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A numerical study of crack shielding and deflection under extensive plasticity

Allan Burke-Veliz, Philippa A.S. Reed, Stavros Syngellakis *

School of Engineering Sciences, University of Southampton, Southampton, Hampshire SO17 1BJ, UK

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A B S T R A C T

Experimentally observed crack deflection events in multi-layered material systems, occurring even under pure mode-I loading, are here simulated and explained through elasto-plastic finite element modelling. The crack tip opening displacement is adopted as the crack driving force and estimated along crack paths whose deflection is predicted using the maximum tangential strain criterion. Shielding conditions that promote deflection and bifurcation are evaluated. It is shown that, under conditions of extended plasticity, CTOD evolution as a crack approaches an interface can reveal crack shielding and amplification, and that crack deflection and growth can be assessed from the variation of tangential strains around the crack tip.

1. Introduction

Fatigue failure has been studied extensively to prevent components of engineering systems from going prematurely out of service or causing damage to the whole system. More demanding service conditions have been met with the introduction of tougher materials and complex architectures but they have also resulted in more severe plastic deformation around existing or fatigue-initiated flaws in the component. Such new material systems are encountered in automotive plain bearings where they provide a compromise between various design requirements such as load capacity, size and energy efficiency.

The complex crack growth patterns observed in multi-layer architectures has been attributed to the mismatch of mechanical properties between layers. Through-thickness cracks approaching a stiffer layer appeared to deflect along single-tip or bifurcated paths under service conditions. Similar behaviour has also been observed in multi-layered systems under cyclic three-point bending [1,2] despite the absence of far-field mixed-mode loading conditions. The study of cracks subjected to large scale yielding (LSY) conditions requires the use of crack driving force (CDF) parameters, which should be valid beyond the scope of linear elastic fracture mechanics (LEFM). The *J* integral [3] and crack tip opening displacement (CTOD) [4] have been used to evaluate the crack growth potential of stationary [5–7] and fatigue cracks [8] in diverse materials under elasto-plastic conditions.

Pioneering studies by Suresh et al. [9] and Sugimura et al. [10,11] investigated shielding and anti-shielding effects on the crack growth rate of plastically mismatched layers when the crack tip approached a stiffer or more compliant layer, respectively. Experimental and numerical studies by Joyce et al. [1] on material systems consisting of steel and aluminium alloy layers under three-point bending corroborated previous shielding and anti-shielding observations and reported that, as the crack tip approaches a stiffer layer, CDF values increase with the deflection angle of bifurcated crack paths. Jiang et al. [12] also observed shielding and anti-shielding trends in plastically mismatched steels subjected to four-point bending tests;

* Corresponding author. Tel.: +44 23 80592844; fax: +44 23 80594813.
E-mail address: ss@soton.ac.uk (S. Syngellakis).

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they did not, however, report bifurcated or single-tip deflection as the crack tip approached a stiffer layer, attributing this effect to the presence of negative *T* stress.

Crack deflection has been extensively studied in both brittle and ductile materials [13–16]. Bifurcation has also been widely studied in brittle materials [17–20] where shielding appears more consistently. It has however received less attention in multi-layered architectures composed of ductile materials [21–23]. Factors promoting bifurcation such as compressive residual stresses [18–20] and dynamic instability [24,25] have been investigated leading to critical conditions for each particular case.

Various schemes have been introduced for extending and automatically predicting crack growth in two-dimensional fracture and fatigue analyses based on FE. Re-meshing crack extension schemes [26,27] have been shown to be well suited for such tasks, which can be performed at a reasonable computational cost. Three-dimensional FE crack growth analyses showed [28,29] that re-meshing schemes can be used efficiently on problems with complex geometries and loading conditions. Other schemes involving node release [30] and cohesive elements [31] were shown to improve computational efficiency in general terms and facilitate the inclusion of stress history but they suffer from a certain mesh bias. Recent developments [32] on the use of cohesive elements obviated the need of a pre-determined path, creating such elements where and when the maximum principal stress reaches the proportional limit.

Several criteria [13,15–17] have been shown to predict crack deflection in agreement with experimental results under monotonic loading, small scale yielding and mode-I dominant, mixed-mode loading conditions. Of special interest is the difference observed between the propagation paths under monotonic and cyclic loading described by Mageed and Pandey [33] and Qian and Fatemi [34]. A uniformly consistent criterion for any loading condition has not been established and most of the applications of such criteria with FE analyses have been carried out using closed-form, near-tip solutions derived from elastic analyses. There is a prospect therefore for further investigation of deflected paths within the scope of elastic plastic fracture mechanics (EPFM) through numerical analysis.

As pointed out already, the study of the crack shielding observed in multi-layered architectures has been addressed previously by many authors. However, the consequences of shielding, that is, crack deflection and bifurcation, have not been investigated to a great depth. At the same time, the search of a rational criterion for determining the bifurcation point along a crack in ductile layers provides an opportunity for further development work.

The issues raised above are addressed in this paper. CDF evolution is analytically investigated for stationary and incremented cracks in multi-layer systems with mechanical properties mismatch that are subjected to loads causing large-scale yielding. The state of strain and stress around the crack tip is also studied to search for the conditions that promote crack deflection and bifurcation even under far-field pure mode-I loading. The implementation of re-meshing schemes in FE crack extension modelling is preceded by the step-by-step determination of the deflected path followed by the crack using a validated deflection criterion.

2. Methodology

The study of propagating cracks in multi-layered systems under large-scale yielding conditions is based on two-dimensional FE analyses and appropriate fracture mechanics concepts and methodology. Quasi-static simulations of crack growth are achieved by estimating the state of stress around the crack tip and the CDF parameter for straight and deflected crack paths.

This work is mainly concerned with crack deflection as a consequence of shielding; for this reason, various path deflection criteria are first assessed through two-dimensional FE simulations of and comparisons with the fracture and fatigue experiments carried out by Mageed and Pandey [33]. The crack shielding and deflection study itself is based on FE simulations of three-point bending tests and is carried out in two main stages. Initially, crack shielding and amplification is assessed for straight stationary cracks of variable length under pure mode-I loading that approach either stiffer or more compliant layers. This stage is similar to earlier investigations on shielding and amplification cited in the Introduction apart from the extent of plasticity and the use of CTOD as the CDF parameter. The second stage is concerned with the consequences of shielding and amplification and it addresses this issue in two ways. The first is concerned with the possibility of an initially straight crack under pure mode-I loading propagating along a single deflected path according to the adopted path deflection criterion; the second, with the conditions leading to the experimentally observed propagation of shielded cracks along a bifurcated path.

The performed FE analyses are based on the general-purpose software ANSYS, version 10.0 [35]. Two-dimensional models were built using re-meshing schemes around straight or deflected propagating cracks. Parametric quarter-point elements [36] in spider-web configurations were found to be excessively distorted in preliminary simulations of three-point bending tests under high loads. For this reason, a blunted tip [37] modelled as a semi-circle of very small radius (around 0.1 μm), as shown in Fig. 1, was adopted for predicting reliably large crack tip deformations. The typical element size around the blunted tip was about 10 nm, which can be compared to the overall dimensions of the models described in the subsequent sections to provide an idea of the degree of mesh refinement. Relevant stress and displacement values were read relative to a local polar frame of reference with origin at the centre of the semi-circle. True stress-true strain curves represent the plastic behaviour of the layers beyond the proportional limit. The compliance matrix is re-calculated after each convergence iteration in the solution process to account for the effect of large deformations observed in tests.