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In-plane and out-of-plane constraint effects under pressurized thermal shocks

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ABSTRACT

Transferability of fracture toughness data obtained on small scale specimens to a full-scale cracked structure is one of the key issues in integrity assessment of engineering structures. In order to transfer fracture toughness under different constraints, both in-plane and out-of-plane constraint effect should be considered for the specimens and structures. In this paper both in-plane and out-of-plane constraint effects of a crack in a reference reactor pressure vessel (RPV) subjected to pressurized thermal shocks (PTSs) are analyzed by two-parameter and three-parameter methods. The comparison between elastic and elastic–plastic analysis shows that the constraint effect varies with the material property. T_{11} (the second term of William's extension acting parallel to the crack plane) generally displays a reversed relation to the stress intensity factor (SIF) with the transient time, which indicates that the loading (SIF) plays an important role on the in-plane constraint effect. The thickness at the crack tip contributes more than the loading to the out-of-plane constraint, such that T_{33} (the second term of William's extension acting along the thickness) displays a similar relation to ε_{33} (strain along the thickness direction) and a different relation to T_{11} during the transient. The results demonstrate that both in-plane and out-of-plane constraint effect should be analyzed separately in order to describe precisely the stress distribution ahead of the crack tip.

1. Introduction

Transferability of fracture toughness data obtained on small scale specimens to a full-scale cracked structure is one of the key issues in integrity assessment of engineering structures. Since it is found that the measured fracture toughness varies with the geometry of the component, standard procedures are defined in such a way that a lower bound value for the toughness is measured. The reason that geometry size of the tested specimens affects fracture toughness is attributed to different stress and strain fields ahead of the crack tip. The character of the stress fields near the crack front has been extensively studied. The classical linear elastic and elastic–plastic fracture mechanics were based on the theory of the first singular term of the asymptotic expression, which is the stress intensity factor (SIF, K) (Irwin, 1958) and HRR solution (Hutchinson, 1968; Rice and Rosengren, 1968), respectively. Traditional fracture mechanics approaches assumed that the near-tip stress–strain state is controlled by a single parameter such as the linear elastic SIF K, and the J-integral (or, equivalently, the crack tip opening displacement). According to this methodology, fracture toughness values, obtained from standard tests on deep-cracked specimens, can be quantified by the critical values of one of those parameters under plane strain conditions (e.g. K_{Ic}, J_{Ic}) and then applied in assessment of fracture behavior and bearing capacity of a real structure. However, it is known that the critical crack driving force for fracture depends on the triaxiality level of the near-tip stress fields. For a given crack driving force parameter (e.g. J-integral), higher triaxiality and, consequently, higher principal stresses promote cleavage fracture (high constraint condition). On the other hand, lower triaxiality leads to a decrease of opening mode stresses and the development of plastic deformations in the vicinity of the crack tip, which enhances resistance to cleavage initiation (low constraint condition).

In order to consider the stress triaxiality of the crack tip, more accurate two-parameter approaches, such as K–T (Williams, 1957), J–T (Betegon and Hancock, 1991), J–Q (O'Dowd and Shih, 1991, 1992) and J–A_2 (Li and Wang, 1986; Chao et al., 1994), have been developed. These approaches have been applied successfully in engineering designs though they are limited to describe the effect of the in-plane constraint on the crack-tip field and fracture toughness. For linear elastic analysis, different cracked structures have different T-stress (denoted as T_{11}) for a given mode I SIF depending on their geometry and the loading applied to them. A negative T-stress indicates a loss of constraint where relatively more plasticity occurs and a positive T-stress indicates a highly constrained condition with limited plasticity preceding fracture (Williams, 1957). In elastic–plastic fracture mechanics, the Q-stress (O'Dowd and Shih, 1991, 1992) is commonly used as the measure of in-plane constraint. The Q-stress is the difference

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Nomenclature

a	crack depth, mm
A_2	second term used to quantify constraint effect
B	biaxiality ratio
$2c$	crack length, mm
E	elastic modulus, MPa
$f_{ij}(\theta)$	angular functions of crack-tip stress field
h	ratio of hydrostatic stress to Von Mises stress
$h(t_i)$	time-dependent heat transfer coefficient, kW/(m^2 K)
J	J-integral, MPa·m
K, K_I	Mode I linear elastic stress intensity factor, MPa $m^{0.5}$
K_{IC}	material fracture toughness, MPa $m^{0.5}$
n	strain hardening exponent
n_j	direction perpendicular to plane of crack
P	cumulative probability level
$p(t_i)$	time dependent pressure, MPa
Q	Q-stress
r	radial coordinate in the polar system
R	radius of the model used in modified boundary layer formulation, mm
R, θ, Z	cylindrical coordinate system
R_i	RPV radius, mm
t	vessel wall thickness, mm
t_c	cladding thickness, mm
t_b	base thickness, mm
t_i	transient time, second
T-stress, T_{11}	second term of William's extension along x direction, MPa
T_{33}	second term of William's extension along z direction, MPa
T_z	ratio of σ_{zz} over ($\sigma_{xx} + \sigma_{yy}$)
T_t	temperature, °C
T_0	reference temperature in master curve method, °C
$T_{0\text{deep}}$	reference temperature obtained from deeply cracked (high constraint) bars, °C
T_{ref}	reference temperature for thermal expansion coefficient, °C
$T_{\text{tem}}(t_i)$	time dependent temperature, °C
$T_{\text{tem}}(\text{initial})$	initial temperature of the vessel wall, °C
$u(R, \theta)$	displacement in x direction
$\upsilon(R, \theta)$	displacement in y direction
W	specimen width, mm
ν	Poisson's ratio
α	material coefficient in Ramberg–Osgood relationship
σ_0	yield stress, MPa
σ_1, σ_2, σ_3	principal stress at different directions, MPa
σ_e	Von Mises stress, MPa
σ_h	average of principal stress, MPa
σ_{ij}	stress at crack tip region, MPa
$(\sigma_{\theta\theta})_{FEA}$	hoop stress from finite element analysis, MPa
σ_{xx}, σ_{yy}, σ_{zz}	stress along different directions, MPa
$(\sigma_{\theta\theta})_{\text{SSY};T=0}$	hoop stress for SSY and zero T-stress, MPa
ε_0	yield strain
ε	strain
ε_{33}	strain in direction 33
θ	angular coordinate in the polar system
Φ	angle of elliptical crack
δ_{ij}	Kronecker delta
EPFM	elastic plastic fracture mechanics
FE	finite element
FPB	five-point bend
HRR	Hutchinson Rice Rosenberg
LLOCA	large loss-of-coolant accident
MBL	modified boundary layer
MLOCA	medium loss-of-coolant accident
PTS	pressurized thermal shock
RPV	reactor pressure vessel
SEN(B)	single edge notch bend
SIF	stress intensity factor
SLOCA	small loss-of-coolant accident
SSY	small scale yielding
WPS	warm prestressing

between the opening stress ahead of the crack tip obtained for example from finite element (FE) analysis and the opening stress calculated by the Hutchinson Rice Rosenberg (HRR) formula for the same value of the J-integral. Absolute high values of the Q-stress imply that higher-order terms of stress cannot be neglected and may be considered as a measure of constraint. The idea of using higher-order terms of the stress distribution was also used by Li and Wang (1986) and Chao et al. (1994). Through a combined numerical and analytical process, they showed that both the second and third terms of the asymptotic stress distribution in an elastic–plastic cracked body can be related to the first term by using a parameter called A_2. In addition, generating fracture toughness vs. T_{11}, Q or A_2 curves is a common approach to include constraint effects in structural integrity procedures (e.g. the R6 code, FITNET FFS procedure).

However, these parameters are only able to characterize the in-plane constraint at the crack tip. Moreover, a relative small reduction in the specimen thickness leads to a significant increase of the apparent fracture toughness without the T_{11} or Q-stress being significantly affected (Meshii and Tanaka, 2010). As a consequence, the use of the T_{11}, Q-stress or A_2 as a reference parameter is insufficient to explain the out-of-plane constraint effect. In fact, fracture toughness depends on the 3D out-of-plane stress level near the crack front as well. It is well known that fracture toughness depends highly on the thickness of the test specimen until a threshold thickness, beyond which the toughness does not decrease further. The toughness at this thickness is called plane strain fracture toughness. It is less than the fracture toughness of thinner plates and is a material property (ASTM-E399). So the application of fracture toughness is inconvenient in the engineering applications if the 3D out-of-plane stress level is not considered accurately. A schematic illustration of the in-plane and out-of-plane constraint for a 3D body subjected to tension loading is shown in Fig. 1.

In order to study the out-of-plane constraint effect on the structures, Brocks et al. (1989) proposed a parameter h, which is defined as the ratio of hydrostatic stress to the Von Mises stress. This parameter has been widely used for the stress triaxiality analysis. However, the in-plane and out-of-plane constraint effect has not been strictly separated in the parameter. Guo (1993), Zhao et al. (2007) and Zhang and Guo (2007) developed another parameter T_z for the analysis of out-of-plane constraint and the effect of T_z on 3D crack-front fields and fracture toughness were systematically studied. For elastic plane strain T_z equals to the Poisson's ratio ν and for elastic plane stress is equal to zero. However, conditions may occur in which T_z can be larger than ν or less than zero. Variations of this parameter have a pronounced effect on the size of the plastic zone ahead of the crack and on the near crack tip stress distribution. In the framework of the T_z model, the approaches of K–T_z, J–T_z, K–T–T_z and J–Q–T_z for 3D constraint analysis have been proposed and their applications to fracture and fatigue have been demonstrated. In addition, in-plane and out-of-plane constraints