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Plastic fracture simulation by using discretized virtual internal bond

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ABSTRACT

The plastic deformation is always localized prior to fracture for ductile materials. To unify the plasticity and fracture together on the micro bond level, a plasticity-fracture-embedded bond potential is proposed for the lattice model. The discretized virtual internal bond (DVIB) is a newly-developed lattice model, which consists of lattice bond cells. With this proposed bond potential, the DVIB can capture the irreversibility feature of the plastic deformation and simulate the plastic fracture propagation of materials with fracture energy conservation. The simulation results are almost independent of mesh size. The unified bond potential stabilizes the lattice model and makes the simulation results more reliable in plastic fracture simulation. It provides a more straightforward, simple and efficient method for plastic fracture simulation.

1. Introduction

The virtual internal bond (VIB) proposed by Gao and Klein [1] is a micro-macro constitutive modeling method for solids. It considers a solid to consist of randomized material particles on micro scale. These material particles are connected with virtual internal bonds. The macro constitutive relation is directly derived from the interactions between particles. The merit of such modeling method is that the micro fracture mechanism is directly incorporated into the macro constitutive relation so that the VIB can simulate fracture behaviors without any separate fracture criterion. The VIB is based on a postulated micro discrete structure, but it ultimately returns to a continuum constitutive relation through a homogenization process. Thus, VIB is still a continuum constitutive model, subjected to the continuum hypothesis and the finite deformation theory of a continuum. To liberate VIB from the continuum hypothesis so as to make it capable of simulating fracture in the finite deformation and large displacement cases, Zhang [2] developed the discretized virtual internal bond(DVIB). The DVIB is a lattice model, which is composed of lattice bond cells with finite number of bonds. In the original version of DVIB [2], a pair-wise interatomic potential was adopted to characterize the interactions between particles within a bond cell. But the pair-wise interatomic potential leads to the fixed macro Poisson ratio. To overcome this limitation, Zhang and Chen [3] employed the modified Stillinger-Weber potential [4] to quantify the energy of a bond cell, which enables DVIB to represent the variable Poisson ratio of material. To address the fixed Poisson ratio problem, the other methods such as the shear-type [5], the beam-like [6], the angular-spring [7] and the nonlocal effect-embedded interaction method [8–11] are also effective ways.

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Nomenclature

A, B	bond parameters
E	elastic tangent modulus
E_p	plastic tangent modulus
f_y	yield strength of bond
f_b	transition strength of bond
F_b	bond force
F_i	nodal force vector of a bond cell
G_F	fracture energy
h	characteristic size of unit cell
$h_{critical}$	critical unit cell size
k_e	elastic stiffness of bond
k_p	plastic stiffness of bond
K_{IC}	fracture toughness
K_{ij}	tangential stiffness matrix of a bond cell
l	bond length
l_0	bond length in un-deformed state
l_y	yield bond length
l_b	transition bond length from plasticity to fracture
l_f	ultimate failure bond length
l_p^*	maximum plastic bond length
l_{uP}	historic maximum unloading bond length in the plastic stage
l_{uF}	historic maximum unloading bond length in the fracture stage
N	number of particles in a unit cell
S	area of the created crack facet
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
W_f	energy provided by a bond to create fracture
$\bar{\mathbf{X}}, \bar{\mathbf{x}}$	bond vectors in the reference and current configuration, respectively
$\mathbf{X}_I, \mathbf{X}_J, \mathbf{u}_I, \mathbf{u}_J$	the coordinate and displacement vectors of the particle I, J
α	ratio of plastic stiffness to elastic stiffness of a bond
γ	coefficient of crack facet created in a unit cell
δ	elongation
Δ	section shrinkage
$\tilde{\varepsilon}_y$	yield strain of bond
$\tilde{\varepsilon}_b$	plasticity-fracture transition strain of bond
$\tilde{\varepsilon}_f$	failure strain of bond
λ	coefficient of bond elastic parameter
ν	Poisson ratio
ρ	material density
σ_y	yield strength of material
σ_t	uniaxial tensile strength of material
Φ	bond potential between particles
ω	number of bonds cut by crack facet in a unit cell
Ω	bond number in a unit cell

The mesh-dependency is another known issue of the lattice model. The meaning of mesh-dependency is dual. One is that the simulated mechanical resistance of material is mesh size-dependent and another one is that the simulated fracture path is mesh scheme-dependent. To remedy the element size-dependency of DVIB, Zhang et al. [12] introduced the fracture energy to the hyperelastic bond potential, which stabilizes the DVIB model. To reduce the mesh scheme-dependency of fracture path, randomizing mesh scheme [13–15] is an effective way. However, the irregular lattice cannot render an elastic homogeneity. Fortunately, this can be addressed by the elemental stiffness-scaling method [16]. Different from the randomizing mesh approach, Chen et al. [10] solved this problem by considering the multiple non-local forces from neighboring particles.

The DVIB can capture the hyperelasticity of material at crack tip which governs the dynamic fracture at a critical length scale [17]. It has been successfully applied to simulate the dynamic fracture propagations [18–20]. So far the advance of DVIB is still within the framework of hyperelasticity and cannot capture the plastic deformation. For the ductile engineering materials, the plastic deformation plays an important role in fracturing process. It is locally accumulated prior to fracture, which cannot be ignored to fully understand the failure mechanism of these materials. From a macroscopic point of view, contin-