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Numerical validation of crack closure concept using non-linear crack tip parameters

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Abstract

Crack closure concept has been widely used to explain different issues of fatigue crack propagation. However, some authors have questioned the relevance of crack closure and have proposed alternative concepts. The main objective here is to check the effectiveness of crack closure concept by linking the contact of crack flanks with non-linear crack tip parameters. Numerical models with and without contact of crack flanks were built for a wide range of loading parameters. The non-linear crack tip parameters studied were the range of cyclic plastic strain, the crack tip opening displacement (CTOD) and the size of reversed plastic zone. Well defined relations between non linear parameters and ΔK were obtained without contact of crack flanks which reinforces the validity of linear elastic fracture mechanics. When the CTOD with contact is plotted versus ΔK_{eff} the values are coincident with those obtained without contact, which shows that the crack closure concept is valid and able to explain the influence of mean stress. The analysis of overloads and high-low load blocks demonstrated the validity of crack closure concept for variable amplitude loading.

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Keywords: Fatigue crack propagation; plasticity induced crack closure; non-linear crack tip parameters; overloads

1. Introduction

Engineering analysis of FCG is usually performed by relating da/dN to the stress intensity factor range, ΔK. Initially it was surprising that the linear-elastic parameter could also successfully describe the rate of plastic

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processes at the crack tip. Later, Rice (1967) showed that the small-scale cyclic plasticity at the crack tip is, indeed, controlled by the value of ΔK. According to Paris law (Paris and Erdogan, 1963), da/dN is uniquely determined by one loading parameter, the stress intensity factor range, ΔK. However, other parameters, like mean stress or load history, influence da/dN,. The concept of crack closure was proposed by Christensen (1963), leading to a decrease of stress intensity at the crack tip and to an increase of fatigue life. As the crack propagates due to cyclic loading, a residual plastic wake is formed. The deformed material acts as a wedge behind the crack tip and the contact of fracture surfaces is forced by the elastically deformed material, which is called plasticity induced crack closure (Elber, 1970). This concept established for the first time that the crack growth rate is not only influenced by the conditions ahead the crack tip, but also by the nature of the crack flanks contact behind the crack tip. The effect of specimen geometry on crack closure has been accounted for using the T-stress concept (Tong, 2002). However, several questions have been raised, questioning the crack closure concept. The interpretation of experimental and numerical results in order to obtain the crack closure values is subjective, since different strategies can be followed giving significant scatter (Philips, 1989). Considering the uncertainty associated with experimental and numerical measurements, crack closure values cannot now be seen as absolutes. Therefore, the importance and even the existence of crack closure effect have been questioned by different authors. Some researchers suggest that closure can only occur under plane stress (Alizadeh, 2007), while others believe that it may not occur at all. Since 1993, Sadananda and Vasudevan (1993), Kujawski (2001), Glinka (2005) and Toribio (2013) have advocated that because the closure occurs behind the crack tip, it has a rather limited effect on the damage process, which takes place at the 'process zone' in front of the crack. According to these researchers the approaches to fatigue behavior based on crack closure (i.e. on what happens behind the crack tip) should be replaced by approaches based on what happens ahead of the crack tip. They argued that closure effects on FCG behavior have been greatly exaggerated, and suggested that the fatigue crack propagation rate is controlled by a two parameter driving force, which is a function of the maximum stress intensity factor, K_{max}, and the total stress intensity factor range, ΔK. Clearly there is no general agreement among researchers regarding the significance of closure concept on fatigue crack behavior.

The difficulties encountered in the use of da/dN-ΔK curves may however be overcome with the use of non-linear crack tip parameters. The direct link between crack closure and crack tip fields has not been totally exploited. This might be due to experimental difficulties in measuring quantitative strain/stress fields near a fatigue crack tip under applied loads and observing in situ crack tip deformation and failure phenomena during real-time fatigue experiments (Lee, 2011). The effects of thickness, stress state, specimen geometry and overloads will be naturally accommodated by non linear parameters. The non-linear crack tip parameters effectively control fatigue damage, therefore their analysis is a gate for the understanding of da/dN variations. Different parameters have been used in literature. Pokluda (2013) stated that the crack driving force in fatigue is directly related to the range of cyclic plastic strain. Heung et al. (1996) linked fatigue crack growth with the size of reversed plastic zone ahead of crack tip. Zhang et al. (2005) linked fatigue crack growth with crack tip shear band cracking, and this with the size of reversed plastic zone generated during the unloading part of the previous stress cycle. Other authors suggested that the total plastic dissipation per cycle is a driving force for fatigue crack growth in ductile solids, and can be closely correlated with fatigue crack growth rates (Klingbeil, 2003). Bodner *et al.* (1983) proposed that fatigue crack growth rate is proportional to the total plastic dissipation per cycle occurring throughout the reversed plastic zone ahead of the crack tip. The crack tip opening displacement (CTOD) is another main crack tip parameter. Pelloux (1970), using microfractography, showed that the concept of COD allowed the prediction of fatigue striations spacing and therefore the crack growth rate. Nicholls (1994) assumed a polynomial relation between crack growth rate and CTOD, while Tvergaard (2004), and Pippan and Grosinger (2013) indicated a linear relation between da/dN and CTOD for very ductile materials.

The main objective of this paper is therefore to check the effectiveness of crack closure concept by linking the contact of crack flanks to the non-linear crack tip parameters. A close look to non-linear crack tip parameters, like plastic strain range or dissipated energy, is the key for a deeper understanding of FCG and the establishment of physically based relations. Besides, the fatigue models will not be limited by the validity of small-scale yield condition.