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Approximation of the crack driving force for cracks at notches under static and cyclic loading

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Abstract

The work deals with the efficient calculation of the elastic-plastic crack driving force (J-integral for monotonic loading and ΔJ-integral under cyclic loading) for short cracks at notches as essential parameter for the reliable static and fatigue assessment of notched structures. The J- or ΔJ-integral is calculated based on analytical solutions for stress intensity factors, estimated by means of well-known weight function solutions in the case of cracks under power-law stress distributions. A plasticity-correction function is applied to the stress intensity factors to obtain the final expression of the crack driving force. The comparison between analytical solutions and finite element calculations in case of cracks at the weld toe in welded joints shows good agreement.

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Keywords: Structural integrity; fracture mechanics; crack driving force; notches

1. Introduction

The most widely spread standards and guidelines for the structural assessment of structures containing cracks, such as EPRI, R6, BS7910 or SINTAP/FITNET, rely on the so-called EPRI estimation scheme (Kumar et al., 1981) or on the reference stress method introduced by Ainsworth (1984) for the evaluation of the crack driving force, see

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Nomenclature

a	crack depth
C_i	material parameter in the Chaboche model
ds	infinitesimal arc length along the integration path Γ
E	elastic modulus
k_t	elastic stress concentration factor
K	stress intensity factor for mode I
K'	parameter in the Ramberg-Osgood equation
$f(L_r)$	plasticity correction function
J	J-integral
L_r	ligament yielding parameter
$m(\xi, a)$	weight function
M_{ij}	coefficients in the expressions of the weight functions
n'	exponent in the Ramberg-Osgood equation
n_j	normal outward vectors
R	stress ratio
T_i	components of the traction vector
u_i	components of the displacement vector
W	strain energy density
ΔJ	cyclic J-integral
ΔW	cyclic counterpart of the strain energy density
ε_{ij}	components of the strain tensor
ε_p	equivalent plastic strain
γ_i	material parameter in the Chaboche model
Γ	integration contour
$\sigma(\xi)$	through-thickness stress distribution
σ_{app}	applied remote stress
σ_{ij}	components of the stress tensor
σ_y	yield stress
σ_0	reference yield stress
ξ	in-depth local coordinate at the notch
χ	stress gradient at the notch

Zerbst et al. (2000, 2007). Note that the reference stress method, compared to EPRI, has a wider application range in that it is not restricted to configurations for which the finite element based h-functions are available. In the present context, it is important that it is not restricted to semi-circular surface cracks, but also allows the analysis of semi-elliptical cracks.

Approximate formulas are also used in fracture mechanics-based methods for the estimation of the fatigue life of components, but with a substantial difference: In monotonic fracture assessment procedures, elastic-plastic fracture mechanics is applied to allow for ductile tearing and plastic collapse, whereas in fatigue assessment most of the calculation schemes apply simplified approaches, which are based on linear-elastic fracture mechanics. Nevertheless, it is well-known that the small-scale yielding condition is not always applicable even in fatigue, for instance in case of the propagation of mechanically/physically short cracks, for which the extension of the plastic region is in the same order of magnitude as the crack length. A further important application of this kind is given by cracks growing at notches. Note, however, that proposals for elastic-plastic fatigue crack growth evaluation are available in the literature, see McClung et al. (1999).

The work presents a simplified calculation scheme based on the reference stress method, according to which the crack driving force for short cracks at notches can be calculated for both static and cyclic loading. Analytical solutions have been generated for different cracks at the weld toe of various welded joints and compared to finite element