Engineering Fracture Mechanics 134 (2015) 459–473

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Does the cyclic J-integral ΔJ describe the crack-tip opening displacement in the presence of crack closure?

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ARTICLE INFO

Article history:
Received 2 June 2013
Received in revised form 2 May 2014
Accepted 18 July 2014
Available online 1 August 2014

Keywords:
J-integral
Cyclic J
Fatigue crack growth
Crack closure
Finite-element analysis

ABSTRACT

In this paper, the correlation of the cyclic J-integral, ΔJ, and the cyclic crack-tip opening displacement, $\Delta CTOD$, is studied in the presence of crack closure to assess the question if ΔJ describes the crack-tip opening displacement in this case. To this end, a method is developed to evaluate ΔJ numerically within finite-element calculations. The method is validated for an elastic–plastic material that exhibits Masing behavior. Different strain ranges and strain ratios are considered under fully plastic cyclic conditions including crack closure. It is shown that the cyclic J-integral is the parameter to determine the cyclic crack-tip opening displacement even in cases where crack closure is present.
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1. Introduction

Within the concept of linear-elastic fracture mechanics the range of the stress intensity factor $\Delta K = K_{max} - K_{min}$ is used to describe fatigue crack growth in structures (K_{max} and K_{min} are the maximal and minimal stress intensity factor in the loading cycle). To this end, ΔK is related to the crack advance per loading cycle da/dN, e.g. by using Paris' law $da/dN = C\Delta K^m$ with the material properties C and m. Mean stress effects on the crack growth rate due to crack closure are typically included by replacing ΔK in the crack growth law with an effective range of the stress intensity factor $\Delta K_{eff} = K_{max} - K_{op}$. K_{op} is the stress intensity factor at which the crack opens.

The concept of linear-elastic fracture mechanics, however, only applies as long as the plastic zone at the crack-tip is sufficiently small. Especially highly loaded components in e.g. turbines and combustion engines operate in the low-cycle fatigue (LCF) regime, where stresses also in the far-field of a crack may exceed the yield stress. Thus, large-scale plastic deformations arise in the components and concepts of elastic–plastic fracture mechanics must be applied.

For elastic–plastic materials, the J-integral introduced by Rice [1] describes the stress and strain fields at the crack-tip. In a two dimensional deformation field the J-integral is

$$J = \int_\Gamma \left(W dx_2 - \sigma_{ij} n_j \frac{\partial u_i}{\partial x_1} \right) ds. \tag{1}$$

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http://dx.doi.org/10.1016/j.engfracmech.2014.07.017
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Nomenclature

a	crack size in mm
C	material parameter of Paris' law in $\sqrt{\text{mm}}$/MPa
$C10, \ldots, C31$	contours for evaluation of J, δJ
$C_1^{\text{kin}}, \ldots, C_5^{\text{kin}}$	material parameter of kinematic hardening model in MPa
$CTOD$	crack-tip opening displacement in mm
$\delta CTOD$	crack-tip opening displacement between PLR_0 and PLR_1 in mm
$\delta CTOD^*$	corrected crack-tip opening displacement between PLR_0 and PLR_1 in mm
$\delta CTOD_{\text{init}}$	initial crack-tip opening displacement in mm
$\Delta CTOD$	crack-tip opening displacement at PLR_1 in mm
da/dN	crack advance per cycle in mm/cycle
ds	increment of arc length in mm
E	Young's modulus in MPa
I_{n}	constant
J	J-integral in MPa mm
δJ	cyclic J-integral between PLR_0 and PLR_1 in MPa mm
ΔJ, Z	cyclic J-integral at PLR_1 in MPa mm
K	stress intensity factor in MPa $\sqrt{\text{mm}}$
K_{op}	stress intensity factor at crack opening in MPa $\sqrt{\text{mm}}$
ΔK	cyclic stress intensity factor in MPa $\sqrt{\text{mm}}$
m	material parameter of Paris' law
n_{j}	outward normal vector
n'	Ramberg–Osgood hardening exponent
R_{ϵ}	strain ratio
r_{dist}	distance from crack-tip in mm
t	steptime
$\tilde{u}_{\text{y}}$	trigonometric function
u_{i}	displacement vector in mm
δu_{i}	displacement vector between PLR_0 and PLR_1 in mm
W	strain energy density in MPa
δW	strain energy density between PLR_0 and PLR_1 in MPa
ΔW	strain energy density at PLR_1 in MPa
x_i	coordinates
$\gamma_1, \ldots, \gamma_5$	material parameter of kinematic hardening model
Γ	arbitrary path surrounding the crack-tip
ϵ_{22}	strain tensor component
ϵ_{ij}	strain tensor
$\delta\epsilon_{\text{ij}}$	strain range tensor between PLR_0 and PLR_1
$\Delta\epsilon$	uniaxial cyclic strain range
$\Delta\epsilon_{\text{ij}}$	strain range tensor at PLR_1
θ	angle
σ_{22}	stress tensor component
σ_{Y}	yield stress in MPa
σ_{CY}	cyclic yield stress in MPa
σ_{ij}	stress tensor in MPa
$\delta\sigma_{\text{ij}}$	cyclic stress tensor between PLR_0 and PLR_1 in MPa
$\Delta\sigma$	uniaxial cyclic stress range in MPa
$\Delta\sigma_{\text{ij}}$	cyclic stress range tensor at PLR_1 in MPa
ν	Poisson's ratio
1st	indicates first calculation
2nd	indicates second calculation
eff	specifies the value that evolves with the onset of crack opening
max	maximum value
min	minimum value
HRR	Hutchinson, Rice, Rosengren singular crack-tip fields
LCF	low cycle fatigue
PLR_0	point of load reversal at minimal load
PLR_1	point of load reversal at maximal load

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