REVISITING LOCAL APPROACHES TO CLEAVAGE FRACTURE: AN OVERVIEW OF PROGRESS AND CHALLENGES FOR ENGINEERING-LEVEL APPLICATIONS

Claudio Ruggieri[1]*

[1]*University of São Paulo, São Paulo, SP, Brazil*
** Presenting Author email: claudio.ruggieri@usp.br*

Abstract

This paper provides an overview of recent progress in probabilistic modeling of cleavage fracture phrased in terms of a local approach to fracture (LAF) and the Weibull stress concept. Emphasis is placed on the incorporation of plastic strain effects into the probabilistic framework by approaching the strong influence of constraint variations on (macroscopic) cleavage fracture toughness in terms of the number of eligible Griffith-like microcracks which effectively control unstable crack propagation by cleavage. Some recent results based on a modified Weibull stress model to predict specimen geometry effects on J_c-values for pressure vessel grade steels are summarized in connection with an engineering procedure to calibrate the Weibull stress parameters. These results are compared against corresponding fracture toughness predictions derived from application of the standard Beremin model. Finally, the robustness of LAF methodologies, including specifically the Weibull stress approach, is critically examined along with a discussion of key issues and challenges related to engineering applications in fracture assessments of structural components.

1. Introduction

The increased demand for more accurate structural integrity and fitness-for-service (FFS) analysis of a wide class of engineering structures, including nuclear reactor pressure vessels, piping systems and storage tanks, has stimulated renewed interest in advancing current safety assessment procedures of critical structural components, including life-extension programs and repair decisions of aging structures. Simplified fracture mechanics based approaches for quantitative analysis of material degradation, as of interest in assessments of crack-like flaws formed during in-service operation, focus primarily on the potential for catastrophic failure due to low toughness behavior. While conventional FFS methodologies clearly simplify integrity assessments of in-service structural components, they have limited ability to predict the potential strong influence of constraint on fracture behavior and, perhaps more importantly, do not address the strong sensitivity of cleavage fracture to material characteristics at the microlevel. The early recognition of these limitations prompted a surge of interest in analyzing, predicting and unifying toughness measures across different crack configurations and loading modes based on a micromechanics interpretation of the cleavage fracture process. Here, attention has been primarily focused on probabilistic models incorporating weakest link statistics, most often referred to as local approaches to fracture (LAF) in terms of the Weibull stress methodology, to describe material failure caused by transgranular cleavage for a wide range of loading conditions and crack geometries. However, a fundamental objection to the probabilistic framework from which the Weibull stress concept is derived is that it relies on the assumption that Griffith-like microcracks (which effectively act as precursors of transgranular cleavage in structural steels) form immediately upon the onset of yielding thereby implying that the associated statistical distribution of microcrack size remains unchanged with increased loading and deformation. Since any cleavage fracture model incorporating statistics of microcracks (weakest link philosophy), such as the Weibull stress methodology, involves a local Griffith instability of the largest, most favorably oriented microcrack, it becomes clear that increased plastic strains correlate directly with increased likelihood of cleavage failure

2. Results

Fracture mechanics tests were conducted on compact tension C(T) and precracked Charpy notched (PCVN) specimens with 20% side-grooves (10% on each specimen lateral side) and different geometries in the LS orientation. The C(T) specimens have standard configuration with thickness, B=25.4 mm (1T configuration), width, W=50.8 mm, and crack length to width ratio, a/W=0.5. The PCVN specimens have a fixed S=$4W$ with varying geometry and crack length to width ratio including: 1) $B=W$=5 mm and a/W=0.5 and 3) $B=W$=3 mm and a/W=0.5. The material utilized in the fracture tests is a low alloy, quenched and tempered ASTM A533 Grade B Class 1 extracted from the decommissioned Shoreham nuclear plant reactor pressure vessel with 488 MPa yield stress and 644 MPa tensile strength at room temperature.

Figure 1(a-b) shows the predicted Weibull (cumulative) distributions of J_c-values for the 1T C(T) specimen generated from the distribution of J_c-values for the subsize PCVN configurations with B=5mm and B=3mm. These results are generated from a modified form of the Weibull stress incorporating plastic strain effects with m=16 and σ_{prf}=3800 MPa defining the fractured particle distribution model. In these plots, the solid lines represent the predicted median values of fracture probability whereas the 90% confidence bounds for J_0 (the characteristic toughness) are defined by the dashed lines. In general, the predictions generated from the subsize PCVN geometries are in good agreement with the experimental fracture toughness distribution derived from the C(T) specimen.

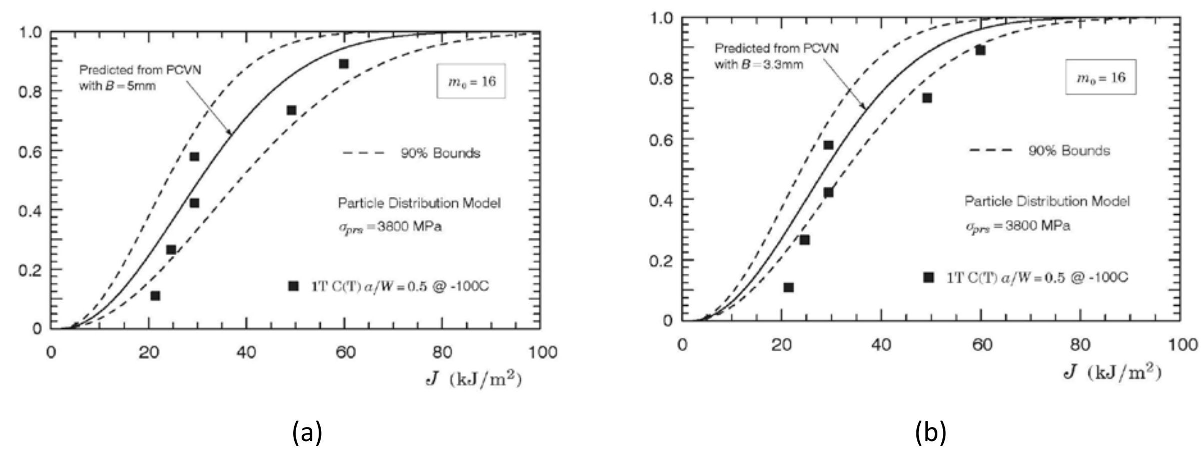

Fig. 1- Predicted cumulative Weibull distribution of experimentally measured J_c-values for the deeply-cracked C(T) specimen generated from the toughness distribution for the PCVN geometries: (a) PCVN with B=5mm (b) PCVN with B=3mm.

3. Conclusions

One objective of this work is to summarize recent advances in the local approach to cleavage fracture modeling, illustrated by selected examples of application to predict effects of specimen geometry on cleavage fracture toughness for typical pressure vessel steels. In particular, it has been shown the effectiveness of a modified form of the Weibull stress incorporating the influence of plastic strain on the number of eligible Griffith-like microcracks nucleated from brittle particles dispersed into the ferrite matrix on fracture assessments and toughness predictions for low constraint crack configurations. Another objective of this work is to discuss some key features associated with the robustness of the Weibull stress approach while, at the same time, considering some challenges for potential new extensions and applications. Specifically for the conventional cases of multiscale predictions of fracture behavior in structural components with diverse range of crack-tip constraint, inclusion of the effects of near-tip plastic strain on cleavage microcracking which impacts directly the magnitude of the Weibull stress appear central to derive improved toughness scaling corrections and, consequently, to obtain more accurate fracture toughness predictions. Adoption of a modified form of the Weibull stress incorporating plastic strain effects does bring fracture toughness predictions into better agreement with experimental measurements.

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