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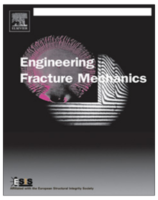

Creep constraint analysis and constraint parameter solutions for axial semi-elliptical surface cracks in pressurized pipes

S. Liu, G.Z. Wang*, F.Z. Xuan, S.T. Tu

Key Laboratory of Pressurized System and Safety, Ministry of Education, East China University of Science and Technology, Shanghai 200237, China

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ABSTRACT

Creep crack-tip constraints for axially cracked pipes with different geometries and sizes of semi-elliptical surface cracks have been analyzed by three-dimensional finite element method and the constraint parameter solutions were obtained. It has been shown that the constraint levels of cracks in the pipes increase with increasing crack depths and lengths. The constraint levels and creep crack growth rates of all cracks in the pipes are lower than those of the standard compact tensile specimens. Without considering the creep constraint effects, the excessive conservatism may be produced in creep life assessments of the axially cracked pipes.

1. Introduction

Many experimental and theoretical evidences have shown that the constraint effect has significant influence on fracture behavior of materials, and the fracture toughness increases due to the loss of constraint [1]. The constraint effect is usually caused by loading configuration, crack size and geometry of specimens or structural components. The quantification of constraint has been widely investigated within the elastic–plastic fracture mechanics frame, and led to the development of two parameter fracture mechanics, such as J–T, J–Q and J–A_2 [2–5]. In these approaches, the first parameter J integral sets the size scale over which high stresses and strains develop, and the secondary parameters T [2], Q [3,4] and A_2 [5] were introduced to quantify the crack-tip constraint.

Under creep conditions, a lot of experimental and theoretical evidences have shown that constraint can affect creep crack growth (CCG) rate [6–18]. For a given C^* value (creep fracture mechanics parameter), the model predications showed that the CCG rates in plane strain (PE) are significantly greater than those in plane stress [7–11]. The experimental results of Tabuchi et al. [12] and Tan et al. [13,14] have shown that there is an effect of specimen thickness on the creep crack growth rate, and the specimens with larger thickness exhibit the higher creep crack growth rate. It also has been found that at the same C^* value the creep crack growth rates measured in the middle tension (M(T)) specimens are lower than those obtained from deep crack compact tension (C(T)) specimens for the austenitic stainless steels [15–17] and ferritic steels [18]. Yokobori Jr. et al. proposed a parameter Q^* for correlating creep crack growth rate [19–22], and their work shown that the creep crack growth rate for a thick specimen is higher than that of a thin specimen [20]. The creep ductility and constraint effects can be estimated by using the parameter Q^* [21], which were defined as "structural brittleness" [22].

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* Corresponding author. Tel.: +86 021 64252681; fax: +86 021 64253513.
E-mail address: gzwang@ecust.edu.cn (G.Z. Wang).

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Nomenclature

a	crack depth
$\dot{a}$	creep crack growth rate
$\dot{a}_0$	creep crack growth rate of the standard specimen
A	coefficient in the power-law creep strain rate expression
A_2	constraint parameter
$2c$	crack length
C^*	C^* integral analogous to the J integral
$C(t)$	$C(t)$ integral
D	inner diameter of pipes
E	Young's modulus
J	J-integral
L	characteristic length
n	power-law creep stress exponent
p	internal pressure
Q	constraint parameter under elastic–plastic condition
Q^*	parameter for correlating creep crack growth rate
r	distance from a crack tip
R	creep constraint parameter
R_i	inner radius
R^*	load-independent creep constraint parameter
R_1^*	R^* value at the deepest point along crack front
R_{avg}^*	average value of R^* along crack front
T	T-stress constraint parameter
t	creep time/pipe thickness
t_{red}	creep redistribution time
W	specimen width
$\dot{\varepsilon}$	creep strain rate
$\dot{\varepsilon}_0$	creep strain rate at normalizing stress
θ	polar coordinate at the crack tip
σ_0	normalizing stress
σ_φ	axial tension stress
σ_{22}	opening stress
$\sigma_{22,\mathrm{CT}}$	opening stress of CT specimen under plane strain
$\Delta\sigma$	opening stress difference
υ	Poisson's ratio
Φ	angular parameter characterizing crack front position

Abbreviations

3-D	three-dimensional
CCG	creep crack growth
C(T)	compact tension
FEM	finite element method
M(T)	middle tension
PE	plane strain

In the standards for measuring creep crack growth rate of materials, the C(T) specimen with deep crack ($a/W = 0.5$) in plane strain is usually recommended [23], in order to ensure that the crack tip has relatively high constraint so as to get conservative creep crack growth rate data. However, the defects formed in manufacturing process and service for pressure pipelines and vessels usually have smaller sizes, such as surface corrosion cracks, internal and surface cracks initiated by nonmetallic inclusions, welding cracks. These cracks often have lower crack-tip constraint. Therefore, the uses of the fracture tests and calculations based on the deep crack C(T) specimens with high constraint in design or life assessment for most practical situations are unduly conservative and overly pessimistic [6,24]. This excessive pessimism caused by the constraint effects in defect assessments can lead to unnecessary repairs or replacement of in-service pipelines at great operational costs [25].