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Fracture assessment based on unified constraint parameter for pressurized pipes with circumferential surface cracks

M.Y. Mu, G.Z. Wang *, F.Z. Xuan, S.T. Tu

Key Laboratory of Pressure Systems and Safety, Ministry of Education, East China University of Science and Technology, Shanghai 200237, China

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ABSTRACT

The fracture assessment capability and methodology based on the unified constraint parameter A_p have been comparably investigated with the conventional procedures without considering constraint effect and the assessment approach based on the constraint parameter Q for pressurized pipes with circumferential surface cracks. The results show that the A_p can be used in failure assessment diagram based fracture assessment by modifying the fracture toughness using the unified correlation formulae of fracture toughness with A_p. A fracture assessment methodology based on the parameter A_p for incorporating both in-plane and out-of-plane constraints has been proposed. The constraint characterization and fracture assessment using the parameter A_p for the pipe cracks may get the best accuracy and can reduce excessive conservatism of the conventional assessments. The benefits from the unified constraint assessments increase with decreasing crack depth and length.

1. Introduction

Defects occurring at fabrication or service stage in engineering structures might be responsible for structural failure. The structural significance of such imperfections, particularly crack-like flaws need to be assessed to prevent failure of the component during service [1]. The fracture criterion based on conventional fracture mechanics assumes that the structural component exhibits the same fracture resistance, K_c, δ_c or J_c, at the onset of unstable fracture as the laboratory fracture toughness specimen [2]. However, defects in large engineering structures (such as pressurized pipes and vessels) are often subjected to a significantly lower level of crack tip constraint than those in laboratory fracture specimens [3]. This ensures that the fracture assessment in low constraint structural components using conventional fracture mechanics methodologies may be excessively conservative. This conservative assessment may lead to unnecessary replacement or repairs of in-service components at great operational cost. Therefore, the constraint effect needs to be considered in fracture assessment for structural components.

Constraint can be regarded as the resistance of a structure against crack-tip plastic deformation [4]. The constraint contains in-plane and out-of-plane constraints. The in-plane constraint is directly affected by the specimen dimension in the direction of growing crack, that is, the length of the un-cracked ligament, while the out-of-plane constraint is affected by the specimen dimension parallel to crack front, that is, the specimen thickness. The quantification of constraint has been studied for a long time, and different constraint parameters have been put forward in the last few decades, such as

* Corresponding author.
E-mail address: gzwang@ecust.edu.cn (G.Z. Wang).

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Nomenclature

a	crack depth
A_2	parameter quantifying second and third term of stress relative to the first term in a cracked elastic-plastic body
A_{PEEQ}	area surrounded by equivalent plastic strain isoline
A_p	a unified characterization parameter of in-plane and out-of-plane constraint
A_{ref}	area surrounded by equivalent plastic strain isoline at fracture measured in a standard test
c	half-crack length
E	the elastic modulus
h	stress triaxiality factor
J	elastic-plastic J- integral
J_{IC}	fracture toughness
J_e	elastic J-integral
J_{ref}	fracture toughness measured in a standard test
K_{I}	elastic stress intensity factor
K_c	fracture toughness characterized by stress intensity factor K
K_{Jc}	fracture toughness calculated from J_{IC}
K_{mat}	material's fracture toughness
K_{mat}^c	modified fracture toughness by constraint
K_P	plastic stress intensity factor
K_r	normalized crack-tip loading
K_{ref}	fracture toughness measured in a standard test
L_r	normalized applied loading
$L_{r(\max)}$	maximum value of L_r
M	bending moment
M_f	fracture moment
M_f^0	fracture moment predicted by conventional assessment
M_f^c	fracture moment predicted by constraint assessment
M_L	limit bending moment
p	internal pressure
P	applied load
P_L	plastic limit load
Q	a constraint parameter under elastic-plastic condition
Q^{BLA}	constraint parameter with reference field of boundary layer analysis
R_i	inside radius
R_o	outside radius
t	pipe wall thickness
T	non-singular term of stress (T-stress for elastic condition)
T_z	factor of the stress-state in 3D cracked body
W	specimen width
ε	strain
ε_p	equivalent plastic strain
σ	stress
σ_0	yield stress
σ_b	ultimate tensile stress
σ_f	flow stress
$\sigma_{\theta\theta}$	opening stress
$(\sigma_{\theta\theta})_{BLA}$	reference opening stress based on boundary layer analysis
σ_φ	axial stress
υ	Poisson's ratio
α	a parameter defining constraint sensitivity of material
k	another parameter defining constraint sensitivity of material
β	a factor defined as $\beta L_r = T/\sigma_0$ or $\beta L_r = Q$
λ	conservatism factor

Acronyms

API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BLA	boundary layer analysis

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