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A non-local approach to crack process modeling in ceramic materials subjected to thermal shock

Jia Li [a,*], Fan Song [b], Chiping Jiang [c]

[a] LSPM, CNRS UPR 3407, Université Paris XIII, Villetaneuse, France
[b] State Key Laboratory of Nonlinear Mechanics, Institute of Mechanics, Chinese Academy of Sciences, Beijing, China
[c] Solid Mechanics Research Center, Beijing University of Aeronautics and Astronautics, Beijing, China

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ABSTRACT

In this paper, we present a non-local approach to fracture modeling in brittle or quasi-brittle materials and its finite element implementation. The proposed fracture model is constructed on the basis of the conventional maximal principal stress criterion for uniform tensile loads and the Griffith–Irwin criterion for crack propagation prediction. Consequently, the proposed fracture criterion can be used to predict both the crack initiation and the crack growth. Moreover, we also showed that when the element size is much smaller than the characteristic length scale of the material, the proposed fracture model is mesh-independent. By using the proposed model, we carried out detailed numerical simulations on cracking process of ceramic materials subjected to thermal shock loading. The comparison with the experimental results shows that the periodic and hierarchical structure of the crack pattern is faithfully reproduced by the numerical simulations.

1. Introduction

Fracture assessment in brittle or quasi-brittle materials is an essential but difficult task in computational mechanics. Developing efficient and accurate finite element models to simulate tensile fracture behavior has been extensively studied in the last two decades. Two types of fracture models, i.e., the damage-mechanics-based models and fracture-mechanics-based models, are most frequently used in cracking simulations. The damage-mechanics-based models assume that the fracture is caused by continuously varying damage in the solid. The crack propagation is described by reducing the material stiffness and strength of the elements. The fracture-mechanics-based models are based on displacement discontinuity between crack surfaces, usually represented by nonlinear interface elements. The constitutive behavior of such elements is described by softening relations between traction and crack relative displacements, as assumed by the cohesive crack model.

The damage-mechanics-based models have been very popular because of its computational convenience [1–6]. These models present numerous advantages such as their capacity in dealing with default development before formation of macro-cracks, the possibility to include micromechanics-based behaviors and the easy numerical implementation. One drawback of the damage-mechanics-based models may be the large spread damage zones, which can hardly be regarded as cracks. On the other hand, the fracture-mechanics-based models have also been largely investigated. Enormous success

* Corresponding author at: LSPM, CNRS UPR 3407, Institut Galilée, Université Paris 13, 99 Avenue Jean-Baptiste Clément, 93430 Villetaneuse, France. Tel.: +33 1 49 40 28 89; fax: +33 1 49 40 39 38.
E-mail address: jia.li@univ-paris13.fr (J. Li).

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Nomenclature

σ_1	first principal stress
σ_c	ultimate tensile stress
$\tilde{\sigma}_{ij}$	non-local stress
$\tilde{\sigma}_1$	non-local first principal stress
$\delta\Pi$	variation of potential energy
δE	variation of kinetic energy
δl	crack growth vector
$\bar{p}$	dimensionless crack length
$\bar{s}$	dimensionless crack spacing
δS	newly created crack surface
v	Poisson's ratio
α	thermal expansion coefficient
ρ	mass density
φ, ψ	space weighting functions
c	specific heat
D	damage
d	side length of the triangle elements.
E	Young's modulus
G_c	fracture energy per unit surface
h	convective heat transfer coefficient
k	thermal conductivity
K_I	stress intensity factor
K_{Ic}	critical stress intensity factor
R	radius of the non-local interaction area
r_0	distance between the crack tip and the position where the non-local tensile stress is maximal
T	temperature field in quenched specimens
T_0	initial temperature of specimens
T_∞	water temperature in quenching bath

has been achieved in fracture analysis with the cohesive model [7–11] or the extended-finite element method (XFEM) [12–16]. The main advantages of these crack models remain in their strictness in analysis; the accurate solutions and easily applied criteria.

Simulating multi-cracking phenomenon is a formidable challenge for numerical fracture mechanics. The ability to predict both the crack initiation and crack growth, the mesh-independency of the numerical results, the stable, robust, accurate and low-cost numerical algorithms are some essential exigencies for fracture models simulating such a phenomenon. Francfort and Marigo [17] developed a so-called damage gradient model in which the damage zone converges to a crack as the length parameter tends to zero. Efficient algorithms were developed in order to resolve complicated cracking problems [18,19]. Pijaudier-Cabot and Bazant [20,21] developed a practical nonlocal model in a continuum damage setting. The development of nonlinear gradient models, initially developed in plasticity behavior description, has afterwards been transferred to damage mechanics [22,23]. Another method involves lattice simulation that considers a solid as a network of bars or beams [24–26]. Several attempts by modeling directly micro-cracks and their growth were reported in earlier researches by using the boundary element method [27–29].

In the framework of notch fracture analysis, the so-called finite fracture mechanics was developed. Neuber [30] first proposed the effective stress criterion based on average stress over a characteristic length related to the notch radius. The failure criterion, proposed by Novozhilov [31] and expanded by Seweryn [32], suggests considering the mean normal stress along the anticipated path of the failure. Pluvinage [33] proposed averaging the stress distribution over the entire process volume to establish more accurate fracture criteria. Introduction of a length scale parameter in crack growth criteria was successively used to predict the crack initiation or to take the non-linear mechanisms into account for crack growth [34–39]. The principal advantage of this class of theories resides in their accuracy and simplicity. However, these analyses were suitable only for individual crack formation and evolution. On the basis of the finite fracture mechanics concept, Li et al. [40,41] developed a Fast Fourier Transform (FFT) code, which is capable to simulate multiple crack onset and crack growth in brittle materials.

In this paper, the ideas described in Li et al. [40,41] were essentially followed. However, the FFT modeling is appropriate only for analyses of periodic structures under periodic loading; Moreover, the criterion proposed in Li et al. [40,41] is capable to forecast the position, but not the orientation and length of the new crack. In the present work, this model is improved and implemented to a finite element code. Thus the location, orientation and length of the newly created crack are explicitly determined. We have demonstrated that the proposed fracture criterion can be used to predict both the crack initiation and the crack growth. Moreover, its mesh-independency was also discussed through some numerical examples.