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Isogeometric boundary element methods for three dimensional static fracture and fatigue crack growth

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Highlights

- We implement an isogeometric BEM routine for fracture by use of dual boundary integral equations.
- We propose a singular integration scheme to improve the quadrature accuracy for elements with high aspect ratios.
- We investigate the approaches to compute stress intensity factors based on a NURBS representation of the crack surfaces.
- We outline a geometric algorithm to propagate the crack based on the fatigue Paris law.

Abstract

We present a novel numerical method to simulate crack growth in 3D, directly from the Computer-Aided Design (CAD) geometry of the component, without any mesh generation. The method is an isogeometric boundary element method (IGABEM) based on non-uniform rational B-splines (NURBS). NURBS basis functions are used for the domain and crack representation as well as to approximate the physical quantities involved in the simulations. A stable quadrature scheme for singular integration is proposed to enhance the robustness of the method in dealing with highly distorted elements. Convergence studies in the crack opening displacement is performed for a penny-shaped crack and an elliptical crack. Two approaches to extract stress intensity factors (SIFs): the contour M integral and the virtual crack closure integral are compared using dual integral equations. The results show remarkable accuracy in the computed SIFs, leading to smooth crack paths and reliable fatigue lives, without requiring the generation of any mesh from the CAD model of the component under consideration.

Keywords: Isogeometric analysis; NURBS; Linear elastic fracture; Boundary element method; Crack growth; Fracture simulations directly from CAD

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1. Introduction

1.1. Damage tolerance assessment

The simulation of crack propagation is crucial in most areas of engineering and science. Predicting fracture is central to devising more durable and safer products and to understand natural phenomena.

We focus in this paper on one particular type of failure simulation known as 'fatigue crack growth' and which occurs in a variety of fields. When subjected to low amplitude cyclic loading, much below those causing significant unrecoverable plastic deformations, materials gradually damage which leads to crack initiation, propagation, and, in turn, to the subsequent global failure of the component.

In fatigue crack growth simulations, the goal is to estimate the number of cycles that a component can undergo before it is unfit for purpose. Evaluating this 'residual life' requires the ability, to both compute the number of cycles to initiation and to estimate the growth of a given crack given a number of loading cycles. We do not discuss the crack initiation phase in this paper, but focus on the problem of simulating the growth of a crack whose initial geometry is known. One of the widely used approaches to predict fatigue crack propagation consists in assuming that the material around the crack behaves in a linear elastic manner, compute the energy release rate, through the evaluation of stress intensity factors, and based on those, to estimate the amount of crack advance using empirical laws such as the Paris law.

1.2. Simulating fatigue crack growth

Simulating (fatigue) crack growth leads to a number of requirements for the associated numerical methods[1]:

1. Computing the displacement and stress fields within the component during crack growth;
2. Representing the crack surface as it grows;
3. Estimating the energy release rate along the crack;
4. Computing the crack propagation angle and crack propagation increment along the crack front.

Point 1. is complicated by the singularity of the stress field along the crack front, which requires dense meshes to be generated and regenerated as the crack grows. Point 2. requires the numerical method to deal with the propagating displacement discontinuity across the crack faces, as those evolve. Point 3. assumes the ability of the method to accurately evaluate stress intensity factors (SIFs). In this paper, we consider two approaches to do so, which are detailed later in the manuscript. The crack growth direction and increment (Point 4.) is provided by the crack growth law. We assume in the following that the crack grows in the direction which maximizes the tangential stress (hoop stress). We use Paris' law to compute the increment in crack growth along the crack front. We focus in the rest of this introduction on points 1. and 2. only, for which a number of methods have been proposed over the years. Points 1. and 2. above represent the major challenge for numerical fracture modeling, i.e. the combined requirement of simulating evolving discontinuities and singularities. This requires meshes used in the finite element method to be generated and regenerated as the crack grows and to use special elements relying, e.g. on Barsoum elements [2] to represent the singularity. This difficulty is compounded by the fact that the cracks are typically two or more orders of magnitude smaller than the component itself which exacerbates the meshing difficulty by leading to large gradients in element size.

In spite of these challenges, the finite element method (FEM) has been used rather widely to simulate the crack propagation directly with certain adaptive re-meshing operation [3–5]. Some commercial software packages such as ADAPCRACK, ZENCRACK and FRANC3D have been developed based on this idea [6–8] and two recent review papers can be consulted for details [1,9]. The complexity of remeshing, in spite of tremendous recent progress in Delaunay triangulation [10] and other meshing procedures [11], re-meshing remains a difficult problem when multiple cracks are interacting or for geometrically complex components where the presence of cracks as internal boundaries significantly constrain the mesh generation and regeneration process.

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[1] Note that because realistic industrial problems are three dimensional, we will not consider methods which have been developed only for two-dimensional crack propagation. We refer the reader to a recent review on 3D crack growth for some details which are not included in the forthcoming literature review [1].