FEM IMPLEMENTATION OF THE COUPLED CRITERION BASED ON MINIMIZATION OF THE TOTAL ENERGY SUBJECTED TO A STRESS CONDITION TO PREDICT MIXED MODE CRACK ONSET AND GROWTH

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Abstract
A numerical procedure predicting crack onset and growth in a mixed mode in brittle materials is developed using the Coupled Criterion of Finite Fracture Mechanics (CCFFM), which assumes crack advances by finite steps and requires both stress and energy conditions are fulfilled. The Principle of Minimum Total Energy subjected to a Stress Condition (PMTE-SC) is implemented by a load-stepping algorithm, minimising the total energy change due to a crack advance allowed by the stress criterion. A simple implementation of PMTE-SC in FEM code Abaqus considers cracks geometrically modelled as topological discontinuities in the FEM mesh, with cracks introduced explicitly during the discretisation of the domain, the crack faces coinciding with the element edges. Several numerical examples are solved for mixed-mode crack onset and propagation.

1. Introduction

In the framework of Finite Fracture Mechanics (FFM), Leguillon (2002) introduced the coupled criterion of the FFM (CCFFM), which is the base of this work. According to CCFFM, the stress and energy criteria are two necessary conditions to allow an abrupt onset of a crack in a finite extension. As a result, failure occurs when the stresses along a surface, which would be the location where the crack will form, reach a critical value, and the crack initiation is energetically enabled to take place. As long as linear elasticity prevails, the CCFFM has been utilised effectively in order to predict the abrupt initiation of cracks in several different types of materials, like composites, ceramics, rocks and nonlinear materials, and configurations including interfaces, holes, and V-notches.

A new formulation of the CCFFM based on the principle of minimal total energy subjected to a stress condition (PMTE-SC), suitable for solving complex fracture problems, was introduced by Mantic (2014). This is primarily due to the fact that it is better suited for a generic computational implementation of a load-stepping technique that addresses issues with the initiation and propagation of multiple cracks. In addition, the total energy can be expressed as a separately convex function in the displacements and the damage variable fields. This makes it possible to apply optimisation techniques that are both efficient and stable to achieve the objective of minimising the total energy with constraints.

For implementing PMTE-SC in FEM code ABAQUS, we use UINTER, a subroutine used to define the interaction between two surfaces. It is called at points on the slave surface of a contact pair with a user-defined constitutive model describing the interaction between the surfaces. Here, the interaction between the cracked surfaces is modelled by a continuous distribution of springs with a linear elastic behaviour, Linear Elastic Spring Interface (LESI). Therefore, the springs interact with the two surfaces of the crack, which act linearly during tension and shear. The mixed mode constitutive law of the active surface springs was described, e.g., by Mantic et al. (2015). The normal and shear stresses at an undamaged spring are proportional to the normal and tangential relative displacements at that point. The failure of springs is defined in terms of energy release rate (ERR) G and fracture energy G_c. It can be shown that G is the energy stored in a spring for the normal stress and shear stress, whereas G_c depends on the fracture mode-mixity angle ψ at that point, see e.g., Mantic et al. (2015).

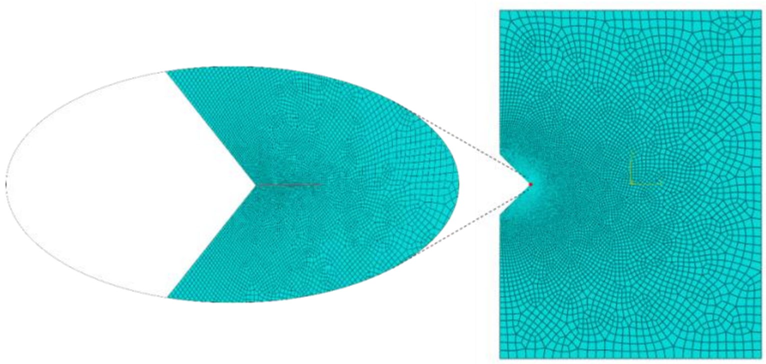

Fig.1 – Finite element model for the V-notch crack problem with a magnified view of the crack

2. Results

A stress criterion is widely used in brittle and quasi-brittle materials to predict failure in the absence of macroscale stress singularities, such as cracks or damaged zones. In the context of the CCFFM, the stress criterion is evaluated, before the crack onset, on the entire surface where the crack will propagate. The utilisation of standard FEM calculations establishes the application of the stress criteria by means of the extraction of the maximum principal stress from the solution. Then, a crack zone is generated using a polar coordinate system with the origin at the location of the maximum principal stress, and a potential crack path is obtained by applying the stress criterion.

To initiate or propagate a crack by a finite increment of its length $\Delta a > 0$, PMTE-SC is used. Several simulation case studies are introduced to find the optimised minimum energy, such as crack surfaces with fully active springs, crack surfaces with fully damaged springs, and crack surfaces with partially active springs. The change of the potential energy of the system is calculated by the code using the incremental virtual crack closure technique (VCCT), as it provides accurate results. It is based on the idea that the change in potential elastic energy due to specific crack growth is identical to the work necessary to close the crack with an equivalent extension. In the context of finite fracture mechanics, this idea is applied from an incremental perspective.

Several fundamental problems for crack onsite and propagation under quasistatic load in mode I, such as a circular hole in an infinite plate under remote tensile load and biaxial load, rhombus hole specimens under compression, and others in mixed mode, are solved. Therefore, this method opens new possibilities for studying the onset and propagation of cracks.

3. Conclusions

In this work, a new method to characterise the crack onset and propagation has been developed based on the Coupled Criterion of Finite Fracture Mechanics (CCFFM). This method predicts an instantaneous crack onset or propagation without requiring an infinitesimal crack growth. This allows the appearance of several fractures simultaneously in the same problem. A computational algorithm based on the new formulation, i.e., PMTE-SC, has been implemented using the Finite Element Method in ABAQUS and Python scripts.

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References

Leguillon, D. (2002) Eur. J. Mech. A Solids 21, 61–72.

Mantič, V. (2014) Proceedings of the 16th European Conference on Composite Materials ECCM16 (Keynote lecture), F. París (Ed.), http://www.escm.eu.org/eccm16/assets/1252.pdf.

Mantič, V., Távara, L., Blázquez, A., Graciani, E., París, F. (2015). Int. J. Fract. 195, 15–38.