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Wave dispersion analysis and simulation method for concrete SHPB test in peridynamics

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ABSTRACT

The Split Hopkinson Pressure Bar (SHPB) technique is a widely used method for measuring mechanical properties of materials subjected to high-strain-rate loads, while it is difficult to simulate the whole testing process including high-rate deformation, local damage and failure of materials by the common numerical methods. In this paper, an improved numerical approach based on the non-local peridynamic (PD) theory is employed to study the elastic wave dispersion and propagation and the impact failure of concrete Brazilian discs in SHPB test. Meanwhile, an improved PMB (Prototype Microelastic Brittle) model and an implementation method of the contact-impact process are introduced. In PD, the nonlocal long-range force controls the numerical dispersion of wave through different material point sizes and horizon sizes. The numerical dispersion can result in a slight distortion of the wave speed and crack propagation speed, which is not conductive to failure analysis of solids. The improved PMB model can effectively lessen the numerical dispersion compared with the original PMB model. Furthermore, the PD simulation of concrete Brazilian disc SHPB test can reproduce damage accumulation and progressive failure of a specimen, and produce typical final failure pattern. The PD simulation method for SHPB test can be used to analyze the dynamic response of solids suffering impact load.

1. Introduction

The Split Hopkinson Pressure Bar (SHPB) technique is a widely used method for measuring mechanical properties of materials subjected to high-strain-rate loads [1–3]. Researchers have explored the impact failure of a Brazilian disc in SHPB by experiments [4] and numerical methods, such as Finite Element Method (FEM) [5], Discrete Element Method (DEM) [6], Boundary Element Method (BEM) [7] and Discontinuous Deformation Analysis (DDA) [8]. However, it is difficult to simulate the whole testing process including high-rate deformation, local damage and failure of materials using the common numerical methods. Peridynamics (PD) is a new nonlocal theory and mesh-free method [9,10]. It has advantages in analyzing crack growth and severe damage of solids subjected to extreme load like impacts [11–15].

It is a fresh and interesting topic to simulate the Brazilian disc test in SHPB using PD. Jia and Liu first studied the wave propagation in SHPB with PD, paving the way for PD in SHPB simulation [16,17]. However, they ignored the fact that the wave dispersion plays a significant role in PD, and did not analyze the impact failure of specimens in SHPB. In this paper, the elastic wave dispersion and propagation in one dimension are studied and failure analysis of concrete Brazilian disc in SHPB test is conducted using the bond-based PD. A systematic PD simulation method for SHPB test is proposed and an

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Nomenclature

$\mathbf{x}, \mathbf{x}'$	the coordinate vector of material point in the reference configuration
$\mathbf{y}, \mathbf{y}'$	the coordinate vector of material point in the current configuration
$\mathbf{u}, \mathbf{u}'$	the displacement vector of material point $\mathbf{x}, \mathbf{x}'$, respectively
ξ	the relative position vector in the reference configuration
$\boldsymbol{\eta}$	the relative displacement vector in the current configuration
ρ	the mass density
$\mathbf{f}$	the constitutive force function
$\mathbf{b}$	the external force density
δ	the horizon
$c(0, \delta)$	the micro-modulus function
$g(\xi, \delta)$	the kernel function, or a spatial distribution function
s	the elongation of a PD bond
s_0	the critical elongation of a PD bond
μ	a factor mapping the breakage of bond
φ	the value of damage of a material point
E	the Young's modulus
ν	the Poisson's ratio
$dV_{\mathbf{x}'}$	the infinitesimal volume of material point $\mathbf{x}'$
V_p	the volume of material point $\mathbf{x}_p$
$\lvert\Delta x\rvert$	the grid spacing of the PD geometric model
Δt	the time-step size
V_{impact}	the impact velocity of the striker bar in SHPB
v	the elastic wave speed of a specific material
L_s	the length of a bar in SHPB
c_r	the repulsive constant coefficient

improved PMB (Prototype Microelastic Brittle) model considering an attenuation function of bond length is introduced. Meanwhile, the implementation of the contact-impact algorithm between two bars, or between a bar and a specimen, is introduced.

The elastic wave dispersion can result in a slight distortion of the wave speed and crack propagation speed, which is not conductive to failure analysis of solids under impact loading. Therefore, the wave dispersion problem in PD should be addressed. Silling first analyzed the plane wave propagation with PD and pointed out that the nonlocal long-range force controls the wave dispersion and that the dispersion behavior in PD is to some degree similar to that observed in some real materials [9]. Weckner et al. [18] and Wildman and Gazonas [19] showed that the PD horizon size and the material point size control the wave dispersion degree in numerical calculation. For the existence of wave dispersion in PD, Silling [9] and Weckner and Silling [20] conducted research to establish PD constitutive models from the measured dispersion relations. Wildman and Gazonas found that the numerical dispersion in PD is more obvious than that in Finite Difference Method (FDM) [19]. They further combined PD and FDM to reduce the numerical dispersion and simulate the wave propagation and dynamic crack growth effectively. Other studies were reported to investigate the wave propagation and failure analysis of solids subjected to wave interaction. Yu et al. compared the experimental, PD and FDM results of stress wave propagation of two bars after collision, all of which are in good agreement [21]. Becker and Lucas studied the propagation of 1D elastic wave subjected to impact loading [22]. Martowicz et al. studied the vibro-acoustic wave interaction in a cracked plate with PD and the wave propagation in graphene nanoribbons [23,24].

Extensive studies on constitutive modeling in the in the framework of both bond-based and state-based PD have been reported. However, we will not review them here due to space limitation. Since the bars in SHPB are perfectly matched, all of which act like one perfect bar under uniaxial compression, the contact forces between bars can be modeled by the constitutive force function [16]. Besides that, Medenci and Oterkus proposed a contact-impact algorithm between a rigid body and a deformable body [25], which is to be implemented to describe the interaction between bars and specimen in this paper.

The remainder of the paper is organized as follows. In Section 2.1, the basic theory of PD, the improved PMB model and the numerical implementation of PD are introduced. In Section 2.2, the modeling method of the impact loading that the striker exerts on the incident bar is described. In Section 2.3, the contact-impact algorithm between bar and specimen in SHPB is presented. Besides that, in Section 2.4 the repulsive force model between material points in specimens is described. In Section 3, the respective influence of constitutive model, horizon size and material point size on the wave dispersion in PD is investigated. In addition, the wave propagation of an unrestrained bar with a uniform strain after release is explored. In Section 4.1, the wave propagation in SHPB is further studied. In Section 4.2, the PD method for simulating the SHPB