CRACK-TIP STRESS-STRAIN FIELDS DURING CYCLIC LOADING
AND EFFECT OF OVERLOAD

J. Toribio, V. Kharin
University of Salamanca, E.P.S., Campus Viriato, 49022 Zamora, Spain
E-mail: toribio@usal.es; vikharin@gmail.com

Abstract Finite-deformation elastoplastic analysis of a plane-strain crack subjected to mode I cyclic loading under small scale yielding was performed. The influence of the load range, load ratio and overload on the crack tip stress-strain field is presented. Two independent parameters of cyclic loading, such as $\Delta K$ and $K_{\text{max}}$, both substantially affect the near tip evolutions of cyclic stresses and plastic strains, in agreement with typical experimental trends of fatigue cracking. This implies that the behaviour of cracks is governed by stress and strain fields ahead of the tip, via their control over the key process variables (damage accumulation and rupture, i.e., bond-breaking), so that the coupled process becomes a two-parameter one in terms of fracture mechanics variables $\Delta K$ and $K_{\text{max}}$.

Keywords: fatigue, crack tip, large strains, overload, computer simulation

1. Introduction. Fatigue is considered to be the cause of up to 90% of mechanical failures, which has been keeping this issue in the fore for decades (Suresh, 1991). Fatigue proceeds by nucleation and growth of cracks until rupture. Analyses of the crack tip stress-strain fields are valuable for understanding the crack behaviour, as far as cyclic evolutions of stresses and strains in the process zone are considered direct drivers of material degradation (damage accumulation) and local rupture (bond breaking) under fatigue (Ellyin and Wu, 1992; Sadananda et al., 1999; Sadananda and Vasudevan, 2004, 2005; Suresh, 1991). Since in situ monitoring of crack-tip stress-strain fields is hardly feasible, simulations seem to be the way to determine them. Accounting for both physical (material’s) and geometrical (large deformations and strains) nonlinearities in modelling is essential for realistic implications for fracture (McMeeking, 1977). Among available analyses of cracks, some, including comprehensive ones, such as the ones of McClung et al. (1991) or Ellyin and Wu (1992), have not accounted for large deformations, whereas others (Gortemaker et al., 1981; McMeeking, 1977; Needleman and Tvergaard, 1983; Toribio and Kharin, 1998 and 1999), although addressing this issue has been focused mostly on the monotonic loading, offering limited data on the cyclic one.

The present study attempts to fill-in a deficiency of data on the crack tip stress and strain fields under cyclic loading towards better elucidation of potential mechanical origins of the experimentally observed trends of the fatigue cracking, as suggested by Sadananda et al. (1999).
2. Modelling. Finite-deformation simulations of the crack tip fields in elastoplastic material were performed for a straight plane-strain crack subjected to mode I loading under small scale yielding (SSY), so that the stress intensity factor (SIF) $K_I$ could be the controlling mechanical variable.

The near-tip situation in rate/time-independent materials under SSY is controlled by the peak values of SIF, the maximum $K_{\text{max}}$ and minimum $K_{\text{min}}$, and the cycle number $N$. Simulated load cases consisted of up to ten cycles at different constant amplitudes and load ratios $R = K_{\text{min}}/K_{\text{max}}$, and the effect of a single overload was considered, too:

- (I) $K_{\text{max}} = K_0$, $K_{\text{min}} = 0$;
- (II) $K_{\text{max}} = 2K_0$, $K_{\text{min}} = 0$;
- (III) $K_{\text{max}} = 2K_0$, $K_{\text{min}} = K_0$;
- (IV) $K_{\text{max}} = K_0$, $K_{\text{min}} = 0$ with an overload to $K_{\text{ov}} = 2K_{\text{max}}$ in the sixth cycle.

At large strains, material strain hardening approaches saturation. Then, elastic—perfectly-plastic constitutive model can be an acceptable approximation. The ideal elastoplastic solid having Young modulus $E$, Poisson ratio $\nu$ and yield strength $\sigma_y$ with von Mises yield criterion and associated flow rule was chosen. Material characteristics were typical for a variety of materials: $\sigma_y/E = 0.003$, $\nu = 0.3$. The model of undeformed crack was a parallel-flanks slot of the width $b_0$ and semicircular tip, as it has been repeatedly substantiated for ductile materials (McMeeking, 1977; Needleman and Tvergaard, 1983; Toribio and Kharin 1999). Since the boundary-layer approach, which was quite suitable under monotonic loading (McMeeking, 1977), manifested ambiguities under cyclic one, the full-scale model of symmetric double-edge-cracked panel under remote tension was used as substantiated elsewhere (Toribio and Kharin, 1999), in which the $K_I$-dominated SSY was carefully ensured. To this end, among other requisites, the reference SIF value was taken here such that $K_0^2/(E\sigma_y b_0) = 1.5$. Large-deformation elastoplastic solutions were generated using a finite-element code with updated lagrangian formulation. The employed mesh and incremental analysis procedure were as outlined elsewhere (Toribio and Kharin, 1999).

3. Results. Calculated near-tip cyclic stress and plastic strain fields in all considered load cases I to IV were similar, and their contour-band plots are shown in Fig. 1 for the axial stress $\sigma_{yy}$ and actual equivalent plastic strain $\varepsilon_{eq}^p = \left(\frac{1}{2} \varepsilon_{ij}^p \varepsilon_{ij}^p\right)^{1/2}$, where $\varepsilon_{ij}^p = \int d\varepsilon_{ij}^p$ are components of the plastic strain tensor attained along the loading history till the given instant. In agreement with published data (Gortemaker et al., 1981; McMeeking, 1977; Needleman and Tvergaard, 1983) extreme stresses at high- and low-peak loads, tensile $\sigma_{yy} > 0$ and compressive $\sigma_{yy} < 0$, respectively, are attained ahead of the crack tip, whereas the equivalent plastic strain at each instant of the loading history remains rising monotonically as the crack tip contour is approached. Note, that for plane-strain