Prediction of Fracture Resistance Curves of Compact Tension Specimens with Various In-plane Sizes Using Local Approach

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1. Introduction

Traditional fracture mechanics has been used to ensure a structural integrity by comparing toughness measured from laboratory specimens and corresponding parameters calculated from numerical analyses, in which the geometry independence is assumed in crack tip deformation and fracture toughness. However, the assumption is applicable only within a limited range of loading and geometric conditions, and this restrictive nature is a major limitation on the application of elastic-plastic fracture mechanics. This paper addresses the geometry dependent fracture toughness issue associated with various in-plane sizes based on local approach. Modified GTN model and Rousselier model are adopted to examine the behavior of SA515 Gr.60 carbon steel at high temperature. After calibration of the material specific fitting constants, fracture resistance curves (*J-R* curves) of standard compact tension (CT) specimens are estimated through finite element (FE) analyses. Then the estimated *J-R* curves are compared with corresponding experimental results to check the applicability of two damage models. Finally, a series of FE analyses as well as fracture toughness tests are performed to investigate the effects of in-plane size of CT specimens.

2. Micro-mechanical models and calibration

2.1 Micro-mechanical models

The key features of two types of micro-mechanical models are summarized as follows:

Modified GTN Model. Gurson model [1] can be used to analyze plastic flow in a porous medium by assuming that materials behave as a continuum. It was modified by other researchers, then, the yield surface became as

$$\Phi = \frac{3}{2}\frac{S_{ij}S_{ij}}{\sigma_{YS}^2} + 2f\cosh\left(\frac{3}{2}\frac{\sigma_m}{\sigma_{YS}}\right) - (1+f^2) = 0 \qquad (1)$$

where, f is the void volume fraction, S_{ij} is the deviatoric stress defined as $S_{ij} = \sigma_{ij} - \sigma_m\delta_{ij}$. Also, Tvergaard and Needleman [2,3] modified the Gurson model by replacing f with an effective void volume fraction, f^*:

$$f^* = \begin{cases} f & \text{for } f \le f_c \\ f_c - \dfrac{f_u^* - f_c}{f_F - f_c}(f - f_c) & \text{for } f > f_c \end{cases} \qquad (2)$$

where, f_c, f_u^* and f_F are the material specific fitting constants.

Rousselier model. This model [4] defines the yield surface as a function of hydrostatic stresses:

$$\Phi = \frac{\sigma_{eq}}{\rho} + D\cdot\sigma_1\cdot f\cdot\exp\left(\frac{\sigma_h}{\rho\sigma_1}\right) - R(\varepsilon_{eq}^P) = 0 \qquad (3)$$

where, σ_1 and D are fitting constants, σ_{eq} is equivalent von Mises stress, σ_h is hydrostatic stress, ρ is material density and $R(\varepsilon_{eq}^P)$ represents work-hardening law. In order to apply Rousselier model to specific material, the σ_1, D and initial void volume fraction (f_0) have to be determined. Rousselier suggested that the value of σ_1 as 2/3 times of yield strength and the value of fitting constant D as 1.5~2.0.

2.2 Calibration of fitting constants

The material specific fitting constants of SA515 Gr.60 carbon steel at 316℃ were calibrated using three dimensional FE model of 1T-CT specimen [5]. Thereby, the fitting constants were determined as f_0=0.0031, f_c=0.019, f_f=0.20, q_1=1.96, q_2=0.781, D=2.0 and σ_1=430.0MPa. Fig. 1 shows the comparison of load-load line displacement (P-δ) curves of standard 1T-CT specimen. The estimated P-δ curves using the fitting constants agreed well to the corresponding experimental one.

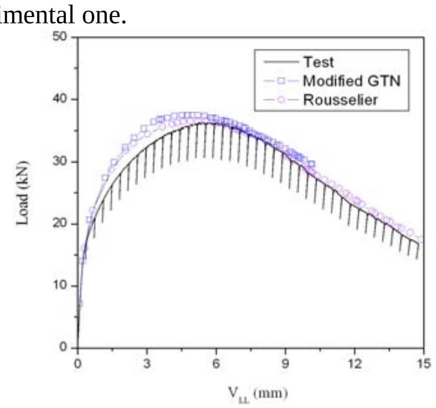

Fig. 1 Comparison of P-δ curves of 1T-CT specimen

3. Estimation of J-R curves

3.1 FE analyses

Several CT specimens were analyzed to investigate the in-plane size effect. The geometry of 1pt CT specimen is the same with that of standard 1T-CT specimen. 2pt and 3pt CT specimens have two and three times increased in-plane size, respectively, with same thickness to the 1pt specimen. ABAQUS 6.4 and user subroutine (UMAT) incorporating damage models were used for numerical simulation. Fig. 2 indicates the FE model of typical 1pt CT specimen in which a cell size around crack tip was set to 250μm. Three dimensional 8 node solid element (C3D8) was adopted and crack extension was simulated by element death method which means Young’s modulus becomes zero and no more load is sustained when the crack growth.

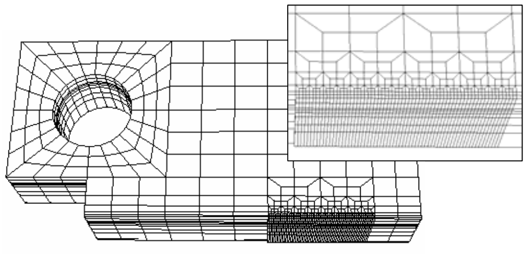

Fig. 2 FE model of 1pt CT specimen.

3.2 Estimation results

Fig. 3 represents the comparison of representative crack growth of 1pt CT specimen of SA515 Gr.60 carbon steel. As shown in the figure, the FE analysis result combined with Rousselier model and test result had similar shape of fracture surface and amount of crack growth. Fig. 4 and Fig. 5 depict the estimated J-R curves of 1pt, 2pt and 3pt specimens using local approach as well as test ones. Both the Modified GTN and Rousselier models gave good results comparing to the test results. During the prediction process, the *J*-integral was estimated from the area of P-δ curves and the crack extension was determined by aforementioned element death method. Also, with regard to simulation of blunting before crack initiation, the construction line suggested in ASTM standard was used in the estimation scheme because it can not be considered by local approach.

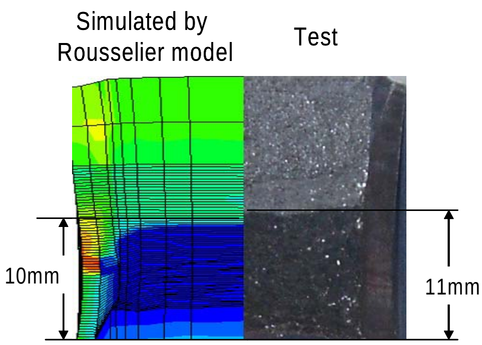

Fig. 3 Comparison of crack growth of 1pt CT specimen.

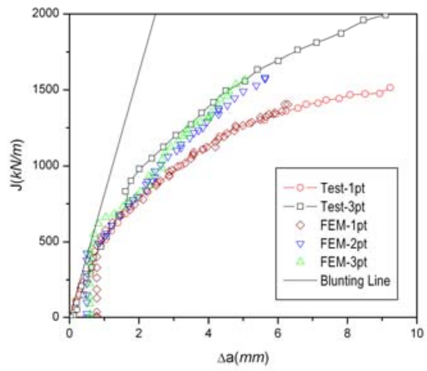

Fig. 4 Estimated *J-R* curves by modified GTN model.

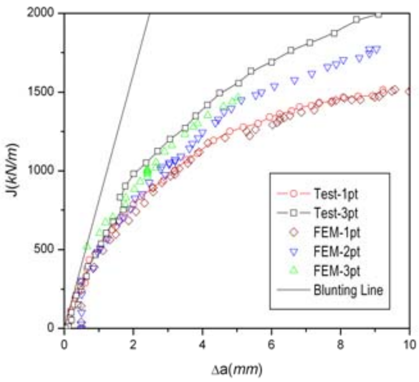

Fig. 5 Estimated *J-R* curves by Rousselier model.

4. Conclusion

An assessment of in-plane size effect based on local approach has been carried out for CT specimens made from SA515 Gr.60 carbon steel. Thereby, it was proven that the numerical simulation is a promising tool for estimation of *J-R* curve while those were somewhat dependent on the micro-mechanical damage models. So, it is believed that the estimated results can be used for integrity evaluation of major nuclear components.

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