Procedia Computer Science
Volume 80, 2016, Pages 245–256
ICCS 2016. The International Conference on Computational Science

Finite Element Model for Brittle Fracture and Fragmentation

Wei Li[1], Tristan J. Delaney[1], Xiangmin Jiao[1], Roman Samulyak[12]*, and Cao Lu[1]

[1] Dept. of Applied Mathematics & Statistics, Stony Brook University, Stony Brook, NY 11794, USA
{wei.li,tristan.delaney,xiangmin.jiao,roman.samulyak,cao.lu}@stonybrook.edu
[2] Computational Science Initiative, Brookhaven National Laboratory, Upton, NY 11973

Abstract
A new computational model for brittle fracture and fragmentation has been developed based on finite element analysis of non-linear elasticity equations. The proposed model propagates the cracks by splitting the mesh nodes alongside the most over-strained edges based on the principal direction of strain tensor. To prevent elements from overlapping and folding under large deformations, robust geometrical constraints using the method of Lagrange multipliers have been incorporated. The model has been applied to 2D simulations of the formation and propagation of cracks in brittle materials, and the fracture and fragmentation of stretched and compressed materials.

Keywords: brittle fracture, fragmentation, collision detection, finite elements method, nonlinear elasticity

1 Introduction

Computational study of brittle fracture networks are of great interest to engineers who work with material that breaks before it can undergo plastic deformation. This can occur when the material is in a "pre-stressed" configuration, where small deformations and strains can lead the material to surpass its internal critical stress. Of great importance to engineers is the prediction of crack nucleation and overall dependence of the resulting crack pattern on material properties.

Computational methods are of growing importance in modeling brittle fracture in materials. Due to the complex nature of fracture mechanics, several phenomenological methods have been proposed. Such methods include generalized and extended finite element methods (X-FEM) [9, 11], cohesive element (CE) models [3], and spring models [15].

The extended FEM (X-FEM) [11] and the generalized FEM (GFEM) [12], which are closely related and both belong to the partition of unity methods (PUM) [9], enrich the traditional FEM function space with families of discontinuous shape functions, which can model the displacements of either the crack tip or opposite sides of the crack plane. The main advantage lies

*Corresponding author.

Selection and peer-review under responsibility of the Scientific Programme Committee of ICCS 2016

doi:10.1016/j.procs.2016.05.317

in the fact that the interface can be studied within each individual element without having to constantly remesh near the crack tip. The types of enrichment functions can model a variety of engineering problems the crack tip including branching [7], material interfaces, and soft discontinuities. More recently, a phantom node method, which is a variant of the extended FEM was developed in [13].

Cohesive zone models (CZM) were first introduced by Barenblatt [3] and have been incorporated into commercial FEM codes. The CZM is intriguing because it explicitly avoids the creation of stress singularities by modeling inter-element traction-displacement relationships. Elements become separated when their tractions exceed a critical threshold, and the location of the "cohesive elements" (CE) can generate complex fracture networks. Cohesive elements have been used in traditional finite element codes by Xu and Needleman [18] and Ortiz and Camacho [6]. Additionally, cohesive zone models have been incorporated into other finite element frameworks such as X/G-FEM [11], meshless methods [2], and isogeometric analysis [14]. While CZMs may provide complex fracture structures, it was noted in [8] that CZMs are dependent on aspects of the mesh.

Spring models were introduced in [5, 10] and have the advantage of very simple implementation of solid mechanics and fracture mechanics. For example, Meakin [10] modeled fracture using a two-dimensional network of springs with a critical tension parameter. Over-strained springs were removed to simulate the propagation of fracture. Beale added random defects and perturbations to a spring model to investigate their effects on the propagation of the crack surface [5]. However, both of these models implemented fracture mechanisms by removing springs; thereby losing mass conservation and "obliterating" material under compression.

Recently, Wei et al. [15] investigated the use of mass conservative spring models, and were able to reproduce complex fracture networks in two and three dimensions. The method used nonlinear optimization of the global energy functional and split vertices adjacent to springs that were strained past a pre-defined threshold. The advantage of this method was that it conserved mass and produced rich crack networks throughout the material. The work demonstrated complex fracture patterns, which qualitatively change due to variations in material properties.

The spring network model of [15] is difficult to integrate into pre-existing finite element software. The intent of this paper is to apply the fracture mechanisms of [15] to existing finite element codes. In this work, we describe the fracture mechanism incorporated into a finite element solid mechanics code as well as collision detection algorithms to prevent inter-element penetration.

The remainder of the paper is divided as follows. In Section 2, the principles of continuum mechanics and their implementation within the finite element method are briefly discussed. In Section 3, the fracture mechanism is described, and particular emphasis is placed on the detection of intersecting elements and their resolution through the introduction of Lagrange multipliers. In Section 4, we present some verification of our FEM code and simulation results with our fracture model. Finally, we present concluding remarks in Section 5.

2 Finite Element Based Brittle Fracture Model

Finite element analysis is an important tool in the study of solid mechanics and fracture mechanics in particular. Linear elastic fracture mechanics (LEFM) has been well-studied using methods such as X-FEM and CZM. However, the range of applications of LEFM is limited by the assumptions of linear elasticity, which is valid for small displacements and small strains. In many applications involving brittle fracture, large displacements and rotations may occur while the strain exhibited within a material may still be in the elastic regime. Therefore, it is