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A new local approach to cleavage fracture and its application in a reactor pressure vessel

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Abstract

The paper presents and applies a local approach to correlate the fracture behavior of a notched and fracture mechanics specimen. The random nature of cleavage fracture process determines that both the microscopic fracture stress and the macroscopic properties including fracture load, fracture toughness and the ductile to brittle transition temperature are all stochastic parameters. This understanding leads to the proposal of statistical assessment of cleavage induced notch toughness of ferritic steels according to a new local approach to cleavage fracture. The temperature independence of the two Weibull parameters in the new model induces a master curve to correlate the fracture load at different temperatures. This proposed index is applied to compare the notch toughness of a ferritic steel with two different microstructures.

Keywords: Ferritic steels, cleavage fracture, notch brittleness, statistical model;

1. Introduction

Reactor pressure vessels (RPVs) in nuclear power plants are subject to biaxial loading during pressurized thermal shocks initiated by the loss-of-coolant accidents (Qian and Niffenegger 2013; Qian et al. 2014). The thermal, pressure and residual stresses in the RPV wall combine to form a biaxial stress state at the crack tip. For the sake of nuclear

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safety, it is important to determine accurate fracture toughness for RPV materials or other similar structures. Thus, the question arises whether results obtained from specimens tested in the laboratory can be transferred to actual RPV in nuclear power plants. In order to transfer K_{Ic} between different specimens, local approach to fracture is presented.

Ferritic steels are commonly used to fabricate RPVs in the commercial light water reactors. Ferritic steels have body centered cubic crystal structures that possess the ductile-to-brittle transition temperature (DBTT) characteristic (Chao et al. 1994; Zhang and Qian 2017). As reviewed in (Lei 2016), the conventional transition temperature method, fracture mechanics, and fracture physics approaches are deterministic method for cleavage fracture study; the Master Curve (MC) method (Wallin 2002) and most of the Local Approach (LA) (Pineau 2006) are statistical model used in cleavage fracture. The Beremin model (Pineau 2006) was the pioneering work in LA for cleavage fracture. The Beremin model is essentially a two-parameter Weibull distribution as below:

$$P = 1 - exp[-(\sigma_W/\sigma_0)^m] \quad (1)$$

with $$\sigma_W = \left(\int_{V_p} \sigma_1^m \cdot dV/V_0\right)^{1/m} \quad (2)$$

where P is the cumulative probability of failure, V_p denotes the volume of the plastic deformation zone as the cleavage fracture process zone, m and σ_0 are the two model parameters known as Weibull modulus and the scale parameter, respectively, σ_1 is the maximum tensile principal stress, V_0 is an elementary volume representing the mean volume occupied by each micro-crack in a solid, dV is the differential volume, σ_W denotes the Weibull stress.

The Beremin model has suffered from the ambiguity in model parameter calibration, i.e., the variation of the model parameters with temperature and geometrical constraint (Bakker and Koers 1991; Hausid et al. 2005; Moattari et al. 2016; Petti and Dodds 2005; Ruggieri et al. 2015). Recent studies (Lei 2016; 2016; 2016; Qian et al. 2018; 2018) have identified the fundamental defects of the Beremin model.

Accordingly, by adopting a three-parameter Weibull distribution density function of microscopic cleavage fracture stress S in place of the power law distribution of microcrack size (a), one has

$$g(S) = m \cdot [(S - \sigma_{th})^{m-1}/\sigma_0^m] \cdot \exp[-(S - \sigma_{th})^m/\sigma_0^m] \quad (3)$$

a new local approach to cleavage fracture is proposed (Lei 2016; Qian et al. 2018):

$$p(\sigma, V_0) = \int_{\sigma_{th}=\sigma_{1,0}}^{\infty} g(S)dS = 1 - \exp\left(\frac{\sigma_1 - \sigma_{1,0}}{\sigma_0}\right)^m \quad (4)$$

$$P = 1 - \exp\left\{\int_{V_p} \ln[1 - p(\sigma, V_0)]\, \mathrm{dV}/V_0\right\} = 1 - exp[-(\sigma_W/\sigma_0)^m] \quad (5)$$

$$\sigma_W = \left[\int_{V_p} (\sigma_1 - \sigma_{1,0})^m \cdot dV/V_0\right]^{1/m} \quad (6)$$

2. Experimental data and method of calibration

2.1. Experimental data

The experimental data of a rolled C-Mn pressure vessel steel 16MnR reported by Wang et al. in (Wang et al. 2004) are used. Cleavage initiation in notched specimens with carbides and inclusions was investigated at 77K and 143K. The same steel went through different heat treatments to obtain the same ferrite grains but with fine carbide (FC) and coarse carbide (CC) particles, respectively. The mechanical tests, scanning electron microscopy (SEM) analysis and measurements, and finite element analysis (FEA) were employed to compare the notch toughness of the specimens with FC and CC particles.

The static four point bending (4PB) tests were conducted at 77K and 143K on 45°-angle V-notched prismatic beams in Fig.1a. Fig. 1b and 1c show the finite element modeling of the specimen, which will be used in the calibration part later. The general yield load P_{gy} of the 4PB specimens was calculated by $P_{gy} = 0.7045\sigma_{ys}B(W - a)^2/L$, where B is specimen thickness, W the height, a = 4.25 mm the notch depth, and L the bending span, with L = B = W = 12.7 mm. Fig.2 summarizes the measured fracture loads P_f.

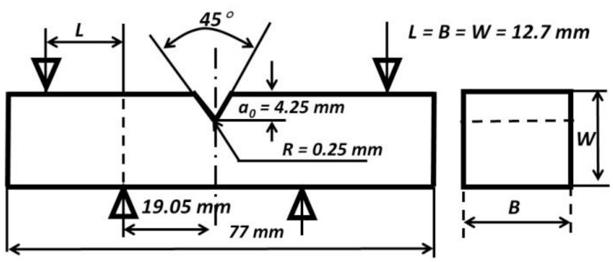


Fig. 1a.Four-point bending specimen: geometry (Wang et al. 2004).

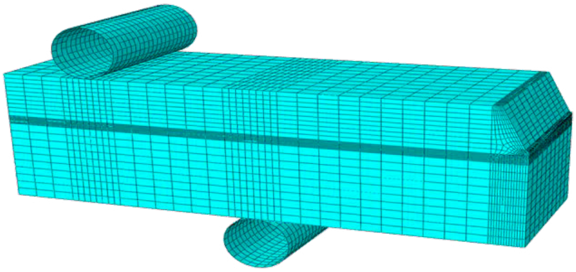


Fig. 1b.Four-point bending specimen: finite element model.

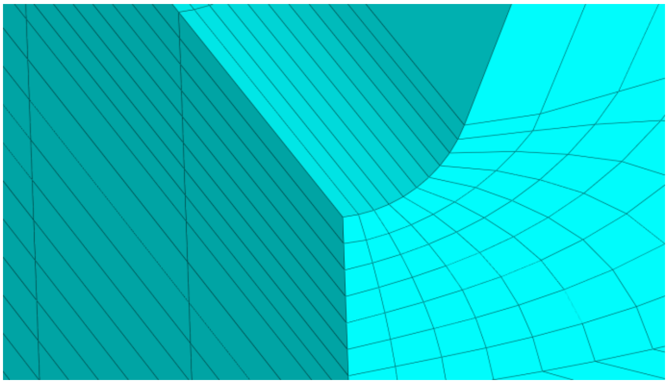


Fig. 1c. Four-point bending specimen: layout of finite elements at notch tip.

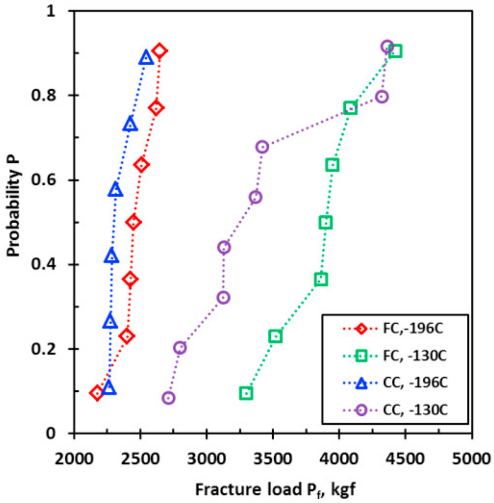


Fig.2.Experimental results of fracture loads P_f (Wang et al. 2004).

2.2. Model calibration procedure

In the present study, finite element analysis (FEA) is conducted using ABAQUS software version 6.14 for stress distribution in the 4PB specimen. 20-node brick elements are used. Only a quarter of the specimen was modeled due to symmetry with a total of 15940 elements as shown in Fig.1b and Fig.1c. Equation (5) is rewritten as

$$LnLn[1/(1-P)] = mLn(\sigma_W) - mLn(\sigma_0) \tag{7}$$

The calibration method for Eq. (7) was developed in (Qian et al. 2017). Fig.3 shows the flow chart of calibration.

3. Results

3.1. Calibration of the new local approach

Using the experimental data in Fig. 2 as input, Eq.(7) was calibrated at 77K for FC and CC specimens, respectively. Fig.4 shows the calibration results at 77K. For FC specimens, $m = 25.6, \sigma_0 = 228.3MPa$; For CC specimens, $m = 11, \sigma_0 = 161.1MPa$. With the calibrated parameters, Weibull stress at different loadings is calculated for the temperature of 77K and 143K, as shown in Fig. 5a and 5b. The model parameters demonstrate the temperature independent characteristics.

3.2. Transferring fracture toughness with the local approach

The presented new local approach is applied to transfer K_{Ic} between different specimens and components. In order to transfer the fracture toughness from standard specimens to real components (e.g. RPV), the actual constraint of a specific geometry is analyzed. The RPV containing a crack, cruciform specimen, compact tension specimen, and three point bending specimen are modeled to quantify the constraint effects, as shown in Fig. 6. More material property and finite element analysis is referred in (Qian, Cao, et al. 2018). Weibull stress and fracture probability according to Equation (5) are calculated to compare the constraint difference in the crack tip.

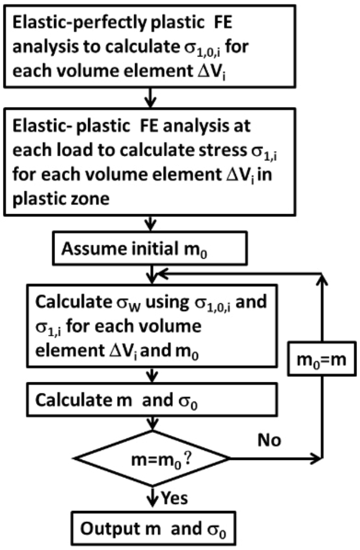


Fig.3.Flow chart for the calibration of Eq.(7).

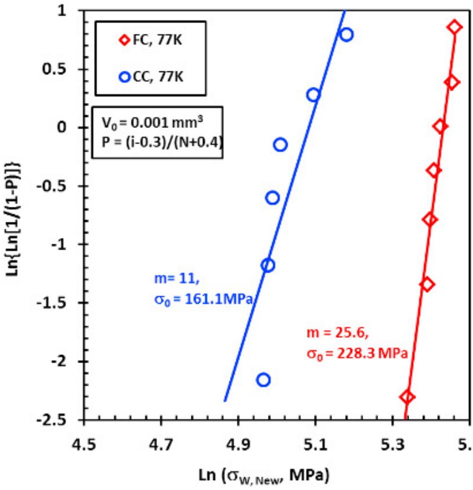


Fig.4.Summary of calibration results of Eq.(7) at 77K

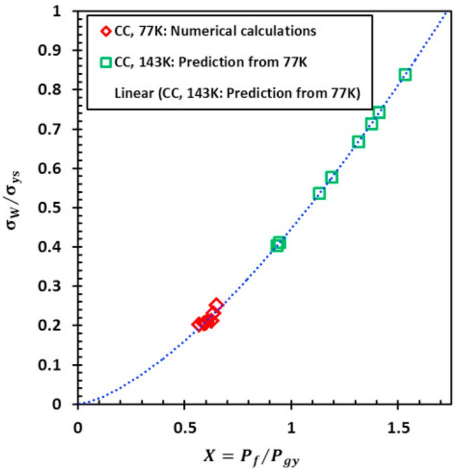


Fig.5a.Weibull stress at 77K and 143K for the CC material.

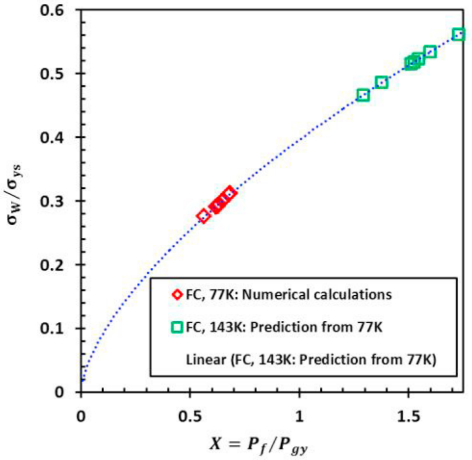
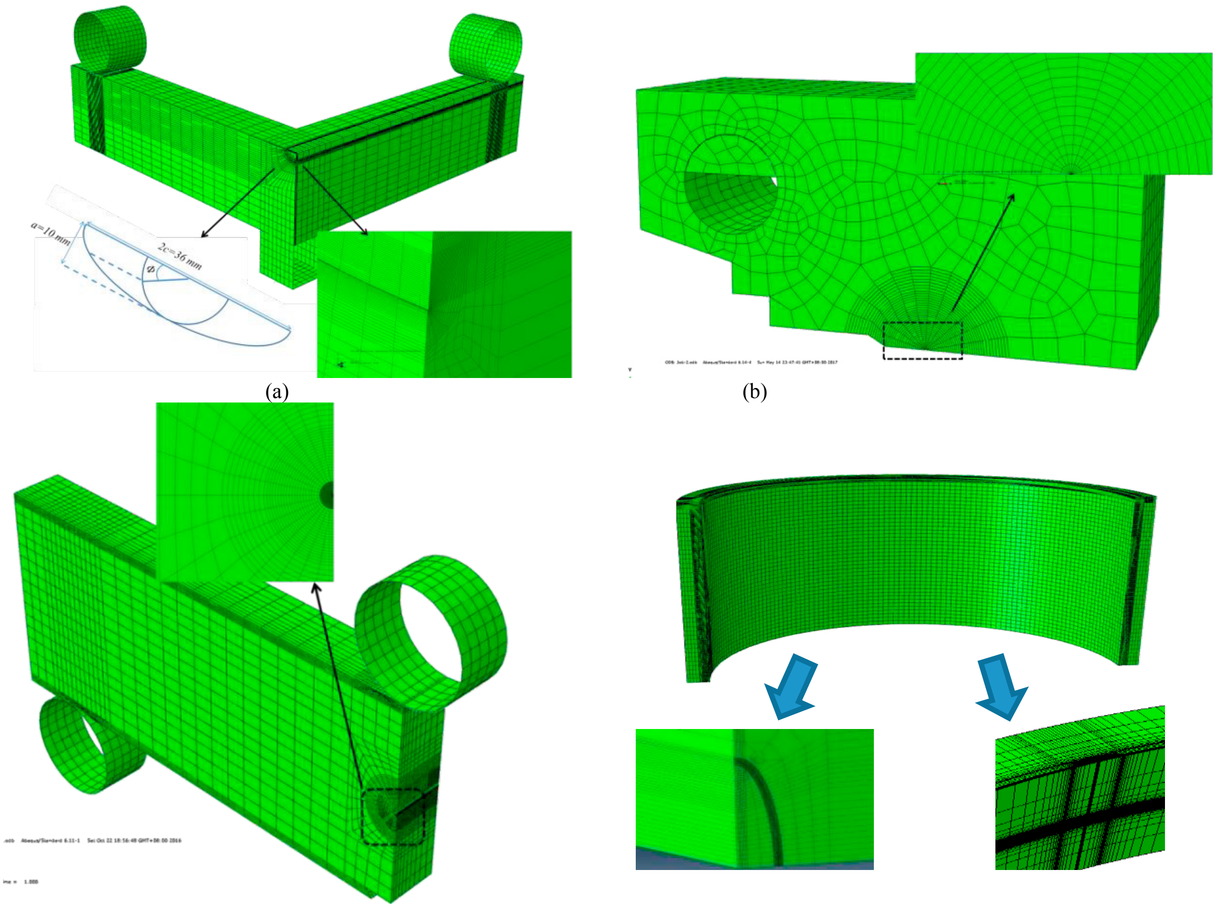


Fig.5b.Weibull stress at 77K and 143K for the FC material.

The new local approach is applied to estimate the probabilities of cleavage initiation for different specimens and components. In order to decide which specimen fails first during the loading, it is better to compare P_f for the same J-Integral. It is clear in Fig. 7 that the compact tension specimen fails first, followed by single edge bending specimen cruciform specimen and the RPV model. The results in Fig. 7 may be used to scale fracture toughness data to account for both in-plane and out-of-plane constraint effect by indexing a given P_f for a specific constraint to obtain J. At a fracture probability of 10%, the fracture toughness difference between compact tension specimen and the RPV model is about 65 MPa·m$^{0.5}$, i.e, 260% of the material toughness. The difference between single edge bending and compact tension specimen is 26 MPa·m$^{0.5}$ (102% of the material toughness). This big difference demonstrates the importance of considering the constraint effects in the integrity analysis.



(a) (b)

(c) (d)

Fig. 6. Finite element modeling for (a) cruciform specimen, (b) compact tension specimen, (c) single edge bending specimen and (d) RPV model.

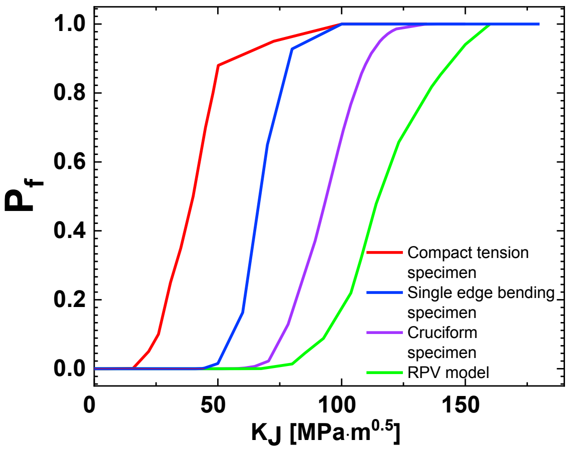


Fig. 7 Comparison of fracture probability vs. K_J for compact tension specimen, single edge bending specimen, cruciform specimen and the RPV model.

4. Conclusions

In this paper, a new statistical model of cleavage fracture is presented and applied to assess notch toughness of ferritic steels against cleavage fracture. The following conclusions can be drawn:

1. A new local approach to fracture is presented and the calibration method is discussed.
2. The proposed calibration method for a new local approach to cleavage fracture is proved feasible using experimental data.
3. The new local approach can be applied to transfer the fracture toughness among different specimens at the same failure probability. At a fracture probability of 10%, the fracture toughness difference between the compact tension specimen and the reactor pressure vessel is about 260% of the material original toughness.

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