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Effect of crack closure on non-linear crack tip parameters

F.V. Antunes [a,*], T. Sousa [a], R. Branco [b], L. Correia [c]

[a] CEMUC, Department of Mechanical Engineering, University of Coimbra, Portugal
[b] CEMUC, Department of Mechanical Engineering, Polytechnic Institute of Coimbra, 3030-129 Coimbra, Portugal
[c] CEMUC, Escola Superior de Tecnologia do Instituto Politécnico de Castelo Branco, Av. do Empresário, 6000-767 Castelo Branco, Portugal

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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. Accordingly, 3D-FE numerical models with and without contact were developed for a wide range of loading scenarios and the crack tip parameters usually linked to fatigue crack growth, namely range of cyclic plastic strain, crack tip opening displacement, size of reversed plastic zone and total plastic dissipation per cycle were investigated. It was demonstrated that: (i) LEFM concepts are applicable to the problem under study; (ii) the crack closure phenomenon has a great influence on crack tip parameters decreasing their values; (iii) the ΔK_{eff} concept is able to explain the variations of crack tip parameters produced by the contact of crack flanks; and (iv) the analysis of remote compliance is the best numerical parameter to quantify the crack opening level. Therefore the crack closure concept seems to be valid. Additionally, the curves of crack tip parameters against stress intensity factor range obtained without contact may be seen as master curves.

1. Introduction

The concepts of linear elastic fracture mechanics (LEFM) based on the elastic stress intensity factor, K, are valid for fatigue crack growth (FCG) analysis of most metals because the plastic zone sizes at the crack tips are usually small. Thus, engineering analysis of FCG is usually performed by relating da/dN to the stress intensity factor range, ΔK. A power law relationship is generally observed at intermediate values of ΔK:

$$\frac{da}{dN} = C(\Delta K)^m \tag{1}$$

where C and m are material constants. Paris and Erdogan [1] proved that da/dN versus ΔK for long cracks in the small-scale yielding range retains the advantage of LEFM, namely an invariance relatively to the shape and size of cracked solids. In other words, Paris law has made it possible to predict fatigue crack propagation behavior for engineering components using the information obtained from laboratory tests. Initially it was surprising that the linear-elastic parameter could also successfully describe the rate of plastic processes at the crack tip. Later, Rice [2,74] showed that the small-scale cyclic plasticity at the crack tip is, indeed, controlled by the value of ΔK. According to Paris law, da/dN is uniquely determined by one loading parameter, the stress intensity factor range, ΔK. However, the large amount of work developed showed that other parameters influence da/dN, like stress ratio or load history. Christensen [3] proposed the concept of fracture surface interaction leading to a decrease of stress intensity at the crack tip and to an increase of fatigue life. Elber [4,5] discussed the concept in terms of fracture mechanics parameters, promoting a strong research effort into the mechanisms and phenomena associated with fatigue crack closure. Ritchie et al. [6] and Suresh and Ritchie [7,8] identified the main closure mechanisms, which are plasticity induced crack closure (PICC), oxide-induced crack closure and roughness induced crack closure. According to Elber's understanding of crack closure, 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. An effective stress intensity factor, $\Delta K_{eff} = K_{max} - K_{open}$, quantifies the portion of loading cycle in which the crack is open. Elber's discovery 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. Crack closure concept seemed to be able to explain the influence of mean stress in both regimes I and II of crack propagation [5,9], the transient crack growth behavior following overloads [10], the growth rate of short cracks [11] and

* Corresponding author. Fax: +351 239 790701.
E-mail address: fernando.ventura@dem.uc.pt (F.V. Antunes).

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the effect of thickness [12,13], among other aspects. This success in explaining different issues of fatigue crack propagation has been used to validate the crack closure concept. Pippan and Grosinger [14] demonstrated that crack closure is not only important under small scale yielding conditions, it is also essential in the regions of low cycle fatigue. The effect of specimen geometry on crack closure has been accounted for using the *T*-stress concept. In the Williams series expansion for linear elastic crack-tip stress field, the second non-singular term, called the elastic *T*-stress, represents the stress acting parallel to the crack plane. The *T*-stress increases from negative to positive values when specimen loading mode changes from tension to bending [15]. The $M(T)$ specimen presents constant negative *T*-stress, while the CT specimen has positive *T*-stresses that increase with crack length [16]. The sign and magnitude of the *T*-stress substantially change the size and shape of the plane strain crack-tip plastic zone at finite load levels [17,18]. Positive *T*-stress strengthens the level of crack-tip stress triaxiality and restricts yielding; while negative *T*-stress reduces the level of crack-tip stress triaxiality and favors the development of plasticity. Therefore, larger closure values could be expected for negative *T*-stresses. Complementary concepts have been proposed by different authors. Dai and Li [19] considered that the plastic deformation modifies the elastic stress field and defined a plasticity-corrected *K* to account for the effect of plasticity. This K_{pc} was proposed as a new mechanical driving force parameter for predicting FCG rate, able to explain important phenomena associated with the plastic zone around a fatigue crack tip, such as the effects of load ratio *R*, single overload and the FCG behavior under cyclic compression. Ranc et al. [20] quantified the effect of heterogeneous temperature on stress intensity factor. The energy dissipated in the cyclic plastic zone ahead of crack tip produces thermal expansion of the material which affects the stress field. The stress intensity factor has to be corrected by a negative value which reduces the crack driving force. Pokluda [21] states that the effective stress field at the crack tip is a superposition of remote and local SIFs. The internal stresses created by dislocation configurations and secondary phases are to be considered as an important additional factor affecting the crack propagation rate in fatigue. Christopher et al. [22,23] proposed a novel mathematical model of the stresses around the tip of a fatigue crack, which considers the effects of wake contact and compatibility-induced stresses at the elastic–plastic boundary. Four parameters were considered to characterize the stress field: an opening mode stress intensity factor K_F, the shear stress intensity factor K_S, the retardation stress intensity factor K_R, and the *T*-stress. K_R characterizes the effect of crack tip shielding arising due to plasticity both at the crack tip and in the wake.

However, several questions have been raised, questioning the crack closure concept:

- ΔK_{eff} is commonly estimated by using the ASTM E647 standard recommendation. According to this recommendation K_{op} is the stress intensity factor associated with the load which causes a 2% deviation in the slope of a load–displacement curve. K_{op} corresponds therefore to the first deviation from the linearity of the load–displacement curve during unloading. A lower bound, K_W, can however be defined for crack closure, which is usually less than 20% of K_{op}, and $K_W < K_{ccl} < K_{op}$ [24], being K_{ccl} the effective crack closure level. Note also that the compliance technique is an indirect measurement of crack flank contact. Wei and James [25] reported experimental results using the compliance method together with the offset elastic displacement. They employed two gauges located at the back face and near the crack tip. Comparing the crack closure data measured by both gauges can be found differences as large as about 55%. James [26] has advocated that experimental data on crack closure usually include ill-defined contributions from a number of mechanisms, while the interpretation of compliance-based closure measurements is ambiguous and subjective. A comparison of the conventional closure measurements from the round robin tests organized by the authorized ASTM Task Group E24.04.04 on the same material and specimen geometry has indicated serious inconsistencies depending on the laboratory, investigator and technique used. One of the conclusions drawn from this work was that "scatter of this magnitude would make it very difficult to develop a clear picture of closure effects and to verify quantitative models of closure effects using data from the literature" [27]. Donald and Paris [28] and Kujawski [29] have introduced a new concept of partial crack closure, so called, which recognizes that a significant contribution to fatigue damage occurs in the load range below the opening load as measured by the compliance technique. Closure or interference of crack faces only partially shields the crack tip from damaging action due to cyclic loading.
- There is also a great uncertainty about the numerical parameter that is more adequate to quantify the effect of closure on fatigue crack growth. The most used parameter in numerical analysis is probably the contact status of the first node behind crack tip. Alternatively, the second node behind crack tip has also been used [30,31]). Sehitoglu and Sun [32] proposed that the necessary condition for fatigue crack extension is that the crack tip stress is tensile, which was followed by Wu and Ellyin [33] and Gonzalez-Herrera and Zapatero [34]. Borrego et al. [10] however found excellent correlations measuring the variation of compliance, being the displacement measured at the center of the $M(T)$ specimen. Considering the uncertainty associated with experimental and numerical measurements, crack closure values cannot now be seen as absolutes. Crack closure has therefore a parametric character.
- Crack closure does not include the effect of the portion of load cycle below the opening load, which is expected to affect crack growth [35,36].
- Some materials tested in vacuum exhibit the lack of the *R*-ratio dependence on the fatigue crack growth. This would then indicate that there is no closure. However, if in vacuum the closure is absent, the $da/dN–\Delta K$ curve should be to the left side of the air data and not to the right [37,38].
- Changes of crack opening level were found after heat treatment [39].
- Under tension–tension fatigue loading, experimental test results of the ultra-fine grain size aluminum alloy IN9052 have shown that the fatigue crack closure concept cannot explain the different fatigue crack propagation behaviors between short and long fatigue cracks. [40].

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 [41], while others believe that it may not occur at all. Since 1993 Vasudevan et al. [42–45], Sadananda and Vasudevan [46] 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 total stress intensity factor range, ΔK. These two parameters account for both the applied load and the residual stress contributions. Kujawski [47,48] proposed a new driving force parameter for crack growth: