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Fatigue strength and life determination of weldments based on fracture mechanics

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Abstract

The paper provides an overview on the results of a German cluster project on the use of fracture mechanics to the determination of the fatigue strength of weldments with fatigue cracks originating at the weld toes. The approach includes (a) a concept for short crack propagation for which the common ΔK concept is not applicable and the crack closure effects are still being gradually build-up, (b) a method for determining fatigue life relevant initial crack sizes as they are needed in any fracture mechanics analysis and (c) multiple cracking and crack coalescence at load levels higher than the endurance limit. The analyses are stochastically performed. Both, the endurance limit and the finite life branch of the S-N curve are determined.

Besides a brief introduction into the approach, validation examples are presented. These comprise different weldment types (butt welds, cross joints and longitudinal stiffened plates), two steels (S355NL and S960QL) of quite different strengths, different weld geometries due to different welding techniques (WIG, MAG), as-welded and stress relieved welds and different stress ratios varying from $R = -1$ to $R = 0.5$.

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Keywords: Weldments; fatigue strength, fracture mechanics; initial crack size; short crack propagation; multiple crack propagation

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Introduction

The idea to apply fracture mechanics to the fatigue strength and life of weldments is anything but new. Almost half a century ago Maddox (1970) was one of the first to mention it. In 1974 he wrote: “It is now widely recognized that flaws will inevitably exist in welded structures and the old idea of removing all detectable defects must be replaced by the 'fitness for purpose' design philosophy. This makes it necessary to define reliable methods of assessing the significance of flaws, particularly in the context of fatigue, ….

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The most promising approach to this problem lies in the use of the fracture mechanics based description of fatigue crack propagation." (Maddox, 1974). Since then, many studies have been performed on the issue. There is not enough space here for a detailed discussion of the existing material. What, however, should be pointed out is that even the IIW Recommendations for fatigue assessment of weldments (Hobbacher, 2016) includes fracture mechanics as an option, see also the textbook of Radaj et al. (2006).

With view exceptions, which will be mentioned below, the schemes of the existing approaches for fracture mechanics-based determination of the fatigue strength of weldments are characterized by the following features: (i) the crack driving force is described by the linear elastic ΔK factor, (ii) the initial crack size is assumed as a fixed value originally fitted to or based on back-calculations from S-N data also using the ΔK concept, (iii) the crack closure phenomenon is neglected, (iv) only one crack is considered for which the residual lifetime is obtained, (v) variations in the local geometry of the highly stressed regions in the weldments, e.g. the weld toes, are not taken into account, and (vi) welding residual stresses are not or in a very simplified way taken into account. Any of these assumptions are oversimplifications or at least disputable.

In the German project cluster IBESS (which stands for the German abbreviations for "Integral method for fracture mechanics based determination of the fatigue strength of weldments") eight partners were involved. The aim was to develop a concept taking into account all the points mentioned above and to avoid the shortcomings as far as possible. The cluster was funded by DFG and AiF. For reasons of space, no exhaustive discussion of all aspects is possible here. Instead the reader is referred to a special issue of the journal Engineering Fracture Mechanics which is in progress.

Short and long crack propagation

With respect to fatigue crack propagation three stages can be distinguished: (i) the growth of microstructurally short cracks, (ii) the growth of mechanically/physically short cracks and (iii) the growth of long cracks. In the presence of material defects the second stage usually plays the major role with respect to the overall lifetime (Polak, 2003). Although comparable with respect to their size which is in the order of the dimension of the plastic zone surrounding the crack tip, mechanically and physically short cracks shall be separately discussed in the following.

Mechanically short crack

The crack driving force of mechanically short cracks cannot be described by the linear elastic ΔK concept but requires an elastic-plastic parameter. Within the IBESS project the cyclic J integral ΔJ is used, for the determination of which the authors used an analytical solution of Zerbst et al. (2011). The parameter ΔJ is determined by

$$\Delta J = \frac{\Delta K^2}{E'} \cdot \left[f\left(\Delta L_r\right) \right]^{-2} \tag{1}$$

with the function $f(\Delta L_r)$ being a plasticity correction function determined in conformity with the R6 solution (2009) but modified for cyclic loading such that

$$\Delta L_r = \frac{\Delta\sigma_{app}}{2 \cdot \sigma_0} . \tag{2}$$

and

$$f\left(\Delta L_r\right) = \left[\frac{E \cdot \Delta\varepsilon_{ref}}{\Delta\sigma_{ref}} + \frac{1}{2} \frac{\Delta L_r^2}{E \cdot \Delta\varepsilon_{ref} / \Delta\sigma_{ref}} \right]^{-1/2} . \tag{3}$$

The stresses and strains refer to the stabilized cyclic stress-strain curve. The parameter $\Delta\sigma_{app}$ is the applied cyclic stress range (referring to the gross cross-section) and σ_0 is a reference yield stress for which Madia et al. (2014) provided parametric equations. ΔK is obtained by weight function solutions based on the though thickness profiles of the elastic stresses. For the latter, the authors have generated parametric solutions applicable to Single-V and Double-V joints as well as to T- and cruciform joints subjected to tensile and bending loading which cover a wide range of weld toe radii (from 0.1 to 4 mm) and flank angles (from 10° to 60°) (Kiyak et al., 2016). For more details with respect to the determination of ΔJ see Madia et at. (2017). The analytical approach has been validated against numerical ΔJ solutions. An example for a cruciform joint shows Fig. 1. Details can be found in Tchoffo Ngoula et al. (2017).