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Application of GTN model to TWC pipe test

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1. Introduction

The GTN model uses a micro-mechanical model for ductile fracture, incorporating void nucleation, growth and coalescence. However, standard process is not defined for determination of GTN damage parameters. It can predict tearing modulus very well, but it is difficult to predict the crack initiation. So, in this paper, to predict the crack initiation and tearing modulus, we propose the modeling method for crack tip element. In order to calibrate damage parameters, tensile and fracture toughness test are compared with simulated results for various element size. Tensile and fracture toughness specimens are extracted from STPT 410 steel pipe. The calibrated damage model to simulated long stable ductile tearing in large-scale pipes is applied to simulate pipe test data.

2. Methods and Results

2.1 Summary of TWC pipe test

Pipe fracture test by four-point bending were conducted at CRIEPI (Central Research Institute of Electric Power Industry, Japan) for circumferential cracked pipes made from STPT410 carbon steel (specified in Japanese Industrial Standard), typically used in Class 3 piping of Light Water Reactors. Essential information is given here and more detailed information can be referred to Ref. [1]. Tested pipe specimens had the mean radius of rm=~159mm and the thickness of t=~10mm. Two pipe tests were conducted with different crack sizes for circumferential through-wall cracks, as summarized in Table 1.

Table I: Summary of two circumferential thorough-wall cracked pipe test data

Type of crack	Test No.	θ
Through-wall crack	TW-01	31.8
	TW-02	60.7

2.2 Gurson-Tvergaard-Needleman (GTN) model

The GTN model to simulate ductile damage and failure is given by[2, 3, 4]

$$\Phi = \left(\frac{\sigma_e}{\sigma_0}\right)^2 + 2q_1 f \cosh\left(-q_2 \frac{3p}{2\sigma_0}\right) - \left(1 + q_1^2 f^2\right) = 0 \tag{1}$$

where σ_e is the equivalent stress, p the hydrostatic pressure and σ_0 the yield stress of void-free material. The material parameters q_1 and q_2 depend on the hardening exponent n and on the ratio E/σ_0, where E is the Young's modulus.

The void growth rate can be expressed in terms of the current value of *f (*the void volume fraction) and the plastic strain rate tensor $\dot{\varepsilon}^p$ as

$$\dot{f}_{gr} = (1 - f)\dot{\varepsilon}^p : \mathrm{I} \tag{2}$$

where I is the second order unit tensor

2.3 Calibration method I

To determine GTN model parameters, FE damage analysis is performed to simulate C(T) test. FE damage analysis were conducted by ABAQUS explicit porous analysis[5] and the first order solid reduced elements were used(C3D8R).

The calibration process has two steps. First, To determine the value of initial void volume fraction (f_0) from J-R curve. Second, If can't predict using by initial void volume fraction, calibrate using by fracture void volume fraction (f_f).

Beginning of GTN model parameters are shown in Table. 2. In case of element size 0.2 mm, to calibrate initial void volume fraction (f_0) simulate to C(T) test. The FE mesh used by brick mesh and it shows Fig. 1. In Fig. 2, the effect of f_0 on predicted J-R curves is shown. As f_0 value increases, J-R curve is decreased. And FE result using calibrate parameter f_0 can't predict experimental data. Therefore, to predict experimental data used two calibration parameter f_f and f_0. By matching the experimental J-R curve, an appropriate value of f_f and f_0 can be found.

In case of element size 0.4, 0.6, 0.8 mm, to calibrate f_0 simulate to C(T) test. Others parameters value used by determined value in case of element size 0.2 mm. Final predicted J-R curve is showed in Fig. 3. Resulting variations of f_0 with element size are shown in Fig. 4.

2.4 Calibration method II

The difference between the method I and method II is shape of crack tip element. In the method II, modified crack tip element is used to FE analysis. The shape of crack tip element is shown in Fig. 5. The calibration process has two steps. First, the shape factor (C) is determined by matching crack initiation, as showed in Fig. 6. Second, f_0 is determined

Table II: Damage parameters value of GTN model

Parameter	Value
Void nucleation ε_N, S_N, f_n	None
Void growth f_0 f_c f_f	Calibration variable 0.10[5] 0.2[5]
q_1, q_2	1.44, 0.94[6]
Element size (mm)	0.2

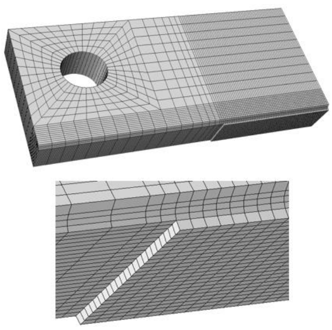

Fig. 1. FE mesh for simulating C(T) test

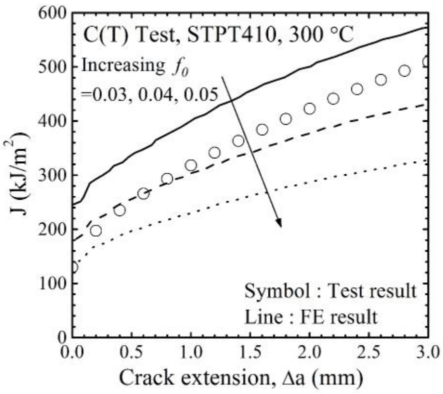

Fig. 2. Effect of f_0 on simulated J-R curves

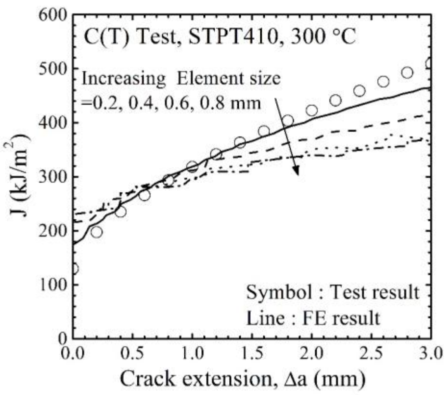

Fig. 3. Comparison of experimental J-R curve with simulated results for various element size

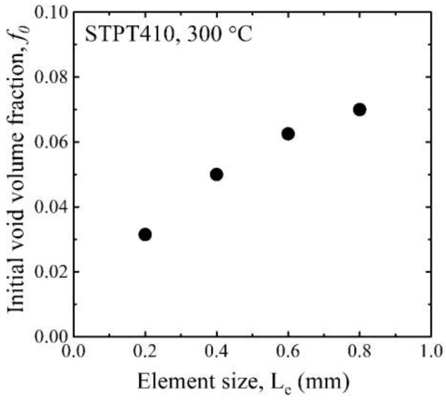

Fig. 4. Variation of f_0 with finite element size

by matching tearing modulus, as showed in Fig. 7.

In case of element size 0.4, 0.6, 0.8 mm, to calibrate f_0 simulate to C(T) test. Others parameters value used by determined value in case of element size 0.2 mm. Final predicted J-R curve is showed in Fig. 8. Resulting variations of f_0 with element size are shown in Fig. 9.

2.5 Ductile Simulation of TWC pipe test

The FE mesh for simulating the TWC pipe test is shown in Fig. 10. FE damage analysis was performed using two different methods; method I and II. Fig. 11 compares simulation result with experimental data(TW-01); the load versus LLD and crack extension versus LLD data. It can be seen that method II agree relatively well with experimental data.

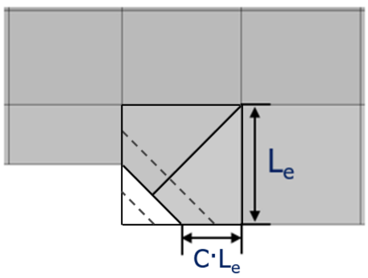

Fig. 5. FE mesh for simulating C(T) test : modified crack tip mesh

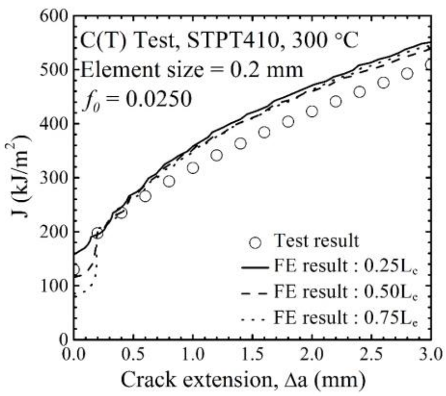

Fig. 6. Effect of C on simulated J-R curves

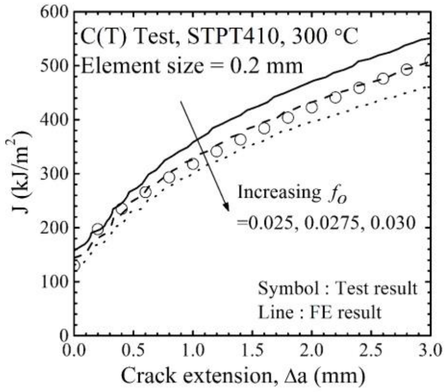

Fig. 7. Effect of f_0 on simulated J-R curves

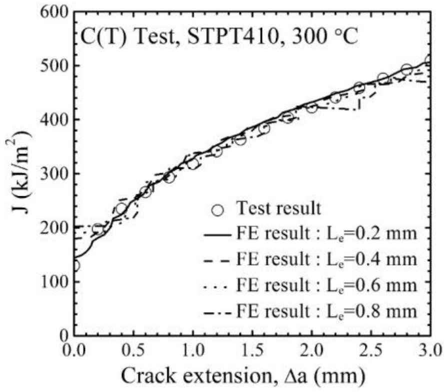

Fig. 8. Comparison of experimental J-R curve with simulated results for various element size

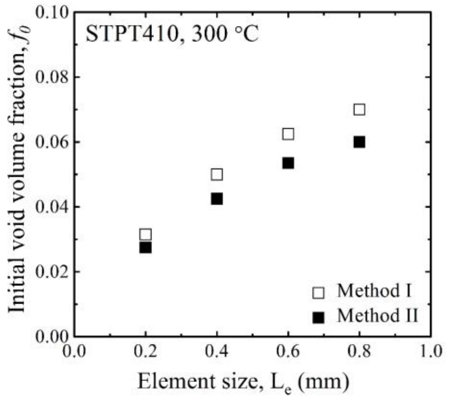

Fig. 9. Variation of f_0 with finite element size

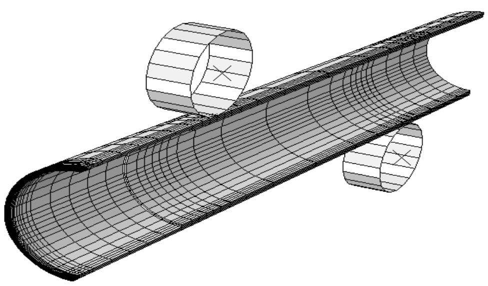

Fig. 10. FE mesh for pipe ductile simulation

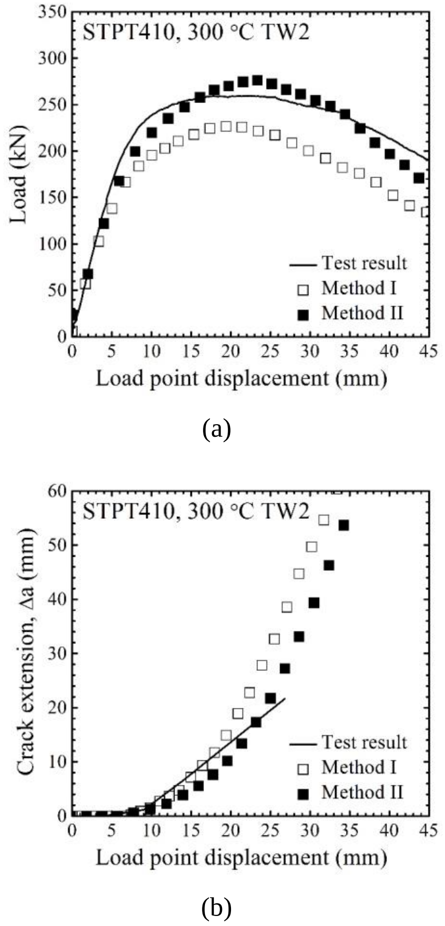

Fig. 11. Comparison of through-wall cracked pipe test data with simulated results: (a) load-LLD curve and (b) crack extension-LLD curve

3. Conclusions

In case of method I (brick crack tip mesh), the use of larger element sizes (0.4 mm to 0.8 mm) gives slightly lower J-R curves than that using the 0.2 mm element size. But, in case of method II (modified crack tip mesh), crack initiation and tearing modulus is more predictable than method I.

For the simulation of through-wall cracked pipe test, the method II agree well with experimental result than method I.

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