ARTICLE IN PRESS

Engineering Fracture Mechanics xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

A novel conjugated bond linear elastic model in bond-based peridynamics for fracture problems under dynamic loads

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ARTICLE INFO

Article history:
Received 20 January 2017
Received in revised form 18 July 2017
Accepted 24 July 2017
Available online xxxx

Keywords:
Linear elastic model
Conjugated bond-based peridynamics
Crack propagation
Dynamic loads
The standard bond-based peridynamics

ABSTRACT

A novel conjugated bond linear elastic model is proposed and implemented into the bond-based peridynamic (BB-PD) framework. In this model, micro-elastic PD bond energy is not only related to the normal stretch of bonds, but also related to the rotation bond angles of a pair of conjugated bonds. Therefore, micro bond energy mechanism in this study is different from that in the classical continuum mechanism or the standard BB-PD. Only one micro-elastic constant in the standard BB-PD results in the limitation of the effective Poisson's ratio for isotropic material. However, the novel conjugated bond linear elastic model incorporating two micro-elastic constants are proposed, which can overcome the limitation of Poisson's ratio in the standard BB-PD. By comparing the strain energy in the proposed model with that in the classical elastic model, the corresponding micro-macro parameter relationships can be established. In addition, energy-based bond rupture criteria are implemented in the proposed numerical model to simulate fracture problems under dynamic loads. In order to verify the ability and accuracy of the proposed numerical model to simulate fracture problems under dynamic loads, some numerical examples are investigated. The present numerical results are in good agreement with the previous experimental and numerical results.

1. Introduction

In computation mechanics, numerical simulation of fracture problems for both static cracks and dynamic cracks is still an active and persistent challenge. There are some different methods to model cracks in finite element and meshfree methods. For the finite element method, one of the simple and robust methods is interelement separation model where cracks are modeled along element interfaces in the mesh [1–4]. Another simple method to model cracks was developed by Remmers et al. [5] who introduced crack segments in finite elements. The embedded discontinuity model was also proposed by Armero and Garikipati [6], Belytschko et al. [7], Samaniego et al. [8] in the finite element mesh to simulate crack problems. Based on the 'local' partition of unity, the extended finite element method (XFEM), which is a very accurate method for crack problems, was developed by Belytschko and Black [9] and Moes et al. [10]. For the previous meshfree method, Rabczuk and Belytschko [11,12] developed a 'cracking particle' model (CPM) in meshfree method, where discontinuities are introduced at

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http://dx.doi.org/10.1016/j.engfracmech.2017.07.031
0013-7944/

Nomenclature

$c(\boldsymbol{\xi})$	micro-modulus constant in bond-based peridynamics
c_n	normal stiffness of bonds
D	ratio of amount of broken bonds to the total amount of interaction in one horizon
E	Young's modulus
$\mathbf{E}$	elastic Lagrange strain tensor
$\boldsymbol{f}$	pairwise force function in conjugated bond-based peridynamics
$\boldsymbol{f}_n$	normal bond force density in conjugated bond-based peridynamics
$\boldsymbol{f}_t$	tangent bond force density
$\mathbf{F}$	approximate deformation gradient
G	shear modulus
G_c	fracture surface energy
$\mathbf{H}_\mathbf{X}$	horizon of a given material point $\mathbf{X}$
$\mathbf{I}$	identity tensor
K	bulk elastic modulus
m_{jik}	moment vector density due to a pair of conjugated bonds
s	bond stretch
s_n	normal bond stretch
$\mathbf{u}(\mathbf{X})$	displacement vectors of the material point $\mathbf{X}$
$\dot{\mathbf{u}}(\mathbf{X})$	velocity vectors of the material point $\mathbf{X}$
$\ddot{\mathbf{u}}(\mathbf{X})$	acceleration vectors of the material point $\mathbf{X}$
w	scalar-valued micro-potential function
w_l	normal stretch strain energy micro-potential
w_β	rotation Strain energy micro-potential due to a pair of conjugated bonds
w_ξ	micro-potential energy function
w_c	critical strain energy potential in the bond
W^C	strain energy density in classical elastic mechanics
W^{PD}	macro-elastic strain energy density
W_l^{PD}	macro-elastic stretch strain energy density
W_β^{PD}	macro-elastic rotation strain energy density
$\boldsymbol{x}$	location of a material point in deformed configuration
$\boldsymbol{x}'$	neighbor particle for a given point $\boldsymbol{x}$ in deformed configuration
$\mathbf{X}$	location of a material point in the reference configuration
$\mathbf{X}'$	neighbor particle for a given point $\mathbf{X}$ in the reference configuration
δ	radius of one horizon
ε_{ij}	strain tensor in the bond $\boldsymbol{\xi}_{ij}$
θ_{jik0}	conjugated bond angle in the reference configuration
θ_{jik}	conjugated bond angle in the deformed configuration
Θ_{jik}	rotation angle of conjugated bonds in the deformed configuration
λ_t	rotation resistance stiffness
μ	scalar factor representing the broken of bond
ν	Poisson's ratio
$\boldsymbol{\xi}$	bond vector in the reference configuration
$\boldsymbol{\eta}$	relative displacement vector between two interacting material points
ρ	material density
$\boldsymbol{\chi}$	unit orientation vector of the bond
$\boldsymbol{\psi}$	unit orientation vector of the conjugated bond

the particle positions. The visibility criterion or some modification of it were also proposed in the meshfree methods for cracking [13–16]. Ventura et al. [17] enriched the MLS base functions around the crack tip to model kinked and curve cracks.

Although these numerical methods have been successfully applied to simulate the fracture problems, theories of these methods are in the framework of continuum mechanics, whose governing equations of motion are based on partial derivatives with respect to the spatial coordinates. The assumption of continuity in continuum mechanics is inherently insufficient for modeling cracks as partial derivatives are undefined along the crack faces where the displacement field is discontinuous. Therefore, some computation methods involving displacement gradients or higher-order spatial derivatives in a domain containing a crack must remove the discontinuous displacement field by redefining the discretized body so that the crack lies on the boundary or by using other techniques for evaluating the spatial derivatives on crack surfaces [9,18,19]. However, the peridynamic formulation eliminates the spatial derivatives altogether by solely depending on an integral formulation of the force acting at a continuum point, resulting in equilibrium equations that are valid everywhere in the body [20].

Please cite this article in press as: Zhou X et al. A novel conjugated bond linear elastic model in bond-based peridynamics for fracture problems under dynamic loads. Engng Fract Mech (2017), http://dx.doi.org/10.1016/j.engfracmech.2017.07.031