Battelle Full-Scale Pipe Fracture Simulation of Carbon Steels with a Circumferential Crack

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1. Introduction

In structural integrity assessment, full-scale test is an accurate and reliable way to evaluate fracture behavior of components containing crack-like defects. However, from a cost-effectiveness perspective it is consequently economically unfavorable. One efficient way to replace such extensive test programs is to use finite element (FE) damage analyses. Recently a simple FE method has been proposed [1] to implement fracture simulation based on the well-known stress-modified fracture strain model [2,3]. Although the technique appropriately simulated ductile failure for miscellaneous cracked components [4,5], the failure simulations using small element size cause numerical instability. In order to overcome this problem and to be applicable to the large-scale structures, this paper introduces element-size-dependent critical damage model. Simulated results are compared with full-scale test data of circumferential cracked pipes taken from Pipe Fracture Encyclopedia [6] to validate the proposed method.

2. Full-Scale Pipe Test Data

Two sets of full-scale pipe test data at 288°C were extracted from Pipe Fracture Encyclopedia [6] for SA333 Gr. B and A106 Gr. B carbon steels. For the sake of space, only for SA333 Gr. 6, geometric variables, dimensions and schematic illustrations of cracked pipes are shown in Table 1 and Fig. 1. The data sets consist of tensile test, fracture toughness test and full-scale circumferential cracked pipe test under four-point bending. For SA333 Gr. B, the 0.2% proof (yield) strength, ultimate tensile strength and reduction of area are 239MPa, 527MPa and 60.0%, respectively.

3. Ductile Fracture Simulation Technique

3.1 Damage model

The damage model used in this paper is based on the phenomenological ductile fracture model which is also known as the stress-modified fracture strain model [2,3]. In this model, fracture strain ε_f for dimple fracture is assumed to depend exponentially on the stress triaxiality σ_m/σ_e:

$$\varepsilon_f = \alpha \exp\left(-\gamma \frac{\sigma_m}{\sigma_e}\right) + \beta \quad ; \quad \frac{\sigma_m}{\sigma_e} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3\sigma_e} \qquad (1)$$

where σ_i (i=1-3) are principle stress components; and α, β and γ are material constants. Damage ω can be calculated by summing incremental damage $\Delta\omega$, given by

$$\Delta\omega = \frac{\Delta\varepsilon_e^p}{\varepsilon_f} \qquad (2)$$

where $\Delta\varepsilon_e^p$ is the equivalent plastic strain increment, calculated from FE analysis implemented in ABAQUS using user subroutines [7]. For SA333 Gr. B, determined fracture strain model is shown in Fig. 3(a).

Table 1. Summary of specimen dimensions for circumferential cracked SA333 Gr. 6 pipes at 288°C.

Specimen ID	D_o (mm)	t (mm)	r/t	a/t	θ/π
TWC (4131-7)	273.1	18.3	6.96	-	0.35
SC (4115-1)	256.2	17.3	6.90	0.70	0.42
SC (4115-2)	272	17.1	7.45	0.71	0.43
SC (4131-8)	270.6	15.1	8.46	0.68	0.48

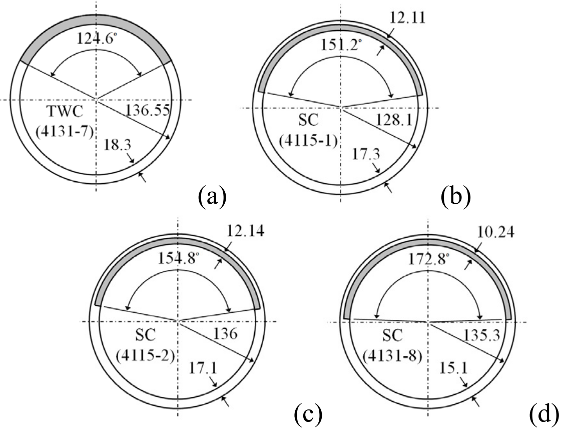


Fig. 1. Schematic of the cross-sectional view for SA333 Gr. 6 pipes in Table 1: (a) through-wall cracked pipe and (b)-(d) surface cracked pipes.

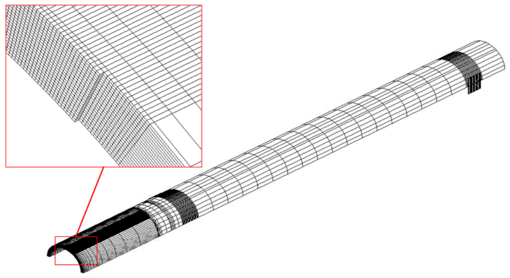
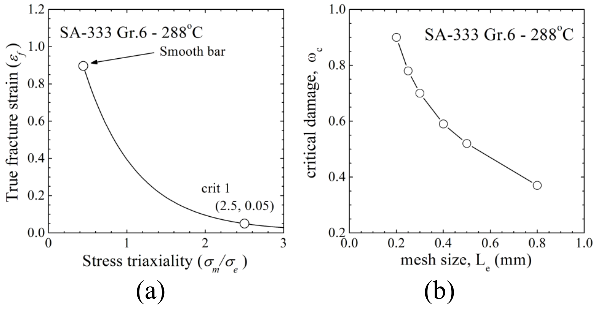


Fig. 2. FE mesh to simulate the through-wall cracked (4131-7) pipe test.



(a) (b)

Fig. 3. Calibration results for ductile fracture simulation: (a) determined fracture strain model and (b) dependence of the critical damage with element size.

3.2 Element size effect

The main concept of the proposed method is that the critical accumulated damage for fracture, ω_c, is assumed to vary with the element size. Then the failure criterion is

$$\omega = \sum \Delta\omega = \omega_c(\text{element size}) \qquad (3)$$

A proper element size for the material calibrated corresponds to the case of ω_c=1. When a larger element is used, a smaller ω_c value can be used to produce the same cracking rate as shown in Fig. 3(b).

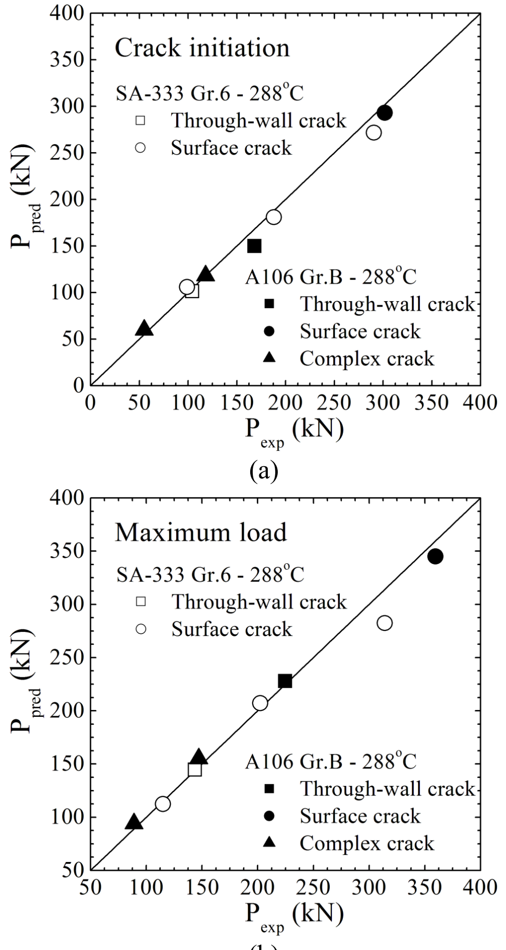
4. FE Analysis and Results

Three-dimensional FE damage analyses were performed using the element size of 0.6mm and 0.8mm for A106 Gr. B and SA106 Gr. 6, respectively. A quarter model was used considering symmetry conditions. Eight-node brick elements with full integrations (element type C3D8 in ABAQUS [7]) were uniformly spaced in the cracked section as shown in Fig. 2. Damage analysis was performed with the non-linear geometry change option.

Figure 4 shows that predicted crack initiation and maximum loads for four different tests of SA333 Gr. 6 pipes and four different tests of A106 Gr. B pipes are compared with experimentally measured values, showing overall good agreements. Predicted loads differ from experimental ones less than 11% for the crack initiation load and 6% for the maximum load.

5. Conclusions

Full-scale pipes with a circumferential crack for SA333 Gr. 6 and A106 Gr. B carbon steels are simulated using FE damage analysis based on the stress-modified fracture strain model. To overcome numerical instability problem due to the small element size and to be applicable to the large-scale structures, a concept of the element-size-dependent critical damage model is introduced. The present method can predict well crack initiation and maximum loads of full-scale pipe tests. This method offers significant advantages in simulating long, stable crack growth in large-scale components.



(a)

(b)

Fig. 4. Comparison of experimental results with simulated ones for (a) crack initiation loads and (b) maximum loads.

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