vessel steels under dynamic loading. Section 2 outlines the frameworks of the Master Curve approach and the Weibull stress model and the procedures to calibrate the Weibull stress model parameters. Section 3 demonstrates the invariance of the Weibull modulus (m) on loading rate and discusses the consequences of this important finding. Section 4 provides some concluding remarks.

2. Probabilistic treatment of cleavage fracture

2.1. The Master Curve approach

Based on the weakest link statistics, ASTM E1921 [6] adopts a three-parameter Weibull distribution to describe the fracture toughness under plane strain, SSY conditions

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

where K_0 represents the fracture toughness value at 63.2% failure probability and K_{min} represents the threshold toughness for the material. For the common ferritic steels, K_{min} has an empirical value of 20 $\text{MPa}\sqrt{\text{m}}$ (independent of temperature and loading rate) [6].

Under plane strain, SSY conditions, the highly stressed volume of material along the crack-front scales with$B \times K_J^4$, where B denote the crack-front length. Therefore, for test programs conducted on specimens other than the 1 T thickness (crack-front length = 25.4 mm) the measured toughness values are adjusted to their 1 T equivalent values using

$$K_{Jc(1T)} = K_{min} + \left[K_{Jc(xT)} - K_{min}\right]\left(\frac{B_{xT}}{B_{1T}}\right)^{1/4} \tag{2}$$

where B_{1T} denotes the 1T thickness and B_{xT} denotes the thickness of the test specimens.

The maximum likelihood method provides the estimate for K_0 from the measured toughness values as

$$K_0 = \left[\sum_{i=1}^{N}\frac{\left(K_{Jc(i)}-K_{min}\right)^4}{(r-0.3068)}\right]^{1/4} + K_{min} \tag{3}$$

where N denotes the total number of specimens tested (both censored and uncensored) while r represents the number of uncensored tests (six minimum) [6]. The E1921 procedures set a limit for deformation, $M_{limit} = 30$, to ensure SSY conditions being satisfied. The corresponding fracture toughness value is given by

$$K_{J_{c(limit)}} = \sqrt{\frac{Eb\sigma_0}{M_{limit}(1-\nu^2)}} \tag{4}$$

where b, E,ν and σ_0 denote the remaining ligament, Young's modulus, Poisson's ratio, and yield stress, respectively. Toughness values greater than $K_{J_{c(limit)}}$ are censored.

Knowing K_0, the median fracture toughness, $K_{J_{c(med)}}$, can be evaluated as

$$K_{J_{c(med)}} = 0.9124(K_0 - K_{min}) + K_{min} \tag{5}$$

The Master Curve for ferritic steels makes possible the prediction of median fracture toughness at any temperature (T) in the transition region, provided the reference temperature (T_0) for the material has been determined from the SSY fracture toughness data at a given temperature. The Master Curve has the form

$$K_{J_{c(med)}} = 30 + 70\exp[0.019(T - T_0)] \tag{6}$$