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BENCHMARK ANALYSIS BY BEREMIN MODEL AND GTN MODEL IN CAF SUBCOMMITTEE

Yasuto Nagoshi[1], Takuya Fukahori[2], Hiroshi Okada[3], Akiyuki Takahashi[3], Masaki Shimodaira[4], Takashi Ueda[5], Takuya Ogawa[6], Kenji Yashirodai[7], Yukio Takahashi[8], Mitsuru Ohata[9]

[1] Mitsubishi Heavy Industries, Kobe, Japan (yasuto.nagoshi.5e@nu.mhi.com)
[2] Mitsubishi Heavy Industries, Nagasaki, Japan
[3] Tokyo University of Science, Chiba, Japan
[4] Japan Atomic Energy Agency, Ibaraki, Japan
[5] IHI Corporation, Yokohama, Japan
[6] Toshiba Energy Systems & Solutions Corporation, Yokohama, Japan
[7] Hitachi, LTD., Ibaraki, Japan
[8] Central Research Institute of Electric Power Industry, Yokosuka, Japan
[9] Osaka University, Suita, Japan

ABSTRACT

The CAF (Constraint-Based Assessment of Fracture in Ductile-Brittle Transition Temperature Region) subcommittee of the Japan Welding Engineering Society developed a draft guideline for fracture evaluation with plastic constraint effect. As evaluation procedures, the Beremin model and the GTN model were selected and their applicability was validated by the experimental fracture tests and numerical simulation by the CAF committee members (Hojo et al. (2023)). For verification of the codes the members used, several benchmark analyses were proposed in the CAF committee. The benchmark analyses were performed focusing on the fracture tests of two kinds of low alloy steel A (Hirota et al. (2021)) and low alloy steel B. In this paper, the results of the benchmark analyses for low alloy steel B were summarized. In the case of using a common shape parameter of the Beremin model, m values (m=10, 20, and 30), it was confirmed that the Weibull stresses, σ_ws of each specimen were nearly the same among participants. m values were determined from two types of specimens (high and low constraint conditions) according to the Toughness Scaling Model proposed by Gao et al. (1998). Although there were some differences in the m values by the participants, it was confirmed that the difference of the Weibull stresses for the Beremin model by participants were not so large. The GTN parameters were optimized by a measured load - load line displacement relation and ductile crack growth of 1T-C(T) specimen at room temperature. It was confirmed that J- Δa curves by the participants according to GTN model were nearly the same.

NOMENCLATURE

f	void volume fraction
f^*	effective void volume fraction
f_c	critical void volume fraction
f_F	void volume fraction at final failure
J	J-integral
K_J	stress intensity factor converted from J
m	shape parameter of Beremin model
P_f	cumulative failure probability
q_1, q_2, q_3	parameters of GTN model
V_0	reference volume which includes a brittle micro crack
Φ	yield function
σ_0	yield stress

σ_1	maximum principal stress
σ_{eq}	von Mises equivalent stress
σ_m	hydrostatic stress
σ_u	scale parameter of Beremin model
σ_w	Weibull stress
σ_{wc}	critical Weibull stress
DBTT	ductile to brittle transition temperature
FEA	finite element analysis
GTN	Gurson-Tvergaard-Needleman
RPV	reactor pressure vessel
SE(B)	single edge notched bend

INTRODUCTION

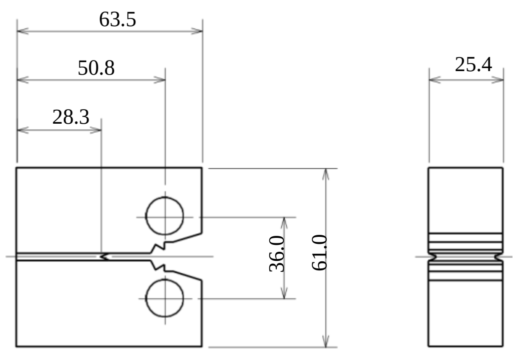
Existing assessment procedures are based on a conventional fracture mechanics approach using fracture toughness from standard test specimens such as Compact (C(T)) specimens. It is well known that fracture toughness from C(T) specimens is lower than those of actual structures with a flaw, such as a reactor pressure vessel (RPV) with a small surface flaw, because the stress fields of those flaws of the actual structures have smaller triaxiality than those of C(T) specimens, which causes lower plastic constraint. Considering the plastic constraint effect on fracture, ISO 27306 which specifies a method for constraint loss correction of fracture toughness was published in 2009 (revised in 2016) . In addition, WES 2808 which specifies a method of assessing brittle fracture for column-to-beam connections under seismic loading was published in 2003. In these standards, excessive conservativity of the conventional fracture mechanics method is eliminated by considering the plastic constraint effects. However, cleavage fracture often occurs after small ductile crack growth in the DBTT region, and assessment methods for this fracture mode have not been established.

In order to establish a guideline for assessment of cleavage fracture after small ductile crack growth considering plastic constraint in the DBTT region, the CAF (Constraint-Based Assessment of Fracture in Ductile-Brittle Transition Temperature Region) subcommittee was organized in the Atomic Energy Research Committee of the Japan Welding Engineering Society. The CAF subcommittee consisted of chair professor Minami (Osaka University), co-chair professor Ohata (Osaka University), and members from universities, research institutes, utilities, plant manufacturers and steel manufacturers. The goal of the committee was to prepare a draft guideline for fracture prediction of a components without excessive conservatism.

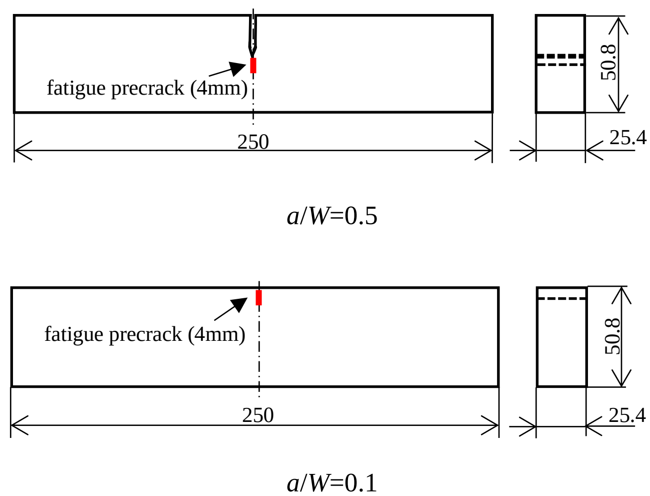
In order to validate the applicability of the Beremin model and GTN model, the codes' verification was inevitable. The Beremin model requires a very fine FE mesh model to reproduce a precise stress-strain filed and a convergence calculation to obtain the Weibull parameters. The GTN model has nine model's parameters, and it is normally performed by using an explicit code. Those characteristics of the models may cause a large scatter on the calculation results depending on the used codes. In this paper, several benchmark problems for the Beremin model and the GTN model were proposed to see the difference of the calculation results from the participants by focusing on the fracture tests of low-alloy steel B. The knowledge of the benchmark analyses was reflected to the guideline of the CAF subcommittee.

MATERIAL AND TEST DATA

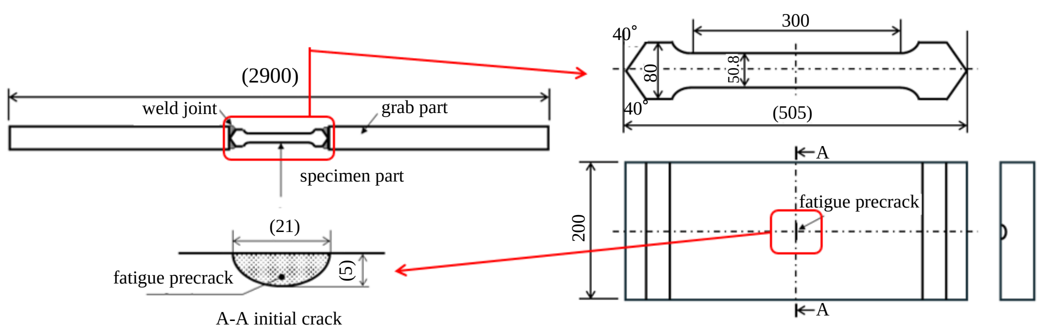
The test data used for the benchmark analyses were the fracture toughness data of 1T-C(T), SE(B), flat plate specimen with a surface flaw under bending and under tension respectively. The specimens were made of pressure vessel low alloy steel material, ASTM A533 Type B Class 1, named as low alloy steel B. The geometry of specimens is shown in Figure 1. Cleavage fracture with no ductile crack growth was observed in the tests at -120ºC and cleavage fracture with some ductile crack growth was observed in the tests at -80ºC. Young’s modulus is 210 GPa at -120ºC and 207 GPa at -80ºC. Poisson’s ratio is 0.3. True stress-true strain curves for the input of the benchmark analyses are shown in Figure 2.



(a) C(T) specimen



(b) SE(B) specimen



(c) Flat plate specimen with a surface flaw

Figure 1. Geometry of specimens

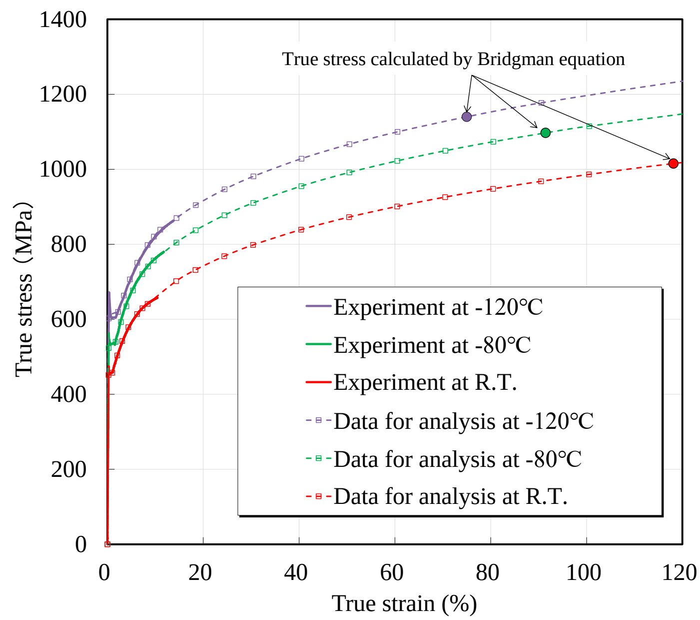


Figure 2. True stress - True strain curve of low alloy steel B for benchmark analyses

ANALYSIS METHOD

The Beremin model was applied for cleavage fracture. A cumulative probability of cleavage fracture, P_f, is expressed by equation (1).

$$P_f = 1 - exp\left(-\left(\frac{\sigma_w}{\sigma_u}\right)^m\right) \tag{1}$$

Here

$$\sigma_w = \left(\frac{1}{V_0}\int_V (\sigma_1)^m dV\right)^{\frac{1}{m}} \tag{2}$$

As a damage mechanics model, the GTN model was applied. The GTN model simulates the void's behavior of initiation, growth and coalescence by an expression of the yield function, as shown in equation (3). When f^* reaches f_F, ductile crack is considered as propagating.

$$\Phi = \left(\frac{\sigma_{eq}}{\sigma_0}\right) + 2fq_1 \cosh\left(\frac{3}{2}\frac{q_2\sigma_m}{\sigma_0}\right) - \left(1 + q_3 f^2\right) \tag{3}$$

Here

$$f^* = \begin{matrix} f & \text{for} & f \le f_c \\ f_c + K(f - f_c) & \text{for} & f > f_c \end{matrix} \tag{4}$$

$$K = \frac{1/q_1 - f_c}{f_F - f_c} \tag{5}$$

BENCHMARK ANAYSIS RESULTS

Nine participants performed the benchmark analyses. Benchmark analyses were conducted in 3 steps described below. The FE codes and element types used by the participants are shown in Table 1. The FE models of the specimens were produced by each participant. A quarter symmetric model was used for the analysis and the minimum element size at the crack tip was 0.03 mm.

Table 1: FE code, element type of benchmark participants

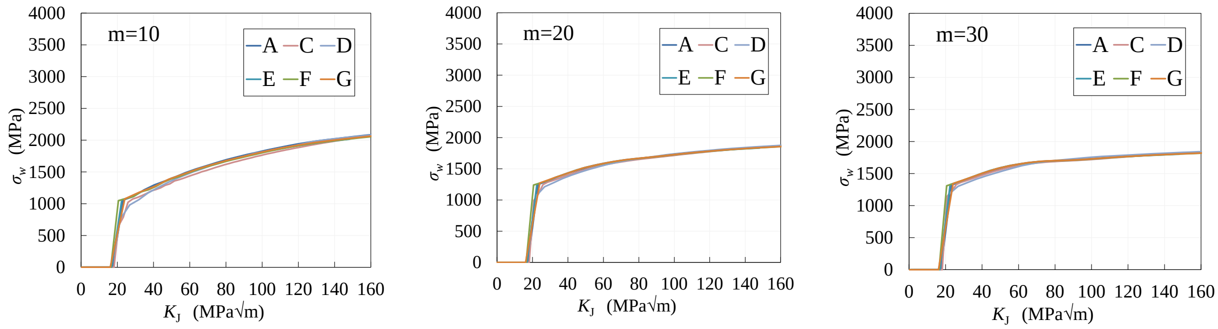
Participant	FE Code	Element type
A	Abaqus 6.12	8 Node Reduced Integration
B	Abaqus 6.12	8 Node Selective Reduced Integration
C	MSC Mark 2019 Feature Pack 1	8 Node Selective Reduced Integration
D	Abaqus 2018	8 Node Reduced Integration
E	Abaqus 2017hf13	
F	Abaqus 6.13-4	
G	Abaqus 2018	
H	In house code	8 Node Selective Reduced Integration
I	MSC Marc 2016	8 Node Selective Reduced Integration

Step1 Weibull stress using fixed m

The Weibull stress σ_w for 1T-C(T), SE(B) and flat plate specimens with a surface flaw was calculated using the fixed m (m= 10, 20, and 30) in this step. The results are shown in Figure 3~Figure 5. The integral region of the FE model for calculation of the Weibull stress was defined as the elements which exceeds the maximum principal stress value corresponding to K_J =20 MPa$\sqrt{\text{m}}$ of C(T) specimen. The reference value of the maximum principal stress for the integral of the Weibull stress calculation by each participant is shown in Table 2. From the figures, it was confirmed that the K_J- σ_w relations were nearly the same among participants for all the specimens. σ_w by participants H and I in less than 20 MPa$\sqrt{\text{m}}$ of K_J is different from those of the other participants. The participants H and I did not set the minimum reference value of the maximum principal stress for the Weibull stress calculation, which may be the reason of the different behavior.

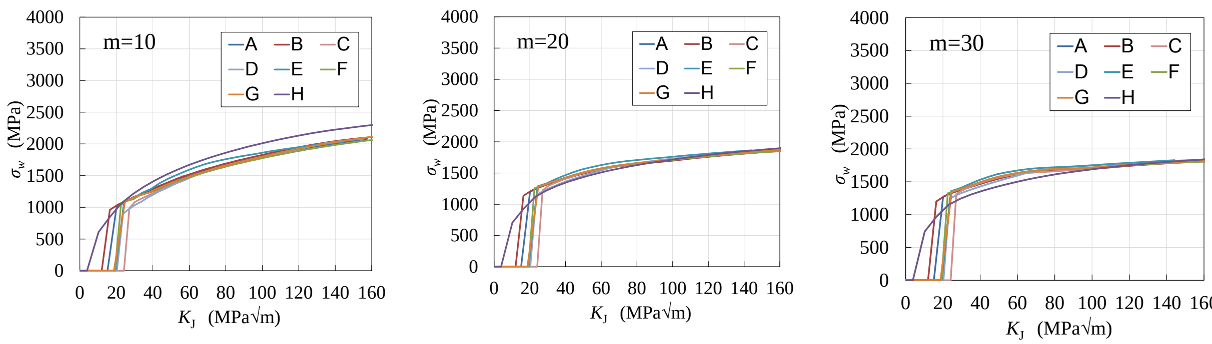
Table 2: Reference value of the maximum principal stress used for the integral range

Participants	A	B	C	D	E	F	G	H	I
Reference value of the maximum principal stress (MPa)	1430	1328	1501	1453	1445	1452	1440	–	–



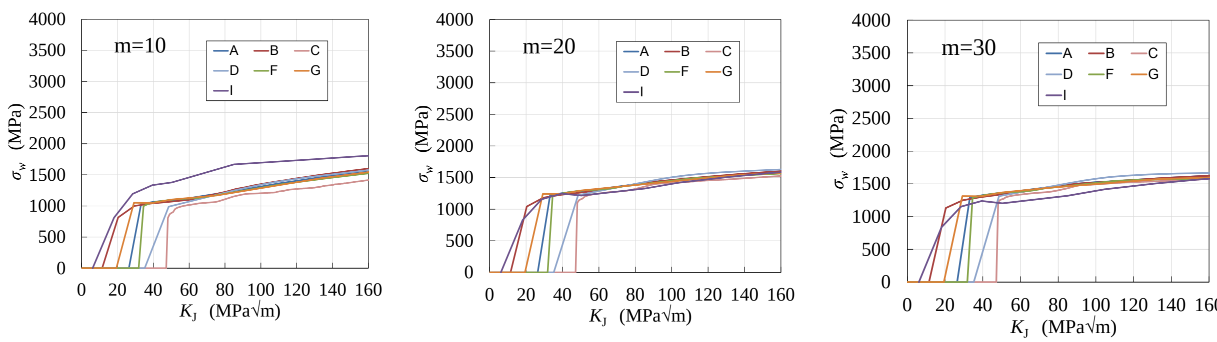
(a) m=10 (b) m=20 (c) m=30

Figure 3. Relationship between Weibull stress σ_w and K_J for 1T-C(T) specimen at -80 °C



(a) m=10 (b) m=20 (c) m=30

Figure 4. Relationship between Weibull stress σ_w and K_J for SE(B) specimen (a/W=0.5) at -80 °C



(a) m=10 (b) m=20 (c) m=30

Figure 5. Relationship between Weibull stress σ_w and K_J for flat plate specimen with surface flaw under tension at -80 °C

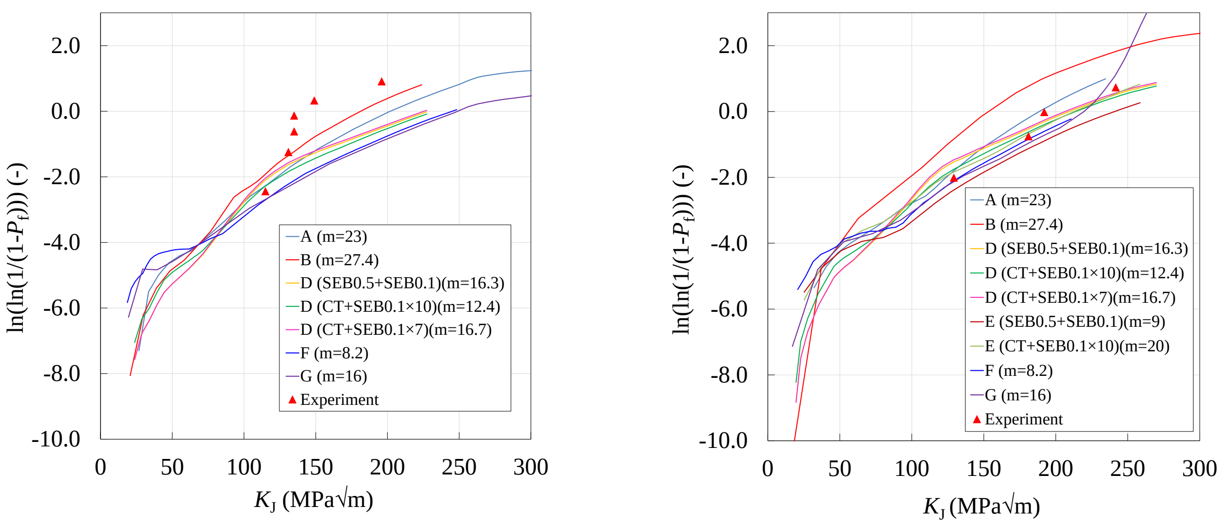
Step2 Fracture prediction using m by Toughness Scaling Model

m values were determined from two types of specimens (high and low constraint conditions) according to the Toughness Scaling Model proposed by Gao et al. (1998) and fracture prediction was carried out for the flat plate specimens with a surface flaw. The *m* value obtained by each participant is shown in Table 3. The P_f - K_J relations of the flat plate specimens with a surface flaw under bending and under tension using the *m* obtained by each participant are shown in Figure 6. For reference, the experimental P_f - K_J relations are shown in the figures. Although there are some differences in the *m* values among the participants shown in Table 3, the P_f - K_J relations by the participants in Figure 6 seem similar. It was also confirmed that failure probability can be accurately predicted for flat plate specimen under bending. For the flat plate specimen under tension, it was confirmed that the prediction of failure probability was closer to the test results in the region of small K_J, although the prediction of fracture probability tended to be lower than the test results in the region of large K_J.

Table 3: *m* values calculated by TSM

Used specimens to determine *m*	A	B	D	E	F	G
SE(B)(*a*/*W*=0.5)＋SE(B)(*a*/*W*=0.1) *1	23	27.4	16.3	9	8.2	15
C(T)＋SE(B)(*a*/*W*=0.1) *2	15	―	12.4	20	―	16.0
C(T)＋SE(B)(*a*/*W*=0.1) *1	21	―	16.7	―	―	―

*1 Seven test results of SE(B)(*a*/*W*=0.1) specimens were used.
*2 Ten test results of SE(B)(*a*/*W*=0.1) specimens were used.



(a) under tension (b) under bending

Figure 6. Relationship between P_f and K_J for flat plate specimen at -120°C

Step3 Fracture prediction with Coupled model

When ductile crack growth is assumed in DBTT region, it is necessary to consider the effect of ductile crack growth for fracture prediction. The benchmark analyses on ductile crack growth were carried out using the GTN model. The GTN parameters were optimized from the load-to-load line displacement and ductile crack growth of the 1T-C(T) specimen at room temperature. The GTN model parameters used for this analysis are shown in Table 4. All participants used these parameters for their analyses because determination of the GTN parameter is complex and time consuming. The relationship between ductile crack growth and *J* using GTN model for 1T-C(T) at room temperature and SE(B) at -80°C are shown in Figure 7. It was confirmed that the relationship between ductile crack growth and *J* was nearly similar among the participants for both specimens. Fracture prediction for brittle fracture after ductile crack growth was carried out using the Beremin model after FE analysis with the GTN model. The prediction of fracture probability for SE(B) specimen at -80°C is shown in Figure 8. It was confirmed that the result of participant A was close to the experimental result. Although the result of participant B tends to predict the failure probability higher than that of participant A, it provides a conservative prediction for the test result.

Table 4: GTN model's parameters

q_1	q_2	q_3	f_0	f_N	f_c	f_F	ε_N	S_N
1.5	1	2.25	1.00×10^{-5}	2.76×10^{-2}	7.00×10^{-2}	2.35×10^{-1}	6.62×10^{-1}	9.42×10^{-2}

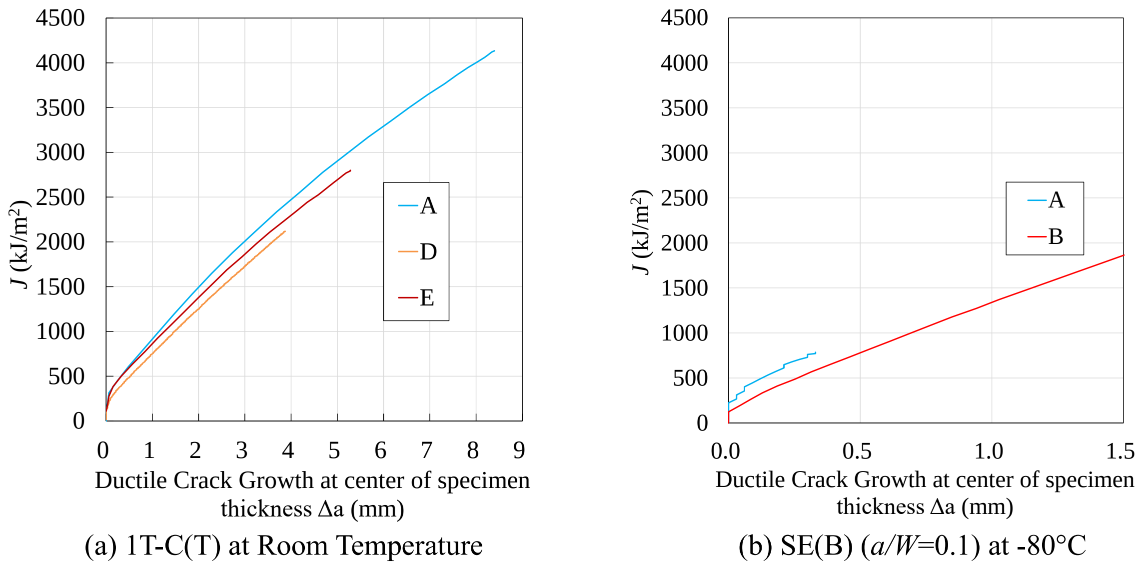


Figure 7. Relationship between ductile crack growth and *J* by GTN model

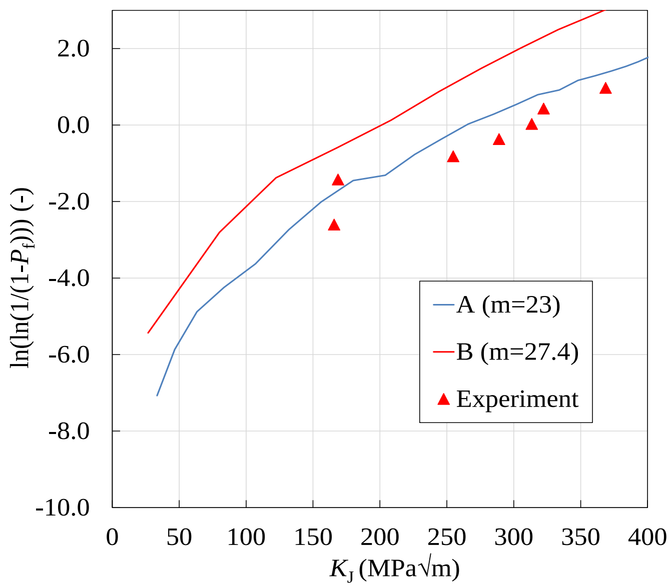


Figure 8. Relationship between failure probability and K_J for SE(B) specimen at -80°C

CONCLUSION

For verification of the codes used for the calculation of the Beremin model and the GTN model, several benchmark analyses were performed for various type of specimens. The Weibull stresses using the fixed *m*s were similar among the participants, and it was confirmed that the codes used by the participants had nearly the same calculation functions. When the participants resolved *m* values using two types of the laboratory specimens with the TSM, the *m* values were different. However, the predicted P_f - K_J relations of the flat plate specimens under tension and bending by the participants were close each other and those predictions were close the experimental results. In addition, it was confirmed that fracture prediction after small ductile crack growth by using the Coupled model were close between two participants and those prediction results nearly agreed with the experimental results.

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REFERENCES

Hirota, T., Nagoshi, Y., Hojo, K., Okada, H., Takahashi, A., Katsuyama, J., Ueda, T., Okada, T., Yashirodai, K., Ohata, M. and Minami, F. (2021). "Benchmark analysis of Beremin model and GTN model by CAF subcommittee," *ASME Pressure Vessels & Piping Conference PVP2021*, July 12-16, Virtual, Online.

Gao, X., Ruggieri, C., & Dodds, R. H. (1998). "Calibration of Weibull stress parameters using fracture toughness data," *International Journal of Fracture*, 92(2), 175-200.

Hojo, K., Hirota, T., Nagoshi, Y., Fukahori, T., Sakima, K., Ohata, M., and Minami, F. (2023). "Constraint Effect on Fracture in Ductile-Brittle Transition Temperature Region (Report 3)," *ASME Pressure Vessels & Piping Conference PVP2023*, July 16-21.