23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

A MICROMECHANICS APPROACH INCORPORATING PLASTIC STRAIN EFFECTS TO PREDICT THE INFLUENCE OF SPECIMEN GEOMETRY ON CLEAVAGE FRACTURE TOUGHNESS FOR A PRESSURE VESSEL STEEL

Claudio Ruggieri
Polytechnic School of Engineering, University of São Paulo, Brazil
claudio.ruggieri@usp.br

Robert H. Dodds
University of Illinois at Urbana-Champaign, IL, USA
rdodds@illinois.edu

Abstract. *This work extends a micromechanics model for cleavage fracture incorporating effects of plastic strain to determine the reference temperature, T_0, for an A515 Gr 65 pressure vessel steel based on a modified Weibull stress ($\tilde{\sigma}_w$). Non-linear finite element analyses for 3-D models of plane-sided SE(B) and PCVN specimens define the relationship between $\tilde{\sigma}_w$ and J from which the variation of fracture toughness across different crack configurations is predicted. The modified Weibull stress methodology effectively removes the geometry dependence of J_c-values*

Keywords : *cleavage fracture, local approach, Weibull stress, plastic strain, constraint effects*

1. INTRODUCTION

The increasing demand to ensure acceptable levels of structural safety, including repair decisions and life-extension programs for aging structures, has spurred the development of advanced procedures for cleavage fracture assessments of critical engineering components such as, for example, nuclear reactor pressure vessels (RPVs), hydrocarbon-processing industry (HPI) pressurized equipment and storage tanks, among others. A case of considerable interest is the utilization of small fracture specimens to facilitate experimental measurements of fracture toughness data in commercial nuclear RPV surveillance programs. In particular, three-point bend testing of precracked Charpy (PCVN) specimens becomes necessary when severe limitations exist on material availability such as, for example, in nuclear irradiation embrittlement studies. However, as the specimen size is reduced (relative to the standard 1T specimen), the evolving crack-tip plastic zones developing from the free surfaces with increased loading affect strongly the crack front size over which high levels of near-tip stress triaxiality (constraint) are maintained. These changes in the crack-tip stress fields over a relatively small thickness in connection with a smaller sampling volume for cleavage fracture influence the measured toughness values, including their statistical scatter and mean value.

To address this issue, Ruggieri and Dodds (Ruggieri and Dodds, 2015; Ruggieri *et al.*, 2015), hereafter referred to as R&D, described a micromechanics methodology based upon a local failure criterion incorporating the effects of plastic strain on cleavage fracture coupled with the statistics of microcracks. They considered a probabilistic framework to address the strong effects of constraint variations on (macroscopic) cleavage fracture toughness based on the Weibull stress concept (also widely known as the Beremin model (Beremin, 1983)) but approached the modeling of cleavage fracture from the point of view of a coupling between the local plastic strain and the number of eligible Griffith-like microcracks nucleated from brittle particles dispersed into the ferrite matrix. A modified Weibull stress ($\tilde{\sigma}_w$) incorporating the effects of plastic strain on cleavage fracture emerged as a probabilistic fracture parameter to define conditions leading to (local) material failure. By postulating unstable crack propagation at a critical value of $\tilde{\sigma}_w$, a toughness scaling methodology that unifies toughness measures across different crack configurations and loading modes was introduced.

This work describes a micromechanics methodology based upon a local failure criterion incorporating the effects of plastic strain on cleavage fracture coupled with the statistics of microcracks. A central objective of this study is to explore application of the micromechanics model incorporating the influence of plastic strain on cleavage fracture developed in previous work by Ruggieri and Dodds (Ruggieri and Dodds, 2015; Ruggieri *et al.*, 2015) to correct fracture toughness for the strong effects of constraint loss. Fracture toughness testing conducted on an A515 Gr 65 pressure vessel steel provides the cleavage fracture resistance data needed to assess specimen geometry effects on experimentally measured J_c-values. Very detailed non-linear finite element analyses for 3-D models of plane-sided SE(B) and PCVN specimens

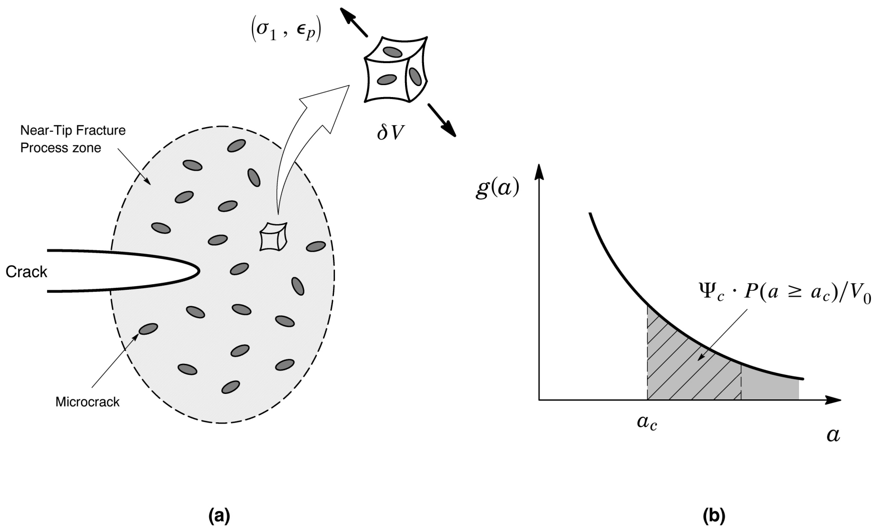


Figure 1. (a) Near-tip fracture process zone ahead a macroscopic crack containing randomly distributed flaws b) Schematic of power-law type microcrack size distribution.

provide the evolution of near-tip stress field with increased macroscopic load (in terms of the J-integral) to define the relationship between $\tilde{\sigma}_w$ and J from which the variation of fracture toughness across different crack configurations is predicted. For the tested material, the modified Weibull stress methodology effectively removes the geometry dependence on J_c-values thereby enabling accurate predictions of fracture toughness distributions which are independent of specimen size and configuration.

2. LOCAL APPROACH TO CLEAVAGE FRACTURE INCORPORATING PLASTIC STRAIN EFFECTS

This section repeats the salient features of the Weibull stress framework incorporating plastic strain effects derived by R&D (Ruggieri and Dodds, 2015). Development of a micromechanics model for cleavage fracture incorporating effects of plastic strain begins by assuming the fracture process zone (FPZ) in a stressed cracked body illustrated in Fig. 1(a) in which a small volume element, δV, is subjected to the principal stress, σ_1, and associated effective plastic strain, ϵ_p. Here, only microcracks formed from the cracking of brittle particles, such as carbides, in the course of plastic deformation contribute to cleavage fracture and, further, the fraction of fractured particles increases with increased matrix plastic strain. An approximate account of such a micromechanism can be made by considering that a fraction, Ψ_c, of the total number of brittle particles in the FPZ nucleates the microcracks which are eligible to propagate unstably and, further, that Ψ_c is a function of plastic strain but plausibly independent of microcrack size as pictured in Fig. 1(b).

Following standard procedures based on the weakest link concept (Ruggieri and Dodds, 2015), a limiting distribution for the cleavage fracture stress can expressed as

$$P_f(\sigma_1,\ \epsilon_p) = 1 - \exp\left[-\frac{1}{V_0}\int_\Omega \Psi_c(\epsilon_p)\cdot\left(\frac{\sigma_1}{\sigma_u}\right)^m d\Omega\right] \tag{1}$$

where m is the Weibull modulus, σ_u denotes the Weibull scale parameter, Ω is the volume of the near-tip fracture process zone most often defined as the loci where $\sigma_1 \geq \psi\sigma_0$, with σ_0 denoting the material yield stress and $\psi \approx 2$, and V_0 represents a reference volume conventionally taken as a unit volume, $V_0 = 1$. The above result then motivates the notion of a modified Weibull stress, $\tilde{\sigma}_w$, defined by

$$\tilde{\sigma}_w = \left[\frac{1}{V_0}\int_\Omega \Psi_c(\epsilon_p)\cdot\sigma_1^m d\Omega\right]^{1/m} \quad . \tag{2}$$

where it is noted that setting $\Psi_c = 1$ recovers the standard Beremin model (Beremin, 1983).

To arrive at a simple form for the failure probability of cleavage fracture including effects of plastic strain, we follow similar arguments to those given by R&D (Ruggieri and Dodds, 2015) to define the fraction of fractured particles as a two-parameter Weibull distribution expressed as (Wallin and Laukkanen, 2008)

$$\Psi_c = 1 - \exp\left[-\left(\frac{\sigma_{pf}}{\sigma_{prs}}\right)^{\alpha_p}\right] \tag{3}$$

where σ_{prs} is the particle reference fracture stress, α_p denotes the Weibull modulus and $\sigma_{pf} = \sqrt{1.3\sigma_1\epsilon_p E_d}$ characterizes the particle fracture stress in which σ_1 is the maximum principal stress, ϵ_p denotes the effective matrix plastic strain and E_d represents the particle's elastic modulus. Here, it is understood that the particle reference stress, σ_{prs}, represents an approximate average for the distribution of the particle fracture stress. For ferritic structural steels, such as the A515 pressure vessel material utilized in this study, typical values of α_p and E_d are 4 and 400 GPa; these values are employed in the analyses reported later.

Now, upon substituting Eq. (3) into Eq. (2) and working out the resulting expression, the modified Weibull stress now takes the form

$$\tilde{\sigma}_w = \left[\frac{1}{V_0} \int_\Omega \left\{ 1 - \exp\left[-\left(\frac{\sigma_{pf}}{\sigma_{prs}} \right)^{\alpha_p} \right] \right\} \cdot \sigma_1^m d\Omega \right]^{1/m} \quad . \tag{4}$$

3. MATERIAL DESCRIPTION AND FRACTURE TOUGHNESS DATA

The material utilized in the fracture tests described next is a typical ASTM A515 Grade 65 pressure vessel steel with 294 MPa yield stress and 514 MPa tensile strength at room temperature (20°C). Table 1 summarizes the tensile testing results for different test temperature which evidence the high hardening behavior of the tested steel with $\sigma_{uts}/\sigma_{ys} \approx 1.7 \sim 1.8$. Other mechanical properties for this material include Young's modulus, $E = 210$ GPa and Poisson's ratio, $\nu = 0.3$.

Table 1. Tensile properties of tested A515 Gr 65 steel measured from transverse plate direction at mid-thickness location (σ_{ys} and σ_{uts} denote the yield stress and tensile strength)

T (°C)	σ_{ys} (MPa)	σ_{uts} (MPa)	σ_{uts}/σ_{ys}
20	294	514	1.8
-10	313	527	1.7
-20	321	532	1.7

Fracture toughness tests were performed on conventional, plane-sided three-point bend fracture specimens with varying crack sizes and specimen thickness in the T-L orientation. The fracture mechanics tests include: (1) conventional, plane-sided SE(B) specimens with $a/W = 0.15$ and $a/W = 0.5$, $B = 30$ mm, $W = 60$ mm and $S = 4W$, and (2) plane-sided, precracked Charpy (PCVN) specimen with $a/W = 0.5$, $B = 10$ mm, $W = 10$ mm and $S = 4W$. Here, a is the crack size, W denotes the specimen width, B represents the specimen thickness and S is the load span.

Cleavage fracture toughness data in terms of J_c-values were determined from the estimation procedure based on η-factors given in ASTM E1820 (American Society for Testing and Materials, 2011) using the experimentally measured plastic area under the load-CMOD curve for each test specimen. The cumulative Weibull distribution of the measured J_c-values at different test temperatures ($T = -10^\circ$C and $T = -20^\circ$C) is displayed in Figure 2. The solid symbols in the plots represent the experimentally measured fracture toughness (J_c)-values for each test specimen. The cumulative probability, $F(J_c)$, is derived by simply ranking the J_c-values in ascending order and using the median rank position defined in terms of $F(J_{c,k}) = (k - 0.3)/(N + 0.4)$, where k denotes the rank number and N defines the total number of experimental toughness values (Mann *et al.*, 1974). The fitting curves to the experimental data shown in this figure describe the three-parameter Weibull distribution (Mann *et al.*, 1974) for J_c-values given by

$$F(J_c) = 1 - \exp\left[-\left(\frac{J_c - J_{\min}}{J_0 - J_{\min}} \right)^{\alpha} \right] \tag{5}$$

in which α defines the Weibull modulus (which characterizes the scatter in test data), J_0 is the characteristic toughness and $J_{\min}$ denotes the threshold J-value corresponding to a $K_{\min}$ of $20\ \mathrm{MPa}\sqrt{\mathrm{m}}$. A parameter estimation of the data set shown in Fig. 2 is performed by adopting the maximum likelihood (ML) method with a fixed value of $\alpha = 2$ as the Weibull modulus of the Weibull distribution describing the J_c-values - the $\alpha = 2$ value characterizes well the scatter in cleavage fracture toughness data under small scale yielding conditions. The ML estimate of the characteristic toughness, J_0, then yields $\hat{J}_0 = 86\ \mathrm{kJ/m^2}$ for the SE(B) specimen with $a/W = 0.5$, $\hat{J}_0 = 160\ \mathrm{kJ/m^2}$ for the SE(B) specimen with $a/W = 0.15$ and $\hat{J}_0 = 155\ \mathrm{kJ/m^2}$ for the PCVN configuration. Ruggieri *et al.* (2015) provide additional details of the material utilized and the fracture toughness tests.

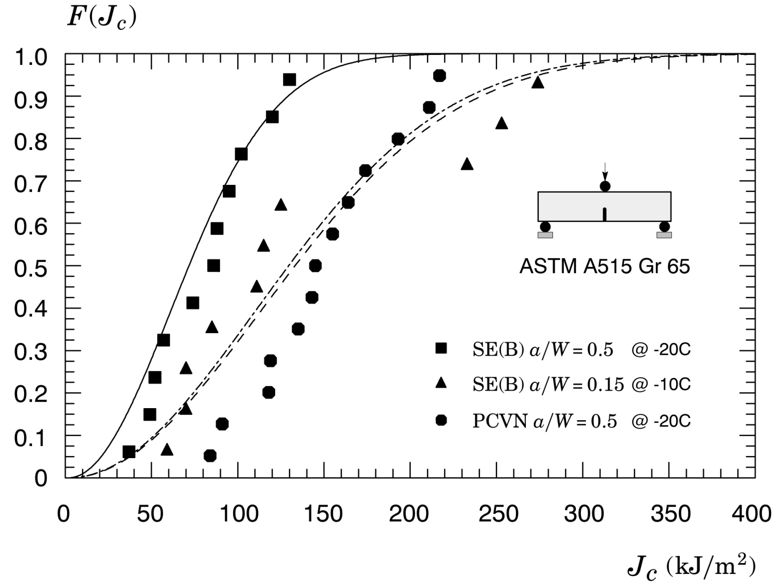


Figure 2. Cumulative Weibull distribution of experimentally measured J_c-values.

4. FINITE ELEMENT PROCEDURES

Nonlinear finite element analyses are described for detailed 3-D models of the tested SE(B) specimens with $a/W = 0.5$ and $a/W = 0.15$, and also for the tested precracked Charpy (PCVN) specimen with $a/W = 0.5$ These configurations have standard geometry ($W = 2B$ and $S = 4W$) and no side-grooves. Figure 3 shows the typical finite element models utilized in the analyses of the deeply cracked SE(B) specimen and PCVN geometry with $a/W = 0.5$. With minor differences, the numerical model for the shallow crack SE(B) specimen with $a/W = 0.15$ has very similar features. A conventional mesh configuration having a focused ring of elements surrounding the crack front is used with a small key-hole at the crack tip; the radius of the key-hole, ρ_0, is 10 μm $(0.01\ \text{mm})$. Symmetry conditions enable analyses using one-quarter of the 3-D models with appropriate constraints imposed on the symmetry planes. The mesh has 32 variable thickness layers defined over the half-thickness $(B/2)$; the thickest layer is defined at $Z = 0$ with thinner layers defined near the free surface $(Z = B/2)$ to accommodate strong Z variations in the stress distribution. The quarter-symmetric, 3-D model for this specimen has approximately 38000 nodes and 34000 elements.

The numerical solutions for the fracture toughness predictions based on the modified Weibull stress methodology described next utilize an elastic-plastic constitutive model with J_2 flow theory and conventional Mises plasticity in large geometry change (LGC) setting incorporating a piecewise linear approximation to the measured tensile response for the material. The mechanical and flow properties for the tested A515 Gr 65 are employed to generate the required numerical solutions at different temperatures. Ruggieri *et al.* (2015) provide details of the material properties adopted in the analyses, including the true stress-logarithmic strain curves at test temperatures ($T = -10^\circ$C and $T = -20^\circ$C). The finite element code WARP3D (Healy *et al.*, 2014) provides the numerical solutions for the 3-D analyses reported here, including a domain integral procedure for numerical evaluation of the J-integral to provide pointwise and front average values of J across the crack front at each loading level.

5. CLEAVAGE FRACTURE PREDICTIONS USING THE MODIFIED WEIBULL STRESS

5.1 Calibration of the Modified Weibull Stress Parameters

Application of the modified Weibull stress methodology outlined above requires correct specification of the m-value and the function Ψ_c entering directly into the calculation of $\tilde{\sigma}_w$ through Eq. (2). Since the Weibull modulus, m, characterizes the distribution of Griffith-like microcracks associated with the cleavage fracture process (see Ruggieri and Dodds (2015) and references therein), we can advantageously evaluate m and Ψ_c using a two-step process as follows.

First, parameter m is determined to establish the best correction for cleavage fracture toughness data measured from two sets of test specimens exhibiting largely contrasting toughness behavior based on the standard Beremin model (*i.e.*, $\Psi_c = 1$). The procedure essentially relies on the toughness scaling model (TSM) proposed earlier by Ruggieri and Dodds (1996) building upon the interpretation of $\tilde{\sigma}_w$ as the (probabilistic) crack tip driving force coupled with the condition

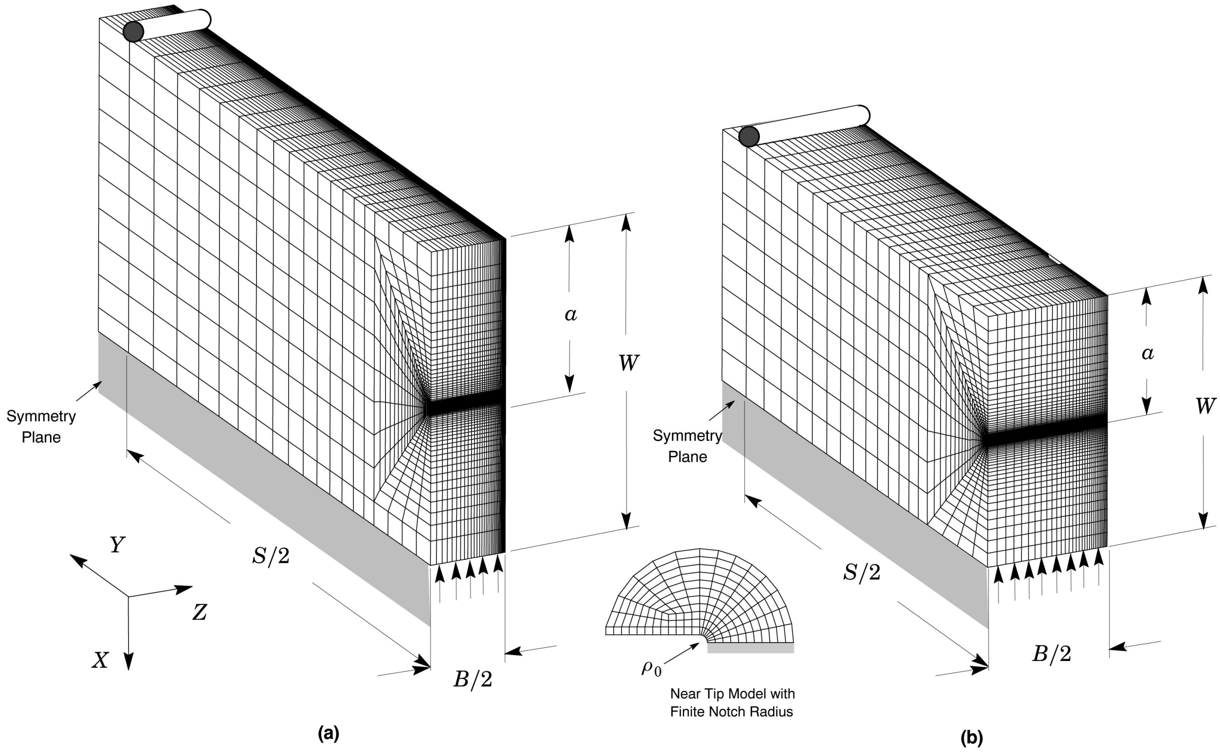
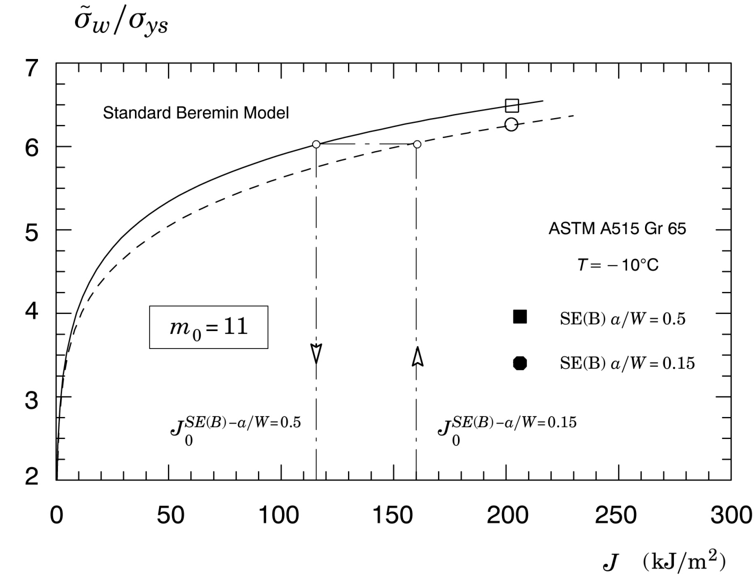


Figure 3. Finite element models used in the 3-D analyses of the tested fracture geometries with $a/W = 0.5$: (a) SE(B) specimen with $B = 30\ \mathrm{mm}$; (b) PCVN geometry.

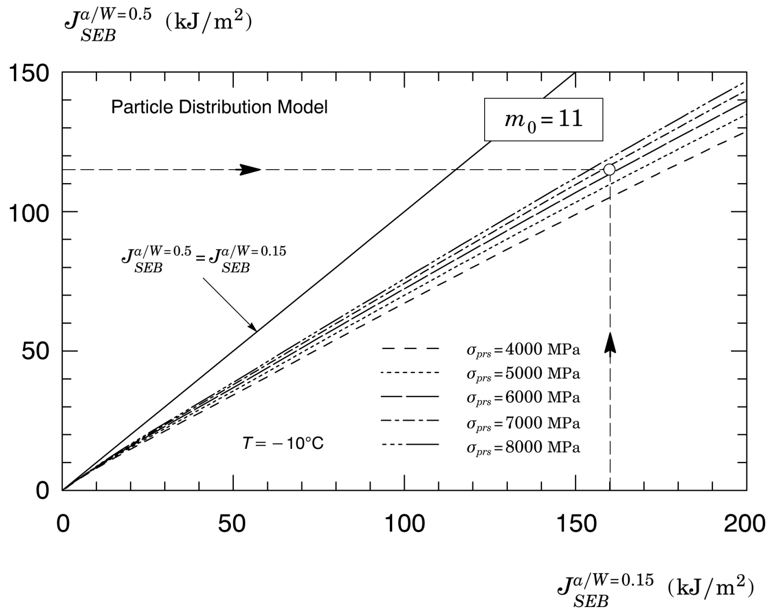
that cleavage fracture occurs when $\tilde{\sigma}_w$ reaches a critical value, $\tilde{\sigma}_{w,c}$. Once the relation between the Weibull stress ($\tilde{\sigma}_w$) and applied loading (J) for a given value of the Weibull modulus, m, is determined, the calibration scheme adopted here defines the calibrated Weibull modulus for the material as the m-value, denoted m_0, that corrects the characteristic toughness J_0^B corresponding to a low constraint configuration (denoted as configuration **B**) to its equivalent J_0^A corresponding to a high constraint configuration (denoted as configuration **A**) such that the residual toughness values defined as $R(m) = (J_{0,m}^A - J_0^A)/J_0^A$ is minimized. In the present application, calibration of parameter m is conducted at the test temperature, $T = -10^{\circ}\mathrm{C}$, by scaling the characteristic toughness of the measured toughness distribution for the shallow crack SE(B) specimen with $a/W = 0.15$ (taken here as configuration **B**) to the equivalent characteristic toughness of the toughness distribution for the deeply-cracked SE(B) specimen with $a/W = 0.5$. The research code WSTRESS (Ruggieri, 2013) is utilized to compute $\tilde{\sigma}_w$ *vs.* J trajectories and to calibrate the Weibull modulus, m for the tested A515 steel based on the standard Beremin model (*i.e.*, $\Psi_c = 1$ as already noted). However, because the specimens were not tested at the same temperature, the present methodology adopts a simple procedure to correct the measured toughness values for temperature using the Master Curve procedure (American Society for Testing and Materials, 2013). Here, the toughness distribution for the deeply-cracked SE(B) specimen at $T = -20^{\circ}\mathrm{C}$ is corrected to the corresponding toughness distribution at $T = -10^{\circ}\mathrm{C}$ thereby enabling direct application of the calibration methodology outlined above in which the characteristic toughness for the shallow crack SE(B) specimen, $J_0^{SEB-a/W=0.15}$, is corrected to its equivalent characteristic toughness for the deeply-cracked SE(B) specimen, $J_0^{SEB-a/W=0.5}$. The characteristic toughness value for the latter configuration at $T = -10^{\circ}\mathrm{C}$ then yields $J_0^{SEB-a/W=0.5} = 115\ \mathrm{kJ/m^2}$. The calibrated Weibull modulus then yields a value of $m_0 = 11$ which is well within the range of previously reported m-values for common pressure vessel and structural steels (see, *e.g.*, Beremin (1983); Ruggieri and Dodds (1996)). Figure 4(a) display the $\tilde{\sigma}_w$ vs. J trajectories based on the standard Beremin model with $m_0 = 11$ for both specimen geometries at the test temperature, $T = -10^{\circ}\mathrm{C}$. In these plots, $\tilde{\sigma}_w$ is normalized by the material yield stress, σ_{ys} - refer to Table 1.

Calibration of the function Ψ_c in previous Eqs. (4) follows from determining parameter σ_{prs} that gives the best correction of measured toughness values at $T = -10^{\circ}\mathrm{C}$ for the shallow and deep crack SE(B) specimens with a fixed value $m_0 = 11$. To illustrate the calibration process, Fig. 4(b) provides the constraint correlations ($J_{SEB}^{a/W=0.15} \rightarrow J_{SEB}^{a/W=0.5}$) for varying values of parameters σ_{prs}. Each curve provides pairs of J-values in the shallow and deep crack SE(B) specimens which produce the same Weibull stress, $\tilde{\sigma}_w$, for a fixed σ_{prs}-value, when Ψ_c describes the simplified particle distribution model while holding fixed $\alpha_p = 4$ and $E_d = 400$ GPa. Here, correcting the characteristic toughness for the shallow crack SE(B) specimen, $J_0^{SEB-a/W=0.15}$, to its equivalent characteristic toughness for the deeply-cracked

SE(B) specimen, $J_0^{SEB-a/W=0.5}$, then yields $\sigma_{prs} = 6500\,\mathrm{MPa}$.



(a)



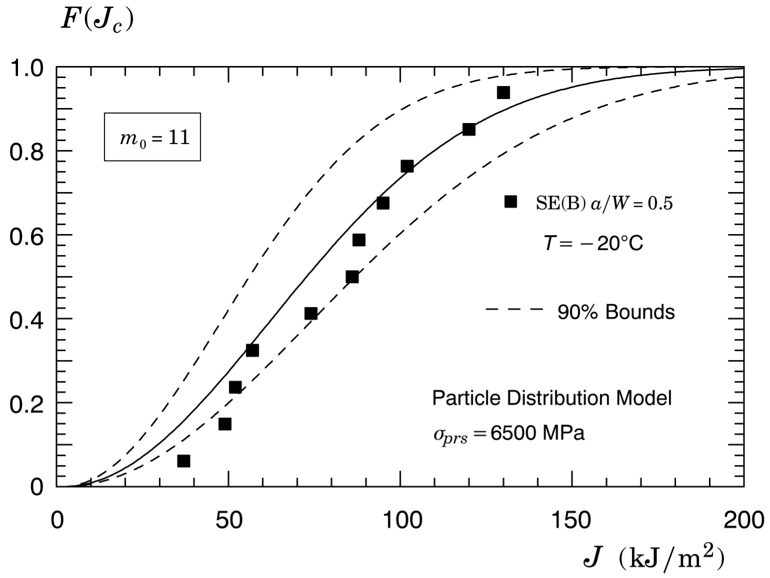
(b)

Figure 4. (a) $\tilde{\sigma}_w$ vs. J trajectories for the SE(B) specimens at $T = -10°\mathrm{C}$ based on the standard Beremin model with $m_0 = 11$. (b) Constraint correlations of J-values at $T = -10°\mathrm{C}$ for $m_0 = 11$ using the simplified particle distribution (WL) model with varying σ_{prs}-values.

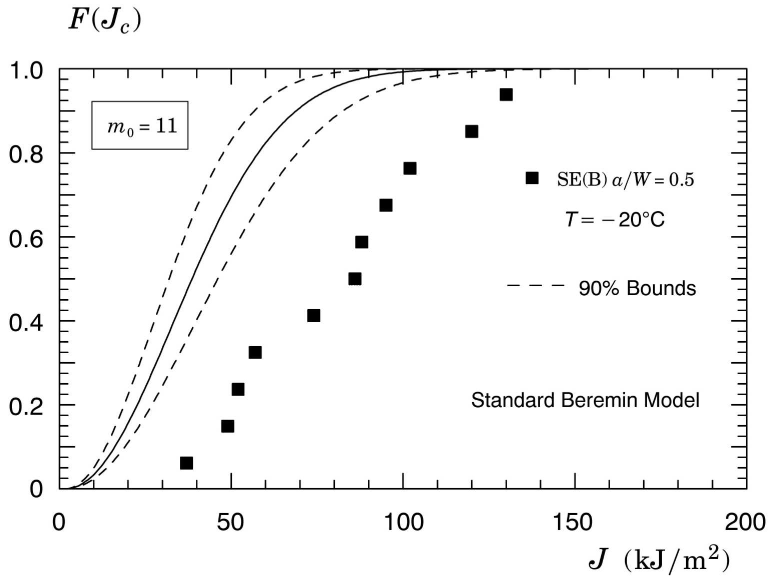
5.2 Prediction of Specimen Geometry Effects on Fracture Toughness

To verify the predictive capability of the modified Weibull stress methodology adopted in the present work, this section describes applications of the $\tilde{\sigma}_w$-based approach to predict effects of geometry and constraint loss on cleavage fracture toughness values (J_c) for an A515Gr 65 pressure vessel steel. Here, we predict the measured distribution of cleavage fracture values for the deeply-cracked SE(B) specimen $(a/W = 0.5)$ with $B = 30\,\mathrm{mm}$ using the measured fracture toughness distribution for the PCVN geometry, both tested at $T = -20°\mathrm{C}$ as already described previously. The correlative procedure to obtain the toughness correction $J_0^{PCVN} \rightarrow J_0^{SE(B)-a/W=0.5}$ follows similar protocol for the toughness scaling methodology already outlined.

Figure 5(a-b) shows the Weibull cumulative distribution function of J_c-values for the SE(B) specimen with $a/W = 0.5$ predicted from the experimental fracture toughness distribution for the PCVN configuration based on the previous modified Weibull stress model using the simplified particle distribution with $\sigma_{prs} = 6500$ MPa and the standard Beremin model. The solid lines in these plots represents the prediction of the median fracture probability whereas the dashed lines define the 90% confidence limits obtained from using the 90% confidence bounds for J_0 determined elsewhere (Ruggieri *et al.*, 2015). The predicted Weibull distribution derived from the simplified particle distribution displayed in Fig. 5(a) agrees well with the experimental data; here, most of the measured J_c-values lie within the 90% confidence bounds. In contrast, the predicted Weibull cumulative distribution based on the standard Beremin model, including the 90% confidence bounds, is entirely shifted to the left of the experimental data thereby providing very conservative estimates of fracture toughness for the deeply-cracked SE(B) specimen.



(a)



(b)

Figure 5. Predicted cumulative Weibull distribution of experimentally measured J_c-values for the SE(B) specimen with $a/W = 0.5$: (a) Simplified particle distribution model with $\sigma_{prs} = 6500$ MPa and $m_0 = 11$; (b) Standard Beremin model with $m_0 = 11$.

6. SUMMARY

This work describes verification studies of a probabilistic framework based on the modified Weibull stress model developed by Ruggieri and Dodds (2015) to predict the effects of constraint loss on macroscopic measures of cleavage fracture toughness applicable to fracture specimens and crack configurations tested in the ductile-to-brittle transition region. The central feature of this methodology lies on the interpretation of the modified Weibull stress, $\tilde{\sigma}_w$, as the probabilistic crack tip driving force coupled with the condition that cleavage fracture occurs when the Weibull stress reaches a critical value, $\tilde{\sigma}_{w,c}$. An important feature of the proposed methodology is the inclusion of the strong effects of near-tip plastic strain on cleavage microcracking which impacts directly the magnitude of $\tilde{\sigma}_{w,c}$ and, consequently, the toughness scaling correction.

A central objective of the present work is to introduce a more advanced and yet simpler methodology for cleavage fracture assessments to describe the fracture process based on local failure criteria coupled with macroscopic (global) fracture parameters, such as the J-integral, thereby removing the specimen geometry and constraint effect dependency of cleavage fracture toughness. Application of the modified Weibull stress methodology predicts accurately well the distribution of fracture toughness, J_c, for an A515 Gr 65 pressure vessel steel tested in the ductile-to-brittle transition region. Overall, the analyses conducted in the present work show that the modified Weibull stress approach based on the simplified particle distribution model holds significant promise as an engineering procedure to multiscale predictions of fracture behavior in structural components with diverse range of crack-tip constraint.

7. ACKNOWLEDGEMENTS

This investigation is supported by Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) through Grant 2012/13053-2 and by the Brazilian Council for Scientific and Technological Development (CNPq) through Grants 473975/2012-2 and 306193/2013-2.

8. REFERENCES

American Society for Testing and Materials, 2011. "Standard test method for measurement of fracture toughness, ASTM E1820-2011".

American Society for Testing and Materials, 2013. "Standard test method for determination of reference temperature, T_0, for ferritic steels in the transition range, ASTM E1921-13a".

Beremin, F.M., 1983. "A local criterion for cleavage fracture of a nuclear pressure vessel steel". *Metallurgical and Materials Transactions A*, Vol. 14, pp. 2277–2287.

Healy, B., Gullerud, A., Koppenhoefer, K., Roy, A., RoyChowdhury, S., Petti, J., Walters, M., Bichon, B., Cochran, K., Carlyle, A., Sobotka, J., Messner, M. and Dodds, R.H., 2014. "WARP3D: 3-D nonlinear finite element analysis of solids for fracture and fatigue processes". Technical report, University of Illinois at Urbana-Champaign, http://code.google.com/p/warp3d.

Mann, N.R., Schafer, R.E. and Singpurwalla, N.D., 1974. *Methods for Statistical Analysis of Reliability and Life Data*. Jonh Wiley & Sons, New York.

Ruggieri, C., 2013. "WSTRESS Release 3.0: Numerical evaluation of probabilistic fracture parameters for 3-D cracked solids and calibration of weibull stress parameters". Technical report, University of São Paulo.

Ruggieri, C. and Dodds, R.H., 1996. "A transferability model for brittle fracture including constraint and ductile tearing effects: A probabilistic approach". *International Journal of Fracture*, Vol. 79, pp. 309–340.

Ruggieri, C. and Dodds, R.H., 2015. "An engineering methodology for constraint corrections of elastic-plastic fracture toughness - Part I: A review on probabilistic models and exploration of plastic strain effects". *Engineering Fracture Mechanics*, Vol. 134, pp. 368–390.

Ruggieri, C. Savioli, R.G., and Dodds, R.H., 2015. "An engineering methodology for constraint corrections of elastic-plastic fracture toughness - Part II:: Effects of specimen geometry and plastic strain on cleavage fracture predictions". *Engineering Fracture Mechanics*. (Submitted for Publication).

Wallin, K. and Laukkanen, A., 2008. "New developments of the Wallin, Saario, Törrönen cleavage fracture model". *Engineering Fracture Mechanics*, Vol. 75, pp. 3367–3377.

9. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.