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Hybrid Finite-Discrete Element Simulation of Crack Propagation under Mixed Mode Loading Condition

A. K. Ariffin, S. Huzni, M.J.M. Nor & N. A. N. Mohamed

Department of Mechanical & Materials Engineering

Universiti Kebangsaan Malaysia

43600 Bangi, Selangor, MALAYSIA

kamal@eng.ukm.my

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Abstract. This paper describes the numerical modeling based on combination of finite element method (FEM) and discrete element method (DEM) has been employed to simulate crack propagation under mixed mode loading. The work demonstrates the ability of combination finite-discrete element method to simulate the crack propagation that is usually performed through, what is termed, transition from continua to discontinua process. Crack propagation trajectory under selected loading angles (30^o & 60^o) are presented. The result obtained using the proposed model compare well with experimental result.

Introduction

Mixed mode crack problems are often encountered in structural integrity assessment. The problem of crack propagation under mixed mode loading is still of great interest in the field of fracture mechanics. Because of the complex nature of the actual loading condition at the crack tip it is important to address crack initiation and propagation under mixed-mode loading and not simplify to pure mode I and/or pure mode II analysis. A reliable prediction of crack initiation with its orientation and propagation path under mixed mode loading is desirable for life prediction of engineering components.

The last several decades have witnessed the great success of the finite element method, along with a tremendous increase of computer power, as a numerical simulation approach for applications across almost every engineering discipline [1]. However, the finite element method (FEM) is rooted in the concepts of continuum mechanics and is not suited to general fracture propagation and fragmentation problems. In contrast the discrete element method DEM is specifically designed to solve problems that exhibit strong discontinuities in material and geometric behavior. The discrete element method idealizes the whole medium into an assemblage of individual bodies, which in addition to their own deformable response interact with each other through a contact type interaction to capture the characteristics of the discontinum and to perform the same response as the medium itself [2]. Many researches have already demonstrated the ability of DEM and noted that DEM suffers large calculation time that is consumed not only at contact check between particulate elements but also at incremental time step [3, 4]. More powerfull solution capability are offers by combine finite-discrete element method. The hybrid finite-discrete element method merges finite element techniques with discrete element algorithm.

In this paper, a combine finite/discrete element analysis was used to simulate crack propagation under mixed mode loading. Finite/discrete element software ELFEN used in this work to analyze crack path of material under two selected loading angle, $\beta = 30^o$ and $\beta = 60^o$. The influence of the element size on crack initiation and propagation that simulate by this hybrid method also presented qualitatively.

Combine Finite-Discrete Element Method

In combine finite-discrete element method solid domains are discretized into finite elements in the usual way dictated by the finite element method. In case of solid domain fracture or fragment, a single domain represented by a single finite element mesh is transformed into a number of interacting domains, each of which is represented by its own separate finite element mesh. This is usually performed through, what is termed, transition from continua to discontinua algorithms [5]. Deformation of each individual body is modeled by finite element discretisation and the inter-body interaction is simulated by the contact condition. Fig. 1 shows the general flow of FE-DE analysis.

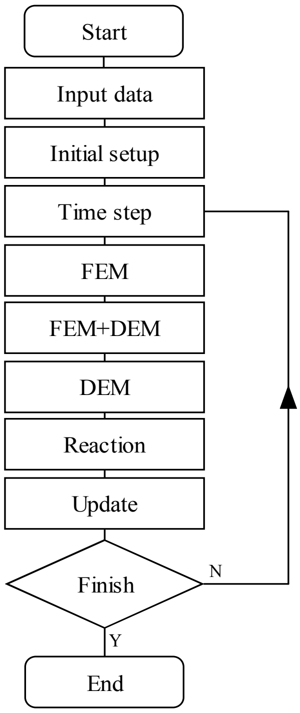


Fig. 1 Schematic of general flow of FE-DE analysis

One of the issues in the development of the combine finite-discrete element method is contact problem. Two important aspect of contact problem in combine-discrete element method are contact detection and contact interaction [5, 6]. Contact detection is aimed at detecting couples of discrete close to each other. Contact interaction employed to evaluate contact forces between discrete elements when contact between discrete elements detected. Three of the classic approaches that usually employed for contact interaction are the least square method, the lagrangian multiplier method and penalty method [7]. In this work penalty method is employed to evaluate contact interaction.

Crack Propagation Model

In this work, strain softening based fracture model is use to simulate crack propagation. The local softening material law depends on the fracture energy release rate G_f, where critical value of is a material characteristic. One model that provides a simple approach to localization zone detection is the Rankine softening plasticity model. This model is employed as fracture criteria and assume to be isotropic. Crack will be initiated when the strength of material at some measuring-point is reduced to zero. The direction of crack coincides with the direction of larges principal plastic stretch [8, 9].

Numerical Results

In this section, several examples of crack propagation simulation using combination finite-discrete element method are presented. Global properties of combine finite-discrete element that used in this work are shown in the Table 1. Those global properties define the fundamental parameters required by contact algorithm. Detail information about the parameters could be found in the [10].

Table 1. Discrete global properties used in this analysis

Tensile strength	570 Mpa
Fracture Energy	29.8 Mpa
Contact damping	0.3
Field	0.25
Normal penalty	1.79×10^9
Tangential penalty	1.7×10^8
Zone	0.5
Smallest element	0.3

Mesh Sensitivity Test. Fig. 2 show the numerical result of mesh sensitivity test. This numerical experiment is designed to look at the influence of the element size on crack initiation and propagation simulated using combination of finite-discrete element method.

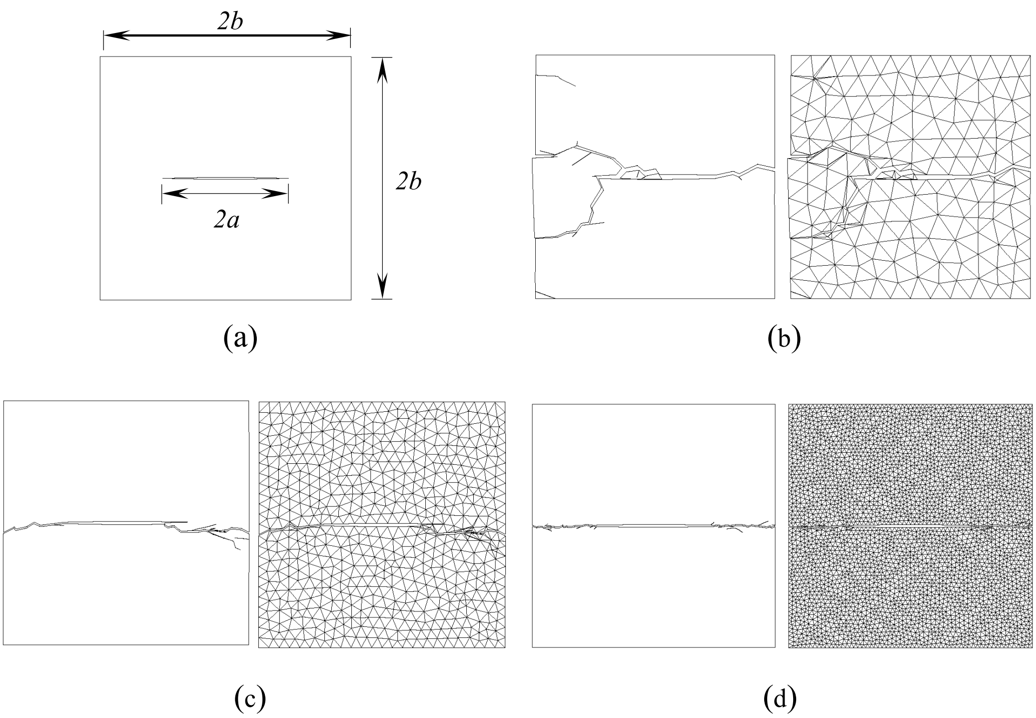


Fig.2 Fracture pattern of model with different mesh size, (a) geometry of model, (b) 5 mm, (c) 2.5 mm, (d) 1 mm

A square plate with a center opening is shown in Fig. 2(a). The top edge of the plate subject to the tensile loading (Mode I) with velocity of 1 m/s. The bottom edge is fixed in both direction x and y. Triangle unstructured mesh developed using advancing front method employed in this work. Three different size of element are selected for this test, i.e. 5 mm, 2.5 mm and 1mm.

Simulation result shows that different element size produce different crack pattern as seen in Fig. 2(b), 2(c) and 2(d).

Crack propagation Under Mixed Mode Loading. A rectangular plate with a notch is subjected to mixed mode loading as seen in Fig. 3. Load is uniformly distribute at the top of boundary segment while bottom of boundary is fixed.

Fig. 4 shows the qualitative comparison of crack direction predicted using hybrid finite-discrete element method and crack path that predicted using finite elemen with adaptive mesh that developed by [11]. In the finite element with adaptive mesh, node release technique is used to model crack initiatiation while crack tip opening angle (CTOA) used as fracture criterion and principal normal stress used as direction criteria.

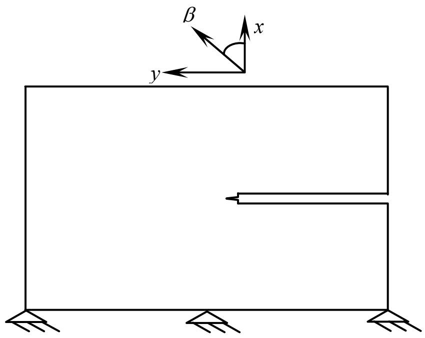


Fig. 3 Geometry and boundary condition of model

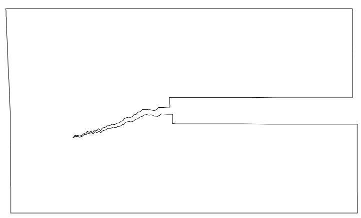
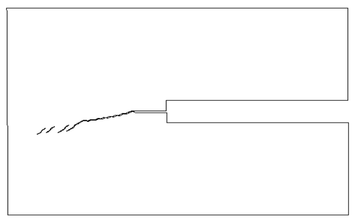
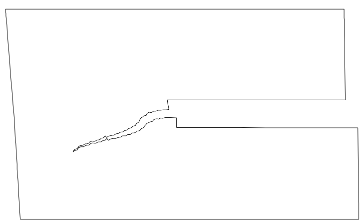
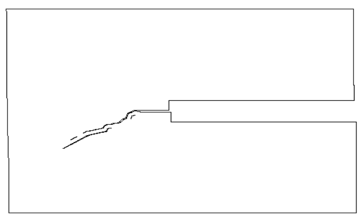
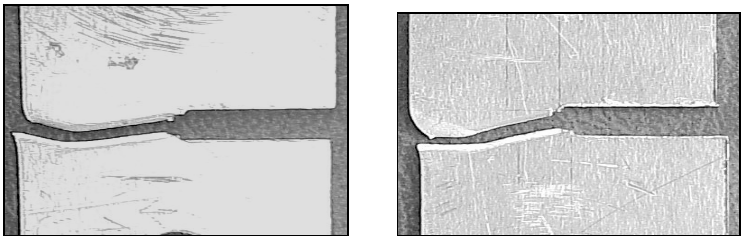
Loading	FEM	FEM-DEM
30^o		
60^o		

Fig. 4 FEM, FEM/DEM

As seen from Fig.4, at the initial stage of crack propagation, both methods (FEM and FEM-DEM) produce the similar crack path for both loading angle (30^o & 60^o). The crack initiate at the node tip and propagate in direction of perpendicular to the maximal principal normal stress, which is vertical due to applied load.

In the hybrid finite-discrete simulation, after the crack obtain a certain length, the crack will stop to propagate and a new crack initiated near the previous crack. In the 30^o loading angle a new crack is initiated in front of previous crack, while in 60^o, the crack is initiate parallel to previous crack and propagates also in the same direction.

Fig. 5 shows the experimental result of crack propagation under two different loading angles, i.e. 30° and 60°. The trend of crack propagation path obtain from simulation is similar to the experimental result.



(a) (b)

Fig. 5 Experimental crack path for (a) 30° & (b) 60°

Summary

A combine finite-discrete element method has been successfully employed for modeling crack propagation under mixed mode loading condition. Simulation results of two different loading angles are presented in this paper and show a good agreement with conventional finite element method and experimental result.

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