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Numerical analysis of residual stresses and crack closure during cyclic loading of a longitudinal gusset

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ABSTRACT

The fatigue strength of welded joints is determined by crack initiation and propagation, the latter forming in several cases the major part of the fatigue life. Failure is usually assumed when the fatigue crack has penetrated the adjacent plate or as specimen fracture in case of fatigue tests. Crack propagation is influenced by crack closure effects, slowing down crack propagation mainly in case of load cycles partly in compression. However, it is well-known that tensile residual stresses occurring particularly in welded joints can decrease crack closure and lead to fatigue behaviour independent of the applied stress ratio, i. e. mean stress. This has been observed for example with welded longitudinal gussets. On the other hand, recent measurements have shown that tensile residual stresses at the weld toe are smaller than further away and that they are relaxed or even become compressive after the first load cycle. Insofar, the role of residual stresses is still unclear. For this reason, numerical investigations have been performed in addition to fatigue tests to clarify the matter further. After describing a numerical model to investigate the crack closure behaviour by the example of a center crack in a plate originally studied by Newman, the crack closure behaviour of a semi-elliptical crack in front of a longitudinal steel gusset is analysed for depths between 5 and 50% of the plate thickness. In addition to the stress-relieved state, also welding-induced residual stresses were generated with a simplified model, calibrated by measurements, and used for the analysis of crack closure. It is shown that the residual stresses strongly affect the crack closure although these are compressive at the weld toe after the first load cycle. The simulations are performed for different load levels and stress ratios.

1. Introduction

The significance of crack closure on fatigue during cyclic loading has been found by Elber almost 50 years ago [1,2]. He observed that a fatigue crack is not only closed during compressive loading, but that it already closes before crossing the zero load, i. e. under a certain tensile load. He postulated that the stress range contributes to the crack propagation only during the time when the crack is open, because the strain does not vary significantly at the crack tip when the crack is closed. This is illustrated in Fig. 1 by the fluctuation of the stress intensity factor K_I at the crack tip, showing the instance $K_{I,op}$, when

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Nomenclature

a	crack depth
a/c	crack aspect ratio
c	half crack length at surface (semi-elliptical crack)
E	Young's modulus
K_I	stress intensity factor for crack opening mode I
$K_{I,min}$	minimum stress intensity factor in a load cycle
$K_{I,max}$	maximum stress intensity factor in a load cycle
$K_{I,op}$	stress intensity factor when crack opens
K'	material parameter in the Ramberg-Osgood equation
n'	material parameter in the Ramberg-Osgood equation
R	stress ratio (=$K_{\mathrm{min}}/K_{\mathrm{max}}$)
r_p	size (diameter) of the plastic zone
t	plate thickness
u_x, u_y, u_z	displacement in x-, y- and z-direction respectively
U	crack closure factor
Δa	crack extension
ΔK_I	range of the stress intensity factor for crack opening mode I
$\Delta K_{I,eff}$	effective part of the range of the stress intensity factor
Δu	relative displacement
ε_a	strain amplitude
σ	stress
σ_a	stress amplitude
R_{eH}	yield stress
μ	Poisson's ratio
α	constraint factor
α_{toe}	angular position along the weld toe

Abbreviations

CMOD	crack mouth opening displacement
FEM	finite element method
IBESS	Integrale Bruchmechanische Ermittlung der Schwingfestigkeit von Schweiβverbindungen, Title of the German cluster project = Integral method for fracture mechanics determination of the fatigue strength of welded joints

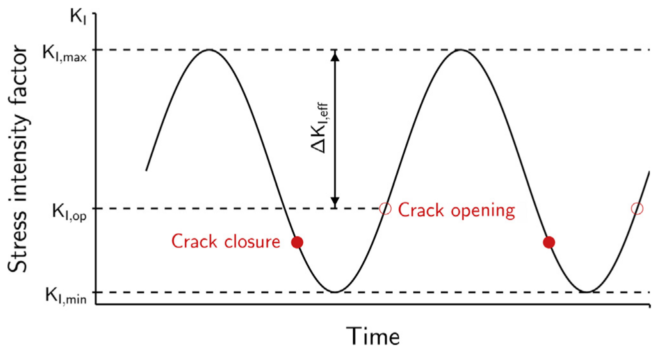

Fig. 1. Effective part of the range of the stress intensity factor due to crack closure.

the crack opens, being well above the minimum stress intensity factor $K_{I,min}$. Elber introduced the effective stress intensity factor

$$\Delta K_{I,eff} = K_{I,max} - K_{I,op} \quad (1)$$

for application in crack propagation analyses. Also the ratio U between the effective and the total stress intensity factor has been introduced as crack closure factor: