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A NEW CALIBRATION APPROACH TO BEREMIN'S PARAMETERS

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ABSTRACT

The Beremin model for cleavage fracture is the most widely applied micromechanical model for predicting the brittle fracture of pressure vessel steels in the transition region. The Beremin model requires the calibration of a pair of parameter (m, σ_u). In this paper, a new calibration approach for the Beremin model parameters was proposed through the intersections of two $m\sim\sigma_u$ curves corresponding to specimens with different constraint levels. In addition, an example calibration in terms of the proposed procedure was carried out for a C-Mn pressure vessel steel (the 16MnR steel).

KEY WORDS: cleavage fracture, Beremin model, Weibull stress, calibration

INTRODUCTION

It is widely known that ferritic steels exhibit a strong transition in the fracture mode from ductile tearing to cleavage fracture when the temperature is lowered. When the operating temperatures for structures constructed of ferritic steels coincide with the ductile-to-brittle temperature (DBTT) region, cleavage fracture may occur resulting in a catastrophic failure. For example, neutron irradiation can induce a shift of DBTT of reactor pressure vessel (RPV) steels and thus a higher possibility for brittle fracture of RPV when subjected an overcooling event.

In the past 30 years, major progresses in the quantitative characterization of cleavage fracture in ferritic steels have led to two groups of methods, which can be distinguished by the type of loading parameter employed. One is based on the macroscopic concept, among which Master Curve method is the most important probabilistic model. The Master Curve method has been standardized as ASTM E1921(1997). The other is the local failure criterion based micromechanical model for cleavage fracture. The most widely applied model in this group is the Beremin model(Beremin et al., 1983). The Weibull stress (σ_w) as the loading parameter is expressed as the integration of the local stress fields over all material volumes in the cleavage fracture process zone ahead of a macroscopic flaw. The values of the Weibull stress are generally calculated from 3D finite element analysis. Therefore, the Beremin model can address the constraint effect on cleavage fracture toughness in a natural manner.

Because the applicability of Beremin model to predict cleavage fracture in structures relies heavily on the model's parameters, the calibration of the parameters m and σ_u is a significant subject. The aim of this paper is to carry out an investigation on the calibration method of Beremin's parameters and propose a new calibration scheme for tuning the parameters (m, σ_u). This paper is structured as follows: Section 2 briefly reviews Master Curve method, Beremin model for cleavage fracture and the Weibull stress based toughness scaling model. Section 3 outlines the existing procedures to calibrate the Beremin model parameters. Section 4 proposes a new approach for the calibration of the Beremin model parameters. Section 5 gives a specific example illustrating the application of the proposed approach for a C-Mn pressure steel (the 16MnR steel).

STATISTICAL MODELS FOR CLEAVAGE FRACTURE

Master Curve Method

Based on the weakest link theory, the distribution of cleavage fracture toughness data measured from 1T size fracture toughness specimens with high constraint at any temperature in the DBT region can be characterized by the following three-parameter Weibull distribution,

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

where $K_{\min}$ is the threshold fracture toughness. In ASTM E1921, $K_{\min}$ is fixed to be $20\,\mathrm{MPa}\sqrt{\mathrm{m}}$ for common ferritic steels. The Weibull scale parameter K_0 (or called the characteristic fracture toughness) is equal to the fracture toughness value at 63.2% failure probability.

The median toughness vs. temperature curve is called the Master Curve, which is uniquely determined by the reference temperature, T_0. The Master Curve is calculated using the formula,

$$K_{Jc(med)} = 30 + 70\exp[0.019(T - T_0)] \tag{2}$$

where T_0 is the reference temperature at which the median fracture toughness for 1T specimens is 100 $\mathrm{MPa}\sqrt{\mathrm{m}}$.

Beremin Model for Cleavage Fracture

Beremin model(Beremin et al., 1983) adopts a two-parameter Weibull distribution to quantify the relationship between the Weibull stress, σ_w, and the cumulative failure probability, P_f:

$$P_f(\sigma_w) = 1 - \exp[-(\frac{\sigma_w}{\sigma_u})^m] \tag{3}$$

where the Weibull slope m and the scale parameter of the Weibull distribution $\sigma_u = \sqrt[m]{\frac{m}{2\alpha}}\sqrt{\frac{2E\gamma_s}{\pi}}$ are the Beremin model's parameters. m quantifies the degree of scatter of experimental failure data. σ_u corresponds to the σ_w value at P_f=63.2%, which is closely related to the microscale material toughness.

The Weibull stress σ_w, which is thought of as a driving force for cleavage fracture, is defined as

$$\sigma_w = \sqrt[m]{\int_{V_{pl}} (\sigma_1)^m \frac{dV}{V_0}} \tag{4}$$

where v_0 is a reference temperature that is often taken equal to $(50\mu\mathrm{m})^3$; σ_1 is the maximum principal stress. V_{pl} represents the fracture process zone and is defined as the region where the maximum principal stress exceeds the yield stress:

$$\sigma_1 \geq \lambda\sigma_{ys} \tag{5}$$

where λ is a constant factor.

Following the theory of Beremin model, Ruggieri and Dodds proposed a Weibull stress-based toughness scaling model (TSM)(Ruggieri and Dodds, 1996) to scale the measured fracture toughness between different specimen geometries. In the TSM model, the equivalence of J-integral values (or K_J values) between different constraints is constructed at the attainment of identical σ_w values even though the macroscopic toughness values may differ obviously.

CALIBRATION OF THE BEREMIN'S PARAMETER

The Conventional Calibration Procedures For The Beremin's Parameters

The difficulty in the calibration of Beremin's parameters lies in the fact that σ_w and σ_u are both a function of m. Some approaches are developed to calibrate the Weibull stress parameters (m, σ_u). The Beremin model parameters were initially calibrated against testing results from notched round bars. In 1992, Minami(Minami et al., 1992) proposed a calibration scheme that uses a maximum likelihood analysis of fracture toughness values measured from high constraint specimens which fail at small-scale yielding (SSY) condition.

However, Gao, Ruggieri and Dodds (GRD) (Gao et al., 1998) analytically and numerically demonstrated that the Minami's procedure will lead to non-uniqueness of (m, σ_u) using the crack-tip stress field under plane strain, SSY condition with $T_{stress}=0$. To overcome this problem, GRD first describes a new calibration method that applies the TSM model to two sets of fracture toughness values exhibiting different constraint levels at fracture. With an assumed m value, the TSM model corrects each K_{Jc} value (or J_c) from two types of specimens to SSY condition which is simulated by modified boundary layer (MBL) model. The calibration process finds m such that the two sets of constraint corrected J_c values have the same Weibull distribution properties (i.e., K_0 or J_0 corresponding to 63.2% failure probability) under SSY condition. Once m is obtained, σ_u can be readily calculated since it is equal to the σ_w value at 63.2% failure probability.

Ruggieri, Gao and Dodds (RGD) (Ruggieri et al., 2000) simplified the GRD method by eliminating the MBL model. Instead, the Weibull distribution of the fracture toughness data measured from low-constraint specimens are scaled to its equivalent value under the constraint condition in high constraint specimen.

Our experience with the RGD calibration method shows that the calculation process remains a bit tedious. Consequently, a new approach to calibrate the Beremin model parameters is presented below.

A New Approach To Calibration

The GRD method and RGD method require a lot of calculations to build the σ_w vs. K_J or $K_{J,A}$~$K_{J,B}$ relationships respectively for a series of assumed m values to construct the toughness scaling diagrams between two different crack geometries. As described by RGD (Ruggieri et al., 2000), the calibration process based on the TSM model essentially seeks a specified m value with which the characteristic fracture toughness K_0 (i.e., the scale parameter) of low-constraint specimens can be corrected to the K_0 value determined with high-constraint specimens.

Therefore, we propose a new calibration procedure based on the intersection of m~σ_u curves for specimens of different constraints, which eliminate the calculation of the σ_w and the toughness scaling based on the same σ_w value in the case of $K_J \neq K_0$. The proposed calibration procedure is described in the following steps.

(1) Test at least two sets of fracture toughness specimens having different constraint conditions in the DBTT region. Here, two sets of specimens are taken as an example. One set corresponds to high constraint condition (specimen A) and the other corresponds to low constraint condition (specimen B).

(2) Generate finite element models for specimen A and B.

(3) Determine the characteristic toughness values $K_{0(A)}$ and $K_{0(B)}$ respectively for specimens A and B.

(4) Assume a series of m values to compute the σ_w values at $K=K_{0(A)}$ and $K=K_{0(B)}$ in the corresponding specimen. Since the value of σ_u is the value of σ_w at $K=K_0$, two m~σ_u curves are obtained as illustrated in Figure 1.

(5) The intersection of the two m~σ_u curves indicates the calibrated (m, σ_u).

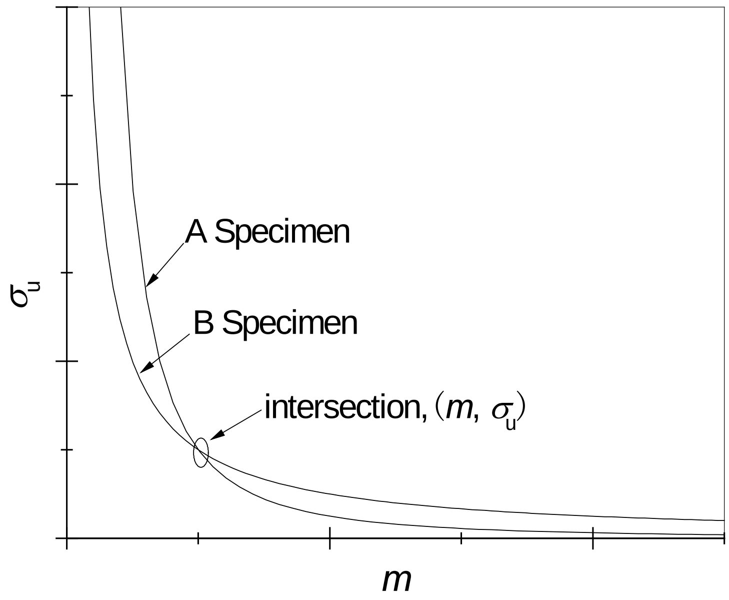

Figure 1. Schematic drawing for the calibration method based on the $m \sim \sigma_u$ curves intersection

The proposed calibration procedure is easier to apply than the GRD and RGD calibration procedure without affecting calibration precision. As the parameter m is determined, the value of σ_u is known simultaneously.

APPLICATION OF THE NEW CALIBRATION APPROACH

Fracture toughness tests on a C-Mn steel (the 16MnR), which is widely used for manufacturing pressure vessels in China, was conducted at different temperatures in the DBTT region using SE(B) specimens of three different sizes.

The proposed calibration procedure is illustrated to calibrate Beremin model parameters for the 16MnR steel at -100°C, and is discussed further below.

Fracture Toughness Tests

1T-SE(B), 0.5T-SE(B) and pre-cracked CVN (PCVN) specimens were machined in the L-T orientation. For 1T-SE(B) and 0.5T-SE(B) specimens, the width to thickness ratio of W/B was equal to 2. The PCVN specimen has a square cross-section with B=W=10mm. All the specimens had a span to width ratio of S/W=4 and a nominal crack depth ratio a_0/W=0.5-0.55.

ASTM E1921-09(2009) was employed to evaluate fracture toughness in the transition temperature region. The critical J-integral value, J_c, was determined from the load-CMOD (crack mouth opening displacement) record for each specimen. According to E1921, the elastic-plastic equivalent stress intensity factor, K_{Jc} at cleavage initiation can be converted from the calculated J_c values as follows,

$$K_{Jc} = \sqrt{\frac{J_c E}{1-\nu^2}} \tag{6}$$

where E is the elastic modulus and υ is the poisson's ratio.

The fracture toughness values determined and the associated reference temperature values, T_0, are listed in Table 1.

Table 1: Results of fracture toughness tests

Test temperature (^{o}C)	Specimen type	K_{Jc} ($\mathrm{MPa}\sqrt{\mathrm{m}}$)	Valid /Total r/N	$K_{Jc(limit)}$ ($\mathrm{MPa}\sqrt{\mathrm{m}}$)	T_0(^{o}C)
-86	1T-SE(B)	51.2, 46.9, 45.2, 90.8, 36.4, 59.8,66.7,69.2,55.3,119.4,54.8	20/20	278.2	-62
-100	0.5T-SE(B)	109.1, 103.6, 103.3, 128.4, 111.7, 54.5, 202.7, 55.6, 185.6, 121.1	9/10	199.8	-111
-100	PCVN	100.9, 211.0, 206.5, 150.7, 254.4, 236.4, 288.1, 284.4, 156.8, 85.9, 192.4, 102.7, 187.9, 193.2, 222.0, 215.8	3/16	125.4	-120 Invalid

Calibration for 16MnR Steel

To calibrate the Beremin model parameters, the fracture toughness specimens of different types were simulated using 3D FE analyses in Abaqus/Standard. Figure 2 illustrates the mesh for the simulation of PCVN specimen as an example.

The load was applied by means of loading device displacement. The J-integral and the corresponding equivalent intensity stress factor K_J were determined using the force from the loading device and the CMOD in a similar method as in the experiments. Only data extracted from the fracture process zone ($\sigma_1 \geq \sigma_{ys}$) were used in the calculation of the Weibull stress. The reference volume V_0 in Equation 3 was taken as $(50\mu m)^3$ in this study.

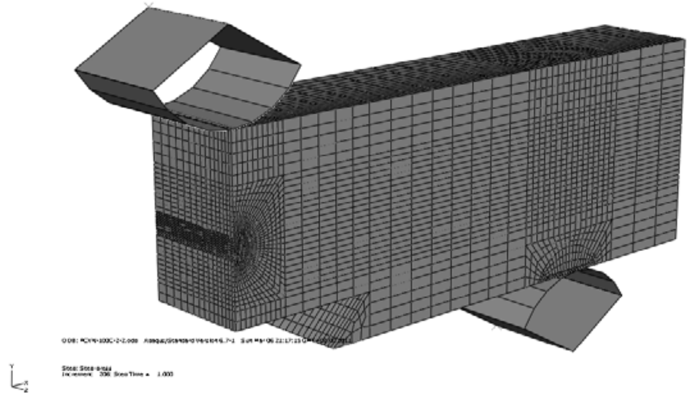

Figure 2. 3D finite element mesh for PCVN specimen

Three different combinations of specimens presented above were used to calibrate Beremin model parameters. Each combination referenced different pairs of high and low constraint specimens. Although the 1T-C(T) specimens were not tested at the same temperature as PCVN and 0.5T-SE(B) specimens, $K_{0(1T)}$ is predicted to be 68.9 $\mathrm{MPa}\sqrt{\mathrm{m}}$ at -100^{o}C through Master Curve approach.

First, RGD calibration procedure was applied. Figures 3-5 illustrate the graphical procedure to determine the Weibull slope m. The calibrated m values together with the corresponding σ_u are listed in Table 2. The values of m from three combinations of specimen types are almost the same, yet the difference in σ_u values varies by as much as 1747MPa. Therefore, the transferability of the m and σ_u

across different constraints should be discussed.

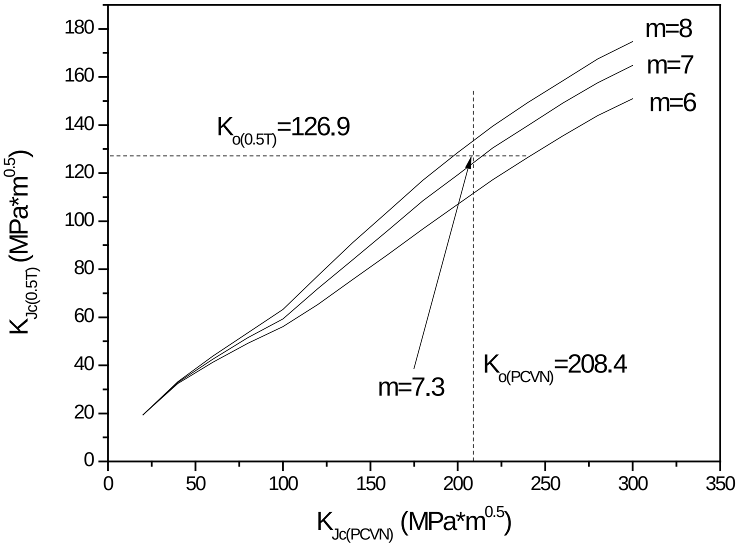

Figure 3. Calibration of the Beremin model parameters using PCVN and 0.5T-SE(B) specimens (RGD method)

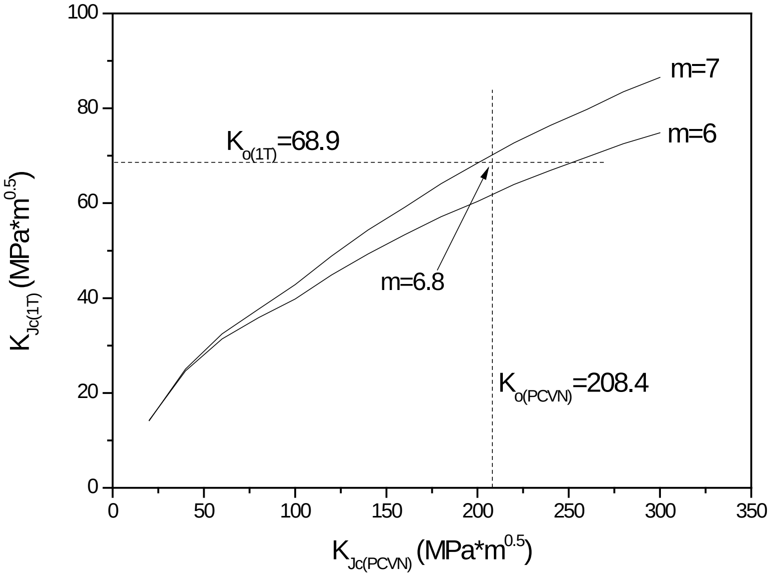

Figure 4. Calibration of Beremin model parameters for 16MnR steel using PCVN and 1T-SE(B) specimens (RGD method)

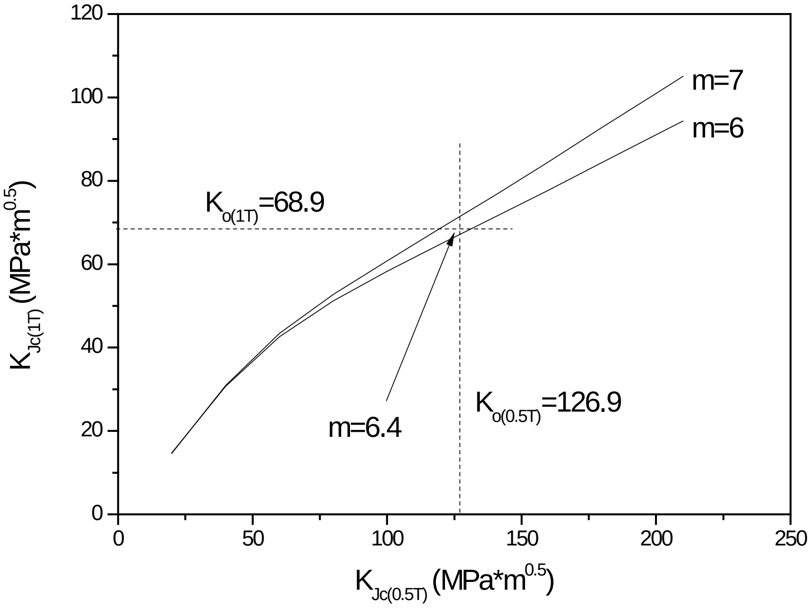

Figure 5. Calibration of Beremin model parameters for 16MnR steel using 0.5T-SE(B) and 1T-SE(B) specimens (RGD method)

Table 2: Three pairs of Beremin model parameters from different combinations of specimen types

Specimen Type	*m*	σ_u (MPa)
0.5T-SE(B) vs. PCVN	7.3	6194
1T-SE(B) vs. PCVN	6.8	6975
1T-SE(B) vs. 0.5T-SE(B)	6.4	7941

The proposed calibration approach described in the previous section is applied to determine the Beremin model parameters for the 16MnR steel in a graphical manner. At K_J=K_0 in the three specimen configurations, initial values of *m*=6,7…,10 were chosen to estimate roughly the intersection of the $m\sim\sigma_u$ curves. The three $m\sim\sigma_u$ curves were found to intersect each other with *m* between 6 and 8. A second calculation was therefore conducted using m=6.1, 6.2, 6.3…,7.9, 8.0. The calibration process using the $m\sim\sigma_u$ curves is illustrated in Figure 6, where the intersections of each curve with the other curves marked with ‘o’ indicate the calibrated (m, σ_u) pairs. As can be seen from Figure 6, the calibration results are exactly equal to the (m, σ_u) values obtained by RGD procedure.

The three pairs of (m, σ_u) values lie in the range $6.2<m<7.5$ where the $m\sim\sigma_u$ curves are almost overlapped. According to the argument of the proposed calibration procedure, it indicates that the three pairs of (m, σ_u) are the equivalent solutions for toughness scaling across different constraint configurations.

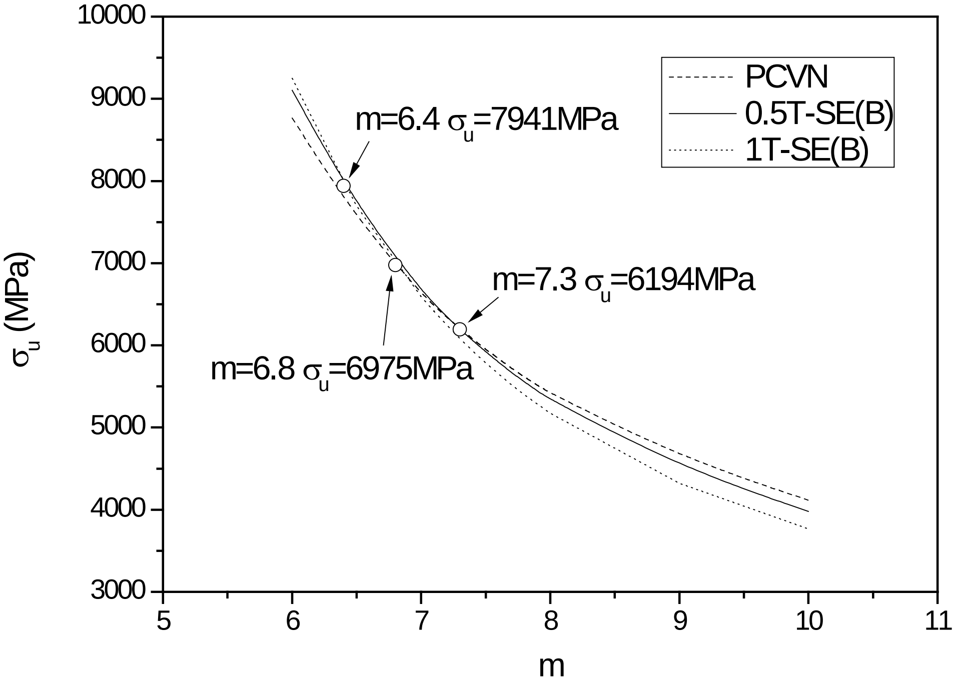

Figure 6. Calibration of Beremin model parameter based on $m \sim \sigma_u$ curves intersection using PCVN, 0.5T-SE(B) and 1T-SE(B) specimens

CONCLUSIONS

A new calibration method was proposed to find Beremin's parameters determined by the intersection of $m \sim \sigma_u$ curves for specimens with different constraint levels. Specific calibration for the 16MnR steel was carried out using the proposed calibration method and the RGD calibration method, respectively. Compared with the RGD calibration method, the new calibration method is characterized by simplicity in calculation, the same calibration accuracy, simultaneous determination of m and σ_u values using more than two different specimen geometries and graphical display of the calibration process which can be helpful to assess the transferability of the parameters m and σ_u across structures having different constraint conditions.

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