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Ductile fracture simulation of full-scale circumferential cracked pipes: (II) stainless steel

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Abstract

This paper reports ductile fracture simulation of full-scale circumferentially cracked pipes using finite element (FE) damage analysis. In the structural integrity, without experimental investigations or with few ones, it is not an easy task to properly evaluate the crack initiation and crack propagation of large-scale components with a crack-like defect. Unfortunately, from an economic perspective, performing experiments of large-scale components would be consequently unfavorable. For these reasons, ductile fracture simulation using FE damage analysis to predict crack behavior is one efficient way to replace the test procedures. In order to simulate ductile tearing of large-scale cracked pipes, element-size-dependent critical damage model based on the stress-modified fracture strain model is proposed. To evaluate fracture behavior of full-scale cracked pipes, tensile and C(T) specimens are calibrated by FE analysis technique. Tensile properties and fracture toughness of stainless steel at 288°C are taken from Battelle Pipe Fracture Encyclopedia. After calibrations, simulated results of the full-scale pipes with a circumferential crack are compared with test data to validate the proposed method.

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Keywords: Ductile fracture; Finite element analysis; Stress-modified fracture strain model; Damage analysis; Full-scale cracked pipes; Experimental validation.

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Nomenclature

a, Δa	crack length and extension in the radial direction, respectively
r, D_o	mean pipe radius and outer pipe diameter, respectively
t	pipe thickness, mm
θ	half circumferential angle
$\Delta\varepsilon_e^p$	incremental equivalent plastic strain
ε_f	fracture strain
σ_1, σ_2, σ_3	principal stress components
σ_e, σ_m	effective stress and hydrostatic stress, respectively
ω, $\Delta\omega$	accumulated damage and incremental damage
ω_c	critical damage for cracking
α, β, γ	material constant for stress-modified fracture strain
L_e	element size, mm
P_{exp}	initiation or maximum loads from experimental data
P_{pred}	initiation or maximum loads from finite element damage simulation

1. Introduction

Many full-scale pipes tests have been done in order to evaluate structural integrity and reliability. Analysis of a full-scale test has a bigger advantage in terms of similarity in boundary condition and loading condition comparing with the real pipes structure. Especially in the case of cracked pipes, it is more crucial to observe not only the initiation maximum load but also the crack propagation at the same geometry with real pipe structure. However, full-scale tests take up too much time and cost, making it as an inefficient method to be applied. To replace full-scale pipes tests, finite element (FE) analysis can be used in prediction of fracture behavior in pipes with defects. So this paper discusses stress-modified fracture strain model to predict maximum load and crack propagation. In order to define parameter using in stress-modified fracture strain model, small specimens such as smooth bar for tensile properties and fracture toughness test specimens such as C(T) are used. The material considered in this study is stainless steel. Mechanical properties and fracture toughness of the material are taken from Battelle Pipe Fracture Encyclopedia. When defined simulation model is applied to large-scale structure such as pipes, small size element used small specimen causes numerical problems. To overcome this problems, this paper introduces element-size-dependent critical damage model. To make element-size-dependent critical damage model, ductile failure simulation parameter (critical damage (ω_c), element size) is re-determined from repeating process. Finally, simulated results of the pipe are compared with full-scale test data (maximum load and initiation load) of circumferential cracked pipes to verify the proposed method for stainless steel.

2. Summary of Pipe Test in Pipe Fracture Encyclopedia

Battelle memorial institute has performed various test. Using these test results in Battelle Pipe Fracture Encyclopedia, it is possible to constitute a set that involve results of tensile test, fracture toughness test, 4 points bending test for cracked pipe at the specific temperature. To apply damage simulation model, in this paper, a test result of through-wall cracked pipe and two set of test results surface cracked pipe are selected. Material of testing pipe is SA-376 stainless steel and testing temperature is 288℃. In three sets, pipe geometry is similar and same tensile specimen, fracture toughness specimen are used. So it possible to defined one damage simulation model that can be applied to the three pipe results. Geometries and dimensions of C(T) specimen used in defining parameter of damage simulation model are shown in Fig 1(a). Likewise, three types of pipe and crack geometries are shown in fig 1(b)-(d) and table 1. Material properties of SA-376 stainless steel are excerpted in Pipe Fracture Encyclopedia. Yield strength, tensile strength and reduction of area at 288℃ are 139MPa, 450MPa, 71.4%, respectively.

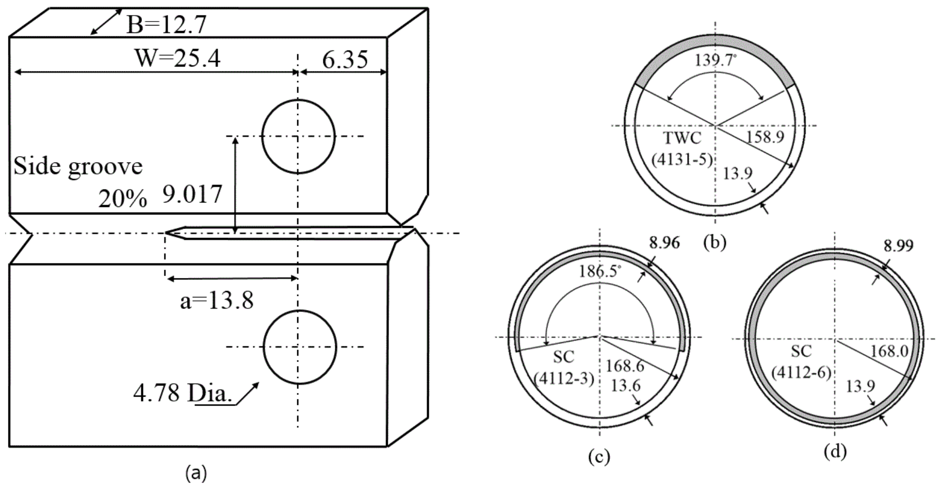

Fig. 1. (a) Schematic of the C(T) specimen (b)-(d)the cross-sectional view for SA-376 pipes : (b) through-wall cracked pipe (c),(d) surface cracked pipes.

Table 1. Summary of specimen dimensions for circumferential cracked SA-376 pipes at 288℃.

Specimen	D_o *(mm)*	t *(mm)*	*r/t*	*a/t*	*θ/π*
Through-wall crack (4131-5)	158.9	13.9	5.22	1.0	0.388
Surface crack (4112-3)	168.6	13.6	5.70	0.659	0.518
Surface crack (4112-6)	168.0	13.9	5.54	0.647	1.0

3. Ductile Fracture Simulation Model

The damage model used in this paper is based on the concept that fracture strain for dimple fracture depends on the triaxiality (the ratio of the mean normal stress and equivalent stress). This model is well-known as stress modified fracture strain model.

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

where σ_i are principle stress components, α, β and γ are material constants.

In Battelle Pipe Fracture Encyclopedia, notched bar tensile tests are not given. Therefore, to reduce number of material constants, analytical study can be used. Rice and Tracey suggested γ is approximately -1.5. And 2 unknown remain, it can be determined by using smooth bar tensile test and fracture toughness test results. This result is shown in fig. 2. Also this result (criteria) is validated with C(T) specimen.

Incremental damage is defined by summing equivalent plastic strain increment and fracture strain, given by

$$\Delta\omega = \frac{\Delta\varepsilon_e^p}{\varepsilon_f} \tag{2}$$

Where $\Delta\varepsilon_e^p$ is the equivalent plastic strain increment, calculated form FE analysis using subroutine of ABAQUS.

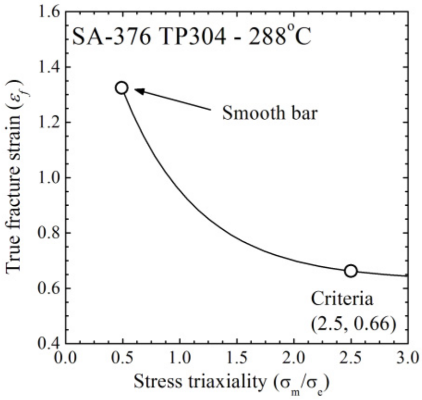

Fig. 2. Determination of criteria for ductile fracture simulation

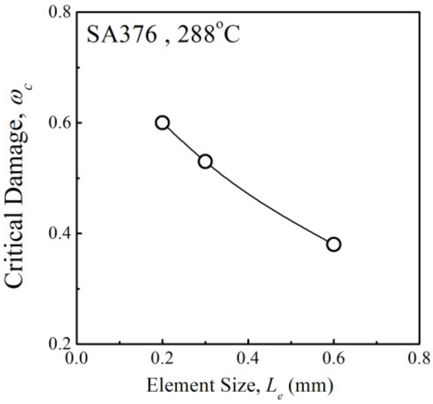

Fig. 3. Dependence of the critical accumulated damage, ω_c, on the element size.

When the value of summation incremental damage, $\omega = \sum \Delta\omega = 1$, it is possible to assume that degradation of material stiffness occur in FE analysis.

Size of elements is important parameter in FE analysis. The size of elements using in damage simulation is determined by reflecting properties of the material. However, size of elements reflected material properties is too small to simulate crack propagation in actual pipe. In this background, element-size dependent critical damage model is introduced. The purpose of Element-size dependent critical damage model is that increasing size of elements using simulation. In order to compensate for increasing size of elements, decreasing accumulated damage w is assumed. To define element-size dependent critical damage model, repeated processes are needed for validating model with same results of stress-modified fracture strain model. This results are shown fig.3.

4. FE analysis and Simulation results

As mentioned earlier, this paper selected 3 sets of test results. To apply Element-size dependent critical damage model, this paper chose value of ω_c is 0.38 and size of element is 0.6mm. A quarter model was used considering symmetry condition in pipe model. Eight-node brick elements with full integration point (C3D8) in ABAQUS and non-linear geometry analysis were used. Surface cracked pipe FE model are shown fig.4. Fig.5 shows results of surface cracked pipe (4112-3) predicted by using Element-size dependent critical damage model. Predicted maximum load and initiation load have an error of 10% less. Fig.6 contains all of selected 3 sets results.

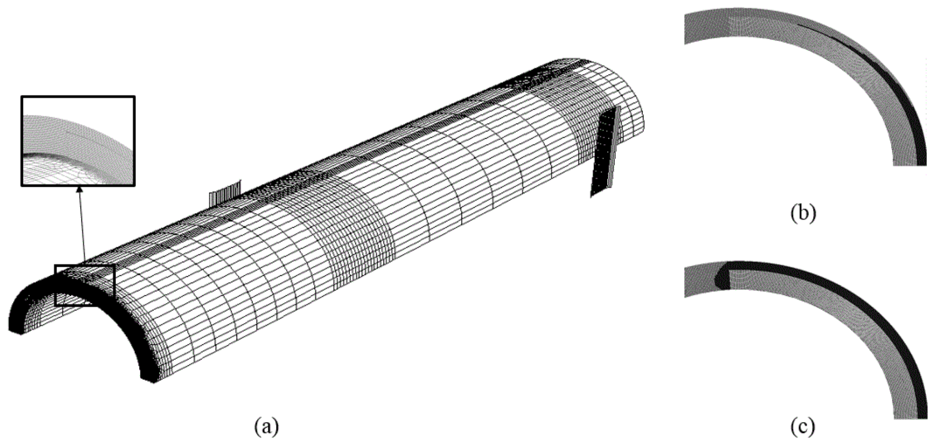

Fig. 4. (a) FE mesh to simulate the surface cracked pipe test (4112-3); and simulated cracked configurations (b) at the maximum load and (c) at LLD=30mm.

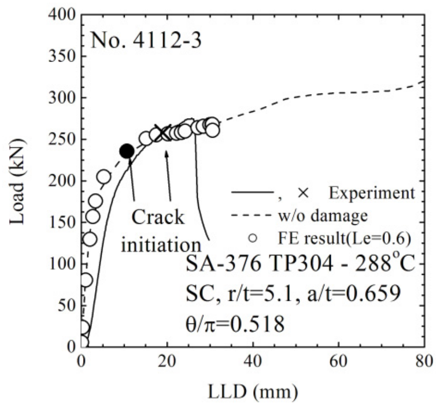

Fig. 5. Comparison of surface cracked pipe test results with simulated ones: 4112-3 test

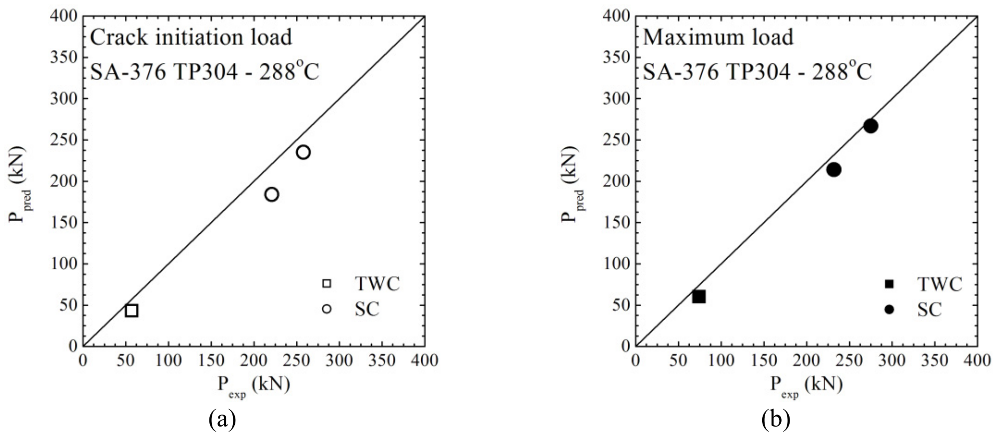

Fig. 6. Comparison of experimentally-measured loads with predicted load for SA-376: (a) loads at crack initiation and (b) maximum loads.

5. Conclusion

In this paper, stress-modified fracture strain model is defined by using results of smooth bar tensile test and fracture toughness test in Battelle Pipe Fracture Encyclopedia. After that, Element-size dependent critical damage model is considered to overcome numerical problems. Through these process, size of elements and accumulated damage ω using damage simulation model are determined. And it is possible to apply cracked pipe.

Though fig.7 shows that predicted maximum load and predicted initiation load are well-agreement, the results have slightly less accuracy comparing with results of carbon steel pipe. In stainless steel pipe, however, the method in this paper offers big advantages in assisting actual pipe test and still worth.

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