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Numerical simulation of fatigue crack propagation interacting with micro-defects using multiscale XFEM

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ABSTRACT

The presence of the micro-defects in the vicinity of a macro-crack tip can either amplify or suppress the SIF (stress intensity factor) of the macro-crack, thus influence the macro-crack propagating path and rate. In the present work, we numerically investigated the influence of the micro-defects (micro-crack and micro-void) on the macro-crack propagation, by using the multiscale method in conjugation with XFEM (eXtended finite element method). This kind of multiscale method can efficiently provide solution of accuracy on both scales without any restrictive assumptions as analytical approximation method. A static crack interacting with multiple randomly distributed micro-cracks is modeled to investigate the influence of the macro–micro-crack inter-distance. Two series of cases are considered, i.e. a growing major crack interacting with nearby micro-crack, a growing major crack interacting with nearby micro-void. The inclination angle of the micro-crack and the radius of the micro-void are varied at studying their influence parametrically on the major crack propagating path and rate. The numerical results can help one to evaluate the residual fatigue life and safety design of components.

1. Introduction

It has been recognized that, accurate prediction of fatigue lives of metallic structures still pose challenges, particularly for structures with existing or developing microscopic discontinuities (such as micro-cracks, voids, inclusions, dislocations). Many experimental investigations [1–3] have demonstrated that, even in ductile materials, the main crack growth is associated with nearby micro-defects nucleation and accumulation. Further mechanical behavior of the main crack interacting with nearby micro-defects determines the fracture resistance of the material. An accurate fatigue life prediction requires fully comprehend of the macro-micro-crack interaction.

Advanced synchrotron radiation X-ray tomography has been used for experimental investigation between the crack and void or porosity. For example, Zhang et al. [4] experimentally investigated fatigue behavior of an Al-Si-Mg alloy and found out that, the SIF (stress intensity factor) increased rapidly when the fatigue crack came close to a micropore. In experimental research conducted by Tsay et al. [5], fractography revealed that the deflection of crack path as the crack tip pierced into porosity balanced the increased fatigue crack growth rate. Wu et al. [6] employed finite element method combined with real 3D imaging data of crack morphology to simulate the corner cracking process, and showed that the short fatigue cracking behaviors are noticeable due to micro-pores. Seo et al. [7] experimentally investigated the effects of a circular micro-defect on the fatigue crack growth and found out, when the crack enters the micro-defect, the prediction of the crack path by the maximum tangential stress criterion is inaccurate due to underestimation of the interaction between the crack tip and the microdefect. Clear understanding on the effects of micro-defects on the fatigue crack growth needs further numerical analysis.

In numerical analysis, the effects of existing micro-cracks has been investigated firstly with exact analytical methods. Gong et al. [8,9] studied the exact formulation for micro-crack interacting with finite main crack, yet digital results have not been given for the problem. However, due to the complexity of the formulation for the interaction, only cases with special configurations of micro-cracks can be solved by analytical methods, under restrictive assumptions. Meguid et al. [10] employed FEM to obtain results for comparison with those obtained by analytical methods. It is demonstrated that, the conventional FEM is not effective in modeling complex structures involving multiple micro-

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defects. Attempts were made to develop special elements containing small discontinuity to simply FEM modeling, such as semi-analytic-type elements [11], hybrid-type elements [12]. However, the evolving crack still requires remeshing, which poses computational complexity. To overcome the difficulties of remeshing as required whenever crack propagates, several methods were developed such as boundary element method [13], element free Galerkin method (EFG) [14], node-based smoothed finite element method (NS-FEM) [15], extended finite element method(XFEM) [16]. The XFEM offers great advantages over others, as it enables the mesh to be independent of crack geometry.

In recent years, several computational multiscale methods were developed which offer great promise in modeling the macro-micro-cracks interaction in terms of computational cost. One kind of the multiscale methods were developed based on homogenization technique, such as homogenized Dirichlet projection method [17,18], statistical volume element (SVE) method [19] or representative volume model [20], multiscale aggregating discontinuities (MAD) method [21]. The homogenization schemes have been applied successfully in solving microscopic heterogeneous materials [22,23] or composite materials [24,25], in which cases an accurate solution for the entire bulk is emphasized. The other kind is based on hierarchical decomposition technique, such as hierarchical multiscale method [26], variational multiscale method (VMM) [27], multiscale extended finite element method (MsXFEM) [23,28], multiscale projection method [29]. These methods can produce results of accuracy at both scale level, the effects of microfield in the macroscale formulation are emphasized. Therefore, in present work, multiscale projection method in conjunction with XFEM is employed for the multiscale analysis.

Numerous single and multiscale numerical methods have been utilized to analyze micro-defects problems. Meguid et al. [30] examined the effects of the presence of a general micro-crack upon the SIF at a main macro-crack under independent mode I, II and III loading. By employing extended finite element method (XFEM) on single scale, Loehnert et al. [31] investigated the effects of crack shielding and amplification of various arrangements of micro-cracks on the stress intensity factors of a macro-crack. Yan et al. [32] utilized boundary condition method to study interaction of multiple cracks in a rectangular plate. Singh et al. [33] developed a homogenized XFEM approach to evaluate the fatigue life of an edge crack plate in the presence of discontinuities. Ouinas et al. [34] numerically modeled the interaction between multiple micro-cracks and a principal crack emanating from a notch. In our previous work [35], a static crack interacting with symmetrically located micro-defects were numerically simulated by multiscale projection method. All these researches demonstrated that, the micro-cracks in vicinity of the main crack tip have significant influence on the main crack. The presence of these micro-cracks can either amplify or shield the main crack in terms of SIF, depending on their locations and geometries relative to the main crack tip. Two reviews on the macro/micro-crack interaction problems are given by Tamuzs and Petrova [36,37], which cover the analytic and numerical study on interaction of a static macro-crack and various configuration of micro-cracks. When the macro-crack propagates, the relative position of macro-crack tip and the micro-defect constantly changes. To our knowledge, till today, report on existing micro-defects interacting with growing main crack are quite limited. Therefore, in the present work, the effects of multiple randomly distributed microcracks are numerically studied, and then one single static micro-defect is arranged near the macro-crack tip, the geometrical parameters are varied to investigate its influence on the macro-crack propagation.

A remainder of the present paper is as follows. An introduction to the problem is provided in the Section 1. A detailed formulation and solution procedure of the multiscale projection is provided in the Section 2, which involves the decoupling of the computation for different scales. A detailed XFEM approximation for cracks and voids is provided in the Section 3, as well as the level set function for crack tracking and interaction integral method for SIF computation. In Section 4, the present method is employed to study the influence of the existing micro-crack or micro-void on the macro-crack propagation, the crack path and propagating rate along the propagating process is obtained and discussed. Finally, the conclusions are summed up in Section 5.

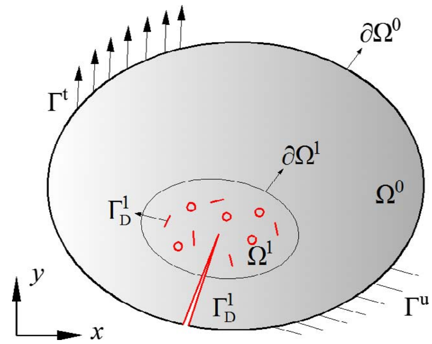

Fig. 1. Multiscale computational domain with multiple micro-defects near macro-crack tip.

2. Multiscale projection method

In this section, we briefly present the basic formulation and procedure of the multiscale projection method. For more details, the readers are referred to literature [29]. In the multiscale projection method, the test function is introduced such that different scale decomposition is accomplished. Such a scale separation enables the multiscale problem to be treated in two parts: a macroscale model which embodies the overall effects of the micro-defects, and a subscale (i.e. microscale) model which models the interaction and evolution of all the cracks.

2.1. Multiscale decomposition formulation

Consider a 2D material structure, within which contains a major crack and multiple randomly located and oriented micro-defects near the major crack tip, as shown in Fig. 1. It is assumed that, the geometric feature of the micro-defects is much smaller than that of the macro-crack, such that, the problem exhibits two scale behavior. The whole computational domain under consideration is denoted as Ω^0, with a boundary $\partial\Omega^0$. A subdomain (i.e. microscale domain) containing the macro crack tip and multiple micro-defects is taken out for subscale analysis, which is denoted as Ω^1, with a boundary $\partial\Omega^1$. The discontinuities on macro and micro scale are denoted as Γ^0_D and Γ^1_D respectively. The length scale of macroscale crack is denoted as l_0, and the length scale of the microscale defects is denoted as l_1. We assume that the geometry and response of the microscale defects is significantly smaller than that of macroscale crack, for that $l_0 \gg l_1$.

It is assumed that, along the boundary of $\partial\Omega^1$, the contribution of micro-defects on the field variables is negligible. In order to meet the assumption, the subdomain Ω^1 has to be chosen as an area with boundary adequately far away from the micro-defects. In our previous work [38], we improved the method by employing corrected XFEM on the macroscale model, consequently the necessary microscale domain size can be reduced. When the boundary $\partial\Omega^1$ is three times of the feature length of micro-crack away from micro-crack midpoints, the error of the SIF is less than 2%.

For the whole domain Ω^0, the governing equation is solved on macroscale model, with coarse scale mesh. The weak form of governing equation can be obtained by multiplying equilibrium equation by macroscale test function η^0,

$$\int_{\Omega^0} \mathrm{div}(\sigma(u^0 + \bar{u}^1))\cdot\eta^0 \mathrm{d}\Omega = \int_{\Omega^0} b\cdot\eta^0 \mathrm{d}\Omega + \int_{\partial\Omega^0} t\cdot\eta^0 \mathrm{d}\partial\Omega^0 + \int_{\Gamma^0_D} t^c\cdot\eta^0_D \mathrm{d}\Gamma \quad (1)$$

where t^c is cohesive tension across cracks. u^0 is the macroscale