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Numerical simulation of thermal-mechanical induced fracture with discretized virtual internal bond

Jiafeng Ding [a], Zhennan Zhang [a,b,*], Shengqi Yang [b], Zhanguo Ma [b], Jianye Mou [c]

[a] School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[b] State Key Laboratory for GeoMechanics and Deep Underground Engineering, China University of Mining & Technology, Xuzhou 221116, China
[c] College of Petroleum Engineering, China University of Petroleum, Beijing 102249, China

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ABSTRACT

The thermal-mechanical coupled discretized virtual internal bond (DVIB) is developed to simulate the fracture problem subjected to the thermal–mechanical field. Different from the conventional lattice model, DVIB considers material to consist of bond cells. Each bond cell can take any geometry with any number of bonds. To enable DVIB to simulate the thermal conduction process, each bond is taken as a thermal channel. The micro bond thermal conductivity and heat capacity coefficient are calibrated based on a volume equivalence approach, which makes it unnecessary to consider the geometry details of cell. The relationship between the macro and the micro thermal parameters are derived. The thermal effect is incorporated into the mechanical process by means of bond deformation decomposition. Through the bond potential, which characterizes the interaction between particles, the thermal effect on the mechanical response of material is accounted. The simulation results demonstrate that this method can simulate the fracture behaviors of material subjected to the thermal-mechanical field with very high accuracy. Because both the thermal and the mechanical field simulation are based on the common discrete lattice structure in DVIB, it is highly efficient and straightforward to deal with the thermal-mechanical induced fracture problem. In addition, the thermal parameter calibration method makes the DVIB quite flexible. The perspective this method should be inspiring.
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1. Introduction

The thermal-induced fracture in solid is a very popular and important problem in practical engineering. It has received much attention so far. Many theories and numerical methods have been developed for this problem. However, there are still many challenges in simulating the thermal-induced fracture process since it involves with the multiscale coupling processes. If this problem is considered in the framework of conventional continuum mechanics, great efforts are dedicated to the study on the stress intensity factor induced by thermal and the corresponding fracture criterion, e.g.[1–13]. Undoubtedly, this approach is effective in most practical engineering. However, the classical continuum fracture mechanics method is only applicable to the existed fractures. It cannot predict the fracture initiation. One of the underlying reasons lies in that it only considers the fracture process on the macro continuum scale. To overcome the single scale limitation of the classical continuum mechanics, Liu and Li [14] derived the macro thermal-mechanical coupled constitutive relation based on the micro

* Corresponding author at: School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China.
E-mail address: zhennanzhang@sjtu.edu.cn (Z. Zhang).

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Nomenclature

a	edge length of the equivalent isosceles right triangle
A	initial bond stiffness
c_{re}	correction coefficient
C	heat capacity
C_H	heat capacity of matrix
$\tilde{C}$	heat capacity coefficient of a bond
E	elastic tangent modulus
F_i	nodal force vector of a bond cell
K_H	thermal conductivity of matrix
K_{ij}	tangential stiffness matrix of a bond cell
l_0	bond length in un-deformed state
L	length of medium or bond
N	particle number of a bond cell
q	internal heat source density
$\tilde{q}$	internal heat source density of a bond
Q_{cont}	heat flux at continuum level
Q_{bond}	heat flux at bond level
T	temperature
$\dot{T}$	temperature rate
$\hat{T}$	temperature variation
u_i	component of the nodal displacement vector
V	volume of 3D unit cell and area of 2D unit cell
W	total strain energy of one bond cell
α	thermal expansion coefficient
Δ	bond deformation
Δ_f	bond deformation corresponding tensile strength
Δ_u	total bond deformation
Δ_M	mechanical bond deformation
Δ_T	thermal bond deformation
ε_t	tensile bond strain
κ	thermal conductivity coefficient of matrix
$\tilde{\kappa}$	thermal conductivity coefficient of a bond
λ	coefficient of bond elastic parameter
ν	Poisson ratio
ρ	material density
ξ	thermal diffusion coefficient
Φ	bond potential between particles
Ω	bond number in a unit cell

Helmholz free energy at the state of finite temperature via the Cauchy-Born rule. The damage mechanics method, e.g. [15,16], free of the consideration of stress intensity factor, can simulate the fracture behaviors by smearing the fracture through the entire element via stiffness degradation. This makes the fracture simulation simpler, but this method itself has some limitations in dealing with the micro fracturing process. The FEM/DEM coupled approach introduces interfaces into the element boundaries and the fracture is only allowed to initiate and propagate along the element boundaries. A cohesive law and a constitutive model are respectively employed to characterize the interface and the bulk material. This method can avoid the remeshing problem while capture the fracture essence. It has been used to simulate the thermal-induced fracture, e.g. [17–19]. But this method is strongly dependent on the meshing scheme. The discrete element method also has been used to simulate the thermal-induced fracture by introducing the thermal conductivity between elements and the additive stress induced by thermal, e.g. [20–23].

The lattice method, free of the continuous field hypothesis, is a highly efficient approach to simulate the fracture behaviors. The discretized virtual internal bond (DVIB) [24]is a newly-developed lattice approach to fracture simulation. It stems from the continuous virtual internal bond method [25]. It is different from the conventional lattice method in that its discrete structure is composed of lattice bond cells. Each bond cell can take any geometry with any number of bonds. A hyperelastic bond potential is introduced to describe the interactions between the particles. Since DVIB was born in 2013, it has been well developed to account for various Poisson ratio [26], the elastic-brittle [27], fracture energy [28] and plastic deformation [29]. In this paper, we extend the DVIB to the thermal-mechanical coupled fracture problem.

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