Available online at www.sciencedirect.com
ScienceDirect
International Journal of Pressure Vessels and Piping 85 (2008) 459–467
International Journal of Pressure Vessels and Piping
www.elsevier.com/locate/ijpvp

A numerical creep analysis on the interaction of twin semi-elliptical cracks

Jun Si, Fu-Zhen Xuan*, Shan-Tong Tu

School of Mechanical Engineering, East China University of Science and Technology, 130, Meilong Street, PO Box 402, Shanghai 200237, PR China

Received 23 May 2007; received in revised form 19 January 2008; accepted 19 February 2008

Abstract

The interaction and coalescence of multiple flaws will significantly influence the service life of components. In this paper, the interaction of two identical semi-elliptical cracks in a finite thickness plate subjected to the remote tension is investigated. The results indicated that interaction of multiple cracks is different between the time-dependent fracture characterized by C^*-integral and linear elastic fracture noted by SIF. The magnifying factors of creep fracture are obviously larger than that of the linear elastic fracture cases. Therefore, the current interaction and coalescence rule developed from linear elastic fracture analysis may lead to a non-conservative result when it is used in the assessment of creep crack. At the end, an empirical equation is developed based on the numerical results.

Keywords: Creep crack growth; Surface flaw; C^* integral; Finite element analysis

1. Introduction

Many high-temperature structures and components contain more than one crack-like defects and flaws. The interaction and coalescence of these cracks or flaws are therefore ineluctable during the evolution of crack and component failure. A good understanding of the behavior of crack interaction and coalescence will provide engineers with the quantitative tools to assess the structural integrity of high-temperature components [1].

Assessment of the structural integrity of components containing defects can be made using different fracture mechanics parameters corresponding to different fracture mechanisms. The stress intensity factor (SIF) is applicable for the linear elastic range. In the elastic–plastic case, the fracture parameter J-integral should be employed to accommodate the influence of plastic deformation. In the presence of creep at high temperature, however, rate-dependent parameter of C^*-integral [2,3] is developed to correlate the data of creep crack growth (CCG) and creep crack initiation (CCI). In addition, results indicate that C^*-integral is the most appropriate one among the existing fracture parameters for the interpretation of CCG and CCI.

The interaction behavior of structural components with multiple semi-elliptic surface cracks under linear-elastic and elastic–plastic fracture mechanics regime has been widely studied [4–9], and some useful recommendations [10–12] have been proposed and applied for the integrity assessment of structures with multiple cracks. However, for the structure operated under creep regime, most of studies are focused on the creep analysis of single semi-elliptical surface crack [13–15], and very little attention has been paid on the interaction of multiple semi-elliptical surface cracks.

In this study, a finite thickness plate containing two semi-elliptical surface cracks under a remote tension is considered, as shown in Fig. 1. The two coplanar surface cracks are assumed to be the same shape and size. The creep fracture parameter C^*-integral involving wide ranges of crack configurations and material constants, i.e., $0.2 \leqslant a/t \leqslant 0.8$, $0.2 \leqslant a/c \leqslant 0.8$, $0.2 \leqslant c/d \leqslant 0.8$, $0 \leqslant 2\phi/\pi \leqslant 2$,

*Corresponding author. Tel.: +86 21 64253513; fax: +86 21 64253425.
E-mail address: fzxuan@ecust.edu.cn (F.-Z. Xuan).

0308-0161/$ - see front matter
doi:10.1016/j.ijpvp.2008.02.001

Nomenclature

a	crack depth
A	area enclosed by the contour
B, n	material constants in the elastic-secondary creep constitutive relation
c	half-width of semi-elliptic surface crack
C^*	time-dependent fracture parameter
C^*_{Normal}	a normalization of C^* parameter
C^*_{Single}	time-dependent fracture parameter without the interaction influence
C^*_{Double}	time-dependent fracture parameter including the interaction influence
d	distance between two cracks
E	Young's modulus
H	length of plate
J	elastic–plastic fracture parameter
K_0	normalized stress intensity factor
K	stress intensity factor
M_{Creep}	interaction factor, seen in Eq. (4)
M_{L}	dimensionless factor, seen in Eq. (10)
P_{L}	plastic limit load
$P_{\mathrm{L}}^{\mathrm{Double}}$	plastic limit load referring to two cracks
$P_{\mathrm{L}}^{\mathrm{Single}}$	plastic limit load corresponding to one crack
Q	parameter of crack geometry
t	thickness of plate
u	displacement
W	width of plate
W^*	strain energy density, seen in Eq. (3)
Γ	integral path
γ_{SIF}	interaction factor under linear elastic fracture
γ_{Creep}	interaction factor, seen in Eq. (9)
$\varepsilon, \dot{\varepsilon}$	strain, strain rate
$\varepsilon_{\mathrm{ref}}, \dot{\varepsilon}^{\mathrm{c}}_{\mathrm{ref}}$	reference strain, creep strain rate at the reference stress
ϕ	angular parameter defining the crack front position
ν	Poisson's ratio
$\sigma, \dot{\sigma}$	stress, stress rate
σ_{ref}	reference stress
σ_{Y}	yield stress of the material
$\sigma_{\mathrm{ref}}^{\mathrm{Double}}$	reference stress referring to two cracks
$\sigma_{\mathrm{ref}}^{\mathrm{Single}}$	reference stress corresponding to one crack

Abbreviations

CCG	creep crack growth
CCI	creep crack initiation
FE	finite element
SIF	stress intensity factor

is calculated by using the finite element (FE) method. Here, a/t is the crack depth aspect ratio, a/c is the crack shape aspect ratio, c/d is the relative distance of two cracks, and $2\phi/\pi$ is the normalized location of the semi-elliptical surface crack front. Based on the calculated results, finally, an empirical expression of the interaction factor is proposed as a function of the crack configurations and material creep exponent.

2. Creep fracture parameter

In the current study, mechanical properties of low alloy Cr–Mo steel [16] are used, which can be described by the elastic-secondary creep constitutive relation

$$\dot{\varepsilon} = \dot{\sigma}/E + B\sigma^n \tag{1}$$

where $\dot{\varepsilon}$ denotes the uniaxial strain rate, $\dot{\sigma}$ is the uniaxial stress rate, E is Young's modulus, and B and n are the steady-state creep coefficient and exponent, respectively. This constitutive relationship has been widely used in the creep deformation analysis. The material constants employed in FE analysis are listed in Table 1.

For three-dimensional (3D) crack situations, Kikuchi and Miyamoto [17] have defined the J-integral in terms of x component

$$J = \int_{\Gamma} (W^* \mathrm{d}y - \sigma_{ij} u_{i,x} \mathrm{d}s) - \int_{A} (\sigma_{iz} u_{i,x})_{,x}\, \mathrm{d}A \tag{2}$$

here W^* is the strain energy density defined by

$$W^*(\varepsilon_{ij}) = \int_0^{\varepsilon_{ij}} \sigma_{ij}\, \mathrm{d}\varepsilon_{ij} \tag{3}$$

The contour, Γ, is contained in the xy plane normal to the z direction, A is the area enclosed by the contour Γ, and u is the displacement.

According to the analogy between J and C^* integral, expression of the C^*-integral for 3D crack is thus obtained through replacing displacement and strain by displacement rate and strain rate in Eqs. (2) and (3).

3. FE analysis

The FE code ABAQUS [18] was used in this analysis. In order to evaluate the interaction effect of multiple cracks, a number of FE computations were carried out for a plate with one semi-elliptical surface crack or two identical semi-elliptical surface cracks. The size of plate considered herein was $H/W = 2$, $W/c = 10$. To reduce the workload in construction of FE model, H, W, c was fixed. The depth of crack, a, and the thickness of the plate, t, varied with the ratio a/c and a/t. All the calculations in this study were subjected to a remote tension with the same value.

The 3D 20-noded brick elements were adopted. Due to the symmetry, only a quarter of the plate was modeled with 10,000–35,000 elements in general. The total meshes varied in the different models, but the crack tip was modeled using