ARTICLE IN PRESS

Computers and Structures xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Computers and Structures

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

Modeling of failure mode switching and shear band propagation using the correspondence framework of peridynamics

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ARTICLE INFO

Article history:
Received 1 March 2018
Accepted 19 August 2018
Available online xxxx

Keywords:
Peridynamics
Adiabatic shear band
Crack propagation
Failure mode transition
Thermo-elasto-viscoplastic

ABSTRACT

This study presents an approach to model dynamic failure mode switching and shear band propagation using the correspondence framework of state-based peridynamics. To effectively model spontaneous shear-band-to-crack switching phenomenon, which is of intrinsic complexity, a combined peridynamic nonlocal and classical local damage model for failure prediction is proposed. The concept of bond failure, often employed in the bond-based peridynamic modeling of brittle materials, is extended to the state-based peridynamics to model cleavage failure in elasto-viscoplastic materials so that the directional and progressive nature of damage can be readily handled. The classical constitutive relation for viscous fluid is adapted for use in non-ordinary state-based peridynamics to model stress collapsing state in shear bands. To show the effectiveness of the proposed approach, a comprehensive numerical study of a pre-notched plate subjected to asymmetric impact loading is conducted, including the phenomenon of shear-band-to-crack switching under an intermediate impact velocity and ductile failure under high impact velocity. A zero-energy mode suppression with an upper bound to avoid over-correction is introduced. By using the proposed modeling approach, dynamic failure mode switching and shear band propagation path are accurately captured.

1. Introduction

The interest in failure mode transitions with increase of impact velocity was generated by the experimental work by Kalthoff and Winkler [1]. In the experiment, it was found that if the impact speed is below a critical value, brittle fracture initiates from the notch tip; if the impact speed is above the critical velocity, ductile failure takes place with a shear band propagating through the specimen. For one thing, the change of failure mode demonstrated in the Kalthoff-Winkler experiment is the opposite of the usual failure mode transition from ductile to brittle [2]; for another, shear bands require more energy to propagate than cracks do, indicating that slightly increasing impact velocity might dissipate more energy [3]. Therefore, it is of considerable interest to study failure mode transitions.

Though a lot of numerical studies of the Kalthoff-Winkler problem were reported, the results are not yet entirely satisfactory. Many numerical studies captured the phenomena of crack initiation at the notch tip and propagation at an angle to the notch-axis using various methods such as the cracking particle method [4–6], SPH using pseudo springs [7], peridynamics [8,9], the discontinuous Galerkin finite element method with the bond-based peridynamics [10], and the phase field model [11], but only a few demonstrated failure mode transitions by using numerical methods with special treatments including the extended finite element method [12], the finite element method with the node release technique [13], and extended meshfree methods [14–16]. In many prior simulations [7,8,11,10], the material of the specimen was treated as a brittle material with which numerical predictions of shear band are unachievable. Failure initiation was studied in several reported simulations [2,17,18]; failure propagation, however, was not modeled.

Zhou et al. [19] redesigned the Kalthoff-Winkler experiment to eliminate the interference of waves between notches by using a single notch specimen. An unusual phenomenon observed in the experiment is that when an impact velocity is below the critical velocity, a shear band initiates from the notch tip at first, and then suddenly the failure mode switches to brittle failure in the middle of the plate. This differs from the Kalthoff-Winkler experiment in which tensile cracks directly initiate from the notch tip. Few numerical simulations have showed the phenomenon of an initial formation of shear band followed by a tensile crack under the same impact velocity. Li et al. [20,21] successfully modeled such a failure

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https://doi.org/10.1016/j.compstruc.2018.08.007
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mode switching phenomenon using the mesh-free Galerkin method.

Peridynamics is a reformulated theory of continuum mechanics that does not require spatial derivatives. The primary advantage of peridynamics lies in its validity in the presence of discontinuities and its ability to model spontaneously occurred discontinuities [22]. The original peridynamic theory, which is referred to as bond-based peridynamics, was proposed by Silling [23]. The bond-based peridynamics has been widely used in analyzing dynamic fracture in various materials including composites [24–26], concretes [27,28], glasses [29–31], rock-like materials [32], functionally graded materials [33], etc. In addition, many works have been dedicated to enhancing peridynamics such as adaptive refinement [34,35], variable horizons [8,36], wave dispersion reduction [37], coupling of local and nonlocal domains [38–42], coupling of molecular dynamics and peridynamics [43], and coupling of local-continuum damage mechanics and peridynamics [44].

Two major problems associated with the bond-based peridynamic theory are its limitation on Poisson ratio and difficulties on adapting classical constitutive models into the peridynamic framework [45]. State-based peridynamics was then proposed to address the above-mentioned limitations of bond-based peridynamics. Ordinary and non-ordinary state-based peridynamics are two categories of state-based peridynamics [45]. For ordinary state-based peridynamics, bond forces always act in a direction parallel to the bond. On the other hand, non-ordinary state-based peridynamics does not have the restriction on the direction of bond forces. There is comparatively limited but a growing number of studies on ordinary state-based peridynamics [46–48]. Non-ordinary state-based peridynamics has been employed to study material deformations [49,50], metal machining [51], stationary crack problems [52], thermoplastic fracture [9], etc. Non-ordinary state-based peridynamics has a few inherent issues [46]. The presence of zero-energy modes has been found in the mathematical formulation of the peridynamic theory [46,52] as well as simulations [53,51].

This paper is aimed at a comprehensive modeling of shear-band-to-crack switching under one impact velocity and shear band propagation using the correspondence framework of peridynamics to takes full advantages of peridynamics in modeling of discontinuity and classical constitutive models in describing complex material behaviors. The modeling of initialization and propagation of shear band is still a challenge due to the small scale of the local deformation and very large strains [14]. The shear band morphology is difficult to be captured by finite element simulations as a result of mesh alignment sensitivity [21]. Failure mode switching and transitions pose another significant challenge for numerical simulations [21]. In this study, non-ordinary state-based peridynamics is employed to tackle complexities involved in numerical simulations of shear-band-to-crack switching and the evolution of shear band. A thermo-elasto-viscoplastic constitutive model with two competing failure criteria is incorporated into a peridynamic model. To deal with zero-energy modes that are inherent in peridynamics [46], a stability control scheme is applied.

The remaining of this paper is arranged as follows. Formulations for modeling dynamic failure mode switching and shear band propagation in the framework of state-based peridynamics are summarized in Section 2. The comprehensive numerical results are presented in Section 3. Finally, concluding remarks are summarized in Section 4.

2. Formulations

2.1. Non-ordinary state-based peridynamics formulation

The state-based peridynamic equation of motion is formulated as [45]

$$\rho\ddot{\mathbf{u}}[\mathbf{x},t]=\int_{\mathcal{H}_{\mathbf{x}}}\{\underline{\mathbf{T}}[\mathbf{x},t]-\underline{\mathbf{T}}[\mathbf{x}',t]\}dV_{\mathbf{x}'}+\mathbf{b}[\mathbf{x},t], \tag{1}$$

where $\mathbf{x}'$ is the position vector of material points within the neighborhood of $\mathbf{x}$. The neighborhood $\mathcal{H}_{\mathbf{x}}$ is typically defined by a sphere of radius δ, which is called the horizon (see Fig. 1). Any two material points within the horizon radius form a bond.

The relative position vector between two material points is denoted by

$$\xi=\mathbf{x}'-\mathbf{x}, \tag{2}$$

and the relative displacement is denoted by

$$\boldsymbol{\eta}=\mathbf{u}'-\mathbf{u}. \tag{3}$$

The deformation vector state is defined as

$$\underline{\mathbf{Y}}=\xi+\boldsymbol{\eta}. \tag{4}$$

The general form of a constitutive model in the state-based peridynamic theory is written as

$$\underline{\mathbf{T}}=\underline{\mathbf{T}}(\underline{\mathbf{Y}},\Lambda), \tag{5}$$

where $\underline{\mathbf{T}}$ is the force vector state field and Λ denotes all other variables.

2.2. Peridynamic correspondence material models

In this work, the total Lagrangian approach is adopted with the balance laws formulated in the referential configuration. The deformation gradient of peridynamic correspondence material models takes an approximate form as [45]

$$\mathbf{F}[\mathbf{x},t]=\left[\int_{\mathcal{H}_{\mathbf{x}}}\omega\underline{\mathbf{Y}}\otimes\xi dV_{\mathbf{x}'}\right]\mathbf{K}^{-1}=\mathbf{I}+\left[\int_{\mathcal{H}_{\mathbf{x}}}\omega\boldsymbol{\eta}\otimes\xi dV_{\mathbf{x}'}\right]\mathbf{K}^{-1} \tag{6}$$

where $\mathbf{K}$ is the non-local shape tensor defined as

$$\mathbf{K}=\int_{\mathcal{H}_{\mathbf{x}}}\omega\xi\otimes\xi dV_{\mathbf{x}'}, \tag{7}$$

in which ω is an influence function defined as

$$\omega=\omega(\|\xi\|,\mathbf{q},t) \tag{8}$$

that depends on the scalar $\|\xi\|$ and the internal variable $\mathbf{q}$. The internal variable is introduced into the influence function in order to consider material failure. Given a classical constitutive model, the first Piola-Kirchhoff stress tensor $\mathbf{P}$ can be calculated from the approximate deformation gradient

$$\mathbf{P}=\hat{\mathbf{P}}(\mathbf{F}[\mathbf{x},t]), \tag{9}$$

The force vector state is then calculated by using the stress tensor as an intermediate step [45]

$$\underline{\mathbf{T}}=\omega\mathbf{P}\mathbf{K}^{-1}\xi. \tag{10}$$

In the present study, a thermo-elasto-viscoplastic material model [54,21,20] is used to simulate dynamic crack propagation and shear band as

$$\dot{\varepsilon}_p=\dot{\varepsilon}_{p_0}\left[\frac{\bar{\sigma}}{g(\varepsilon_p,T)}\right]^m, \tag{11}$$

$$g(\varepsilon_p,T)=\sigma_0(1+\varepsilon_p/\varepsilon_0)^n\left\{1-\zeta\left[\exp\left(\frac{T-T_0}{\kappa}\right)\right]\right\}, \tag{12}$$

where $\bar{\sigma}$ is the von Mises effective stress, ε_p is the accumulated effective plastic strain, $\dot{\varepsilon}_{p_0}$ is a reference strain rate, σ_0 is the yield stress, m is a rate sensitivity parameter, n is the strain hardening exponent, $\varepsilon_0=\sigma_0/E$ is a reference strain, T_0 is the reference temperature, ζ and κ are thermal softening parameters.