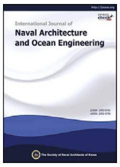
Available online at www.sciencedirect.com

ScienceDirect

Publishing Services by Elsevier

International Journal of Naval Architecture and Ocean Engineering xx (2016) 1−10

http://www.journals.elsevier.com/international-journal-of-naval-architecture-and-ocean-engineering/



Peridynamic simulation of brittle-ice crushed by a vertical structure

Minghao Liu, Qing Wang*, Wei Lu

College of Ship Engineering, Harbin Engineering University, Harbin 150001, China

Received 25 June 2016; revised 4 September 2016; accepted 18 October 2016

Available online ■ ■ ■

Abstract

Sea ice is the main factor affecting the safety of the Arctic engineering. However, traditional numerical methods derived from classical continuum mechanics have difficulties in resolving discontinuous problems like ice damage. In this paper, a non-local, meshfree numerical method called “peridynamics”, which is based on integral form, was applied to simulate the interaction between level ice and a cylindrical, vertical, rigid structure at different velocities. Ice in the simulation was freshwater ice and simplified as elastic-brittle material with a linear elastic constitutive model and critical equivalent strain criterion for material failure in state-based peridynamics. The ice forces obtained from peridynamic simulation are in the same order as experimental data. Numerical visualization shows advantages of applying peridynamics on ice damage. To study the repetitive nature of ice force, damage zone lengths of crushing failure were computed and conclude that damage zone lengths are 0.15−0.2 times as ice thickness.

Keywords: Numerical simulation; Ice−structure interaction; State-based peridynamics; Ice crushing; Ice forces

---

1. Introduction

With increasing interest in oil and gas exploration in cold regions, human activities in these areas are increasing. In Arctic region, the presence of sea ice is an important factor that contributes to the performance of naval architecture. For this reason, much research has focused on cold-region engineering. Vertical structure is a typical structural form in Arctic ocean engineering, such as the jacket platforms being widely used in Bohai Sea. Ice induced force during interaction of ice and vertical structures attracts great attention from scholars.

Sodhi and Morris (1984) conducted small-scale experiments to measure varied ice forces by pushing rigid cylindrical structures of different diameters at different velocities through a level ice sheet. The small-scale experiments showed that the characteristic frequency maintains a linear relationship with the ratio of velocity to thickness. Scale-model tests of interactions between level ice and conical structures were conducted by Tian and Huang (2012) to verify the lower ice force on the structure, and the experimental flexural strength results were discussed. From 2004 to 2005, Huang et al. (2007) conducted series of model tests to explore the mechanism that controls the procedure of ice induced vibration of vertical narrow piles and setup interaction coefficient that is able to reflect the interaction level of ice and structure. Yue et al. (2009) conducted full-scale tests of interaction between level ice and vertical compliant structures to study dynamic ice forces and structure vibrations. Regarding with loading rate, ductile, ductile−brittle transition and brittle ice failure were observed.

Ice damage during ice−structure interaction is a complex process of material failure. Numerical techniques for addressing discontinuities are of significant interest to researchers. But currently, it is short of a numerical method to simulate the complex failure process of ice (Bergan et al., 2010). For the macro approach based on continuum mechanics, the solution of governing equation is related to the partial derivatives of its stress and relative displacement. However, the numerical methods derived from classical

---

* Corresponding author.

E-mail address: wangqing@hrbeu.edu.cn (Q. Wang).

http://dx.doi.org/10.1016/j.ijnaoe.2016.10.003

Please cite this article in press as: Liu, M., et al., Peridynamic simulation of brittle-ice crushed by a vertical structure, International Journal of Naval Architecture and Ocean Engineering (2016), http://dx.doi.org/10.1016/j.ijnaoe.2016.10.003

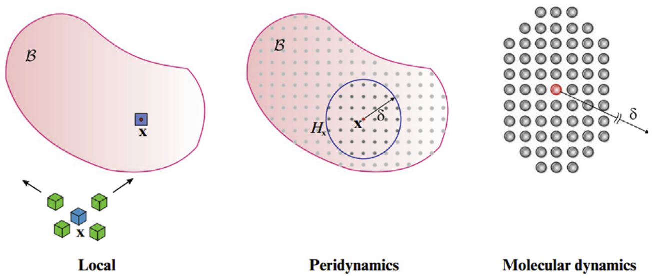
continuum mechanics, which has difficulties in resolving discontinuity, have also restricted the research progress of the polar ocean engineering. Peridynamics is a meshless method to solve the equation of motion by using integral form. Therefore, it has obvious advantages for the simulation of complex material damage.

Silling (2000) proposed the original peridynamic theory called *bond-based peridynamics* in 2000, and it reformulates the continuum mechanics equations. Similar to molecular dynamics, peridynamic equation of motion uses a nonlocal method to describe the force between particles, so that there is no requirement to know the crack location in advance. The essence of the equations is that integration rather than differentiation used in the calculation, which also avoids redefining the body of discontinuity (see Fig. 1). Brbaru et al. (2009) developed adaptive refinement algorithms for non-local peridynamics in elastic material regarding with one dimension model. In addition, compared with classical elasticity, they discussed many types of numerical convergence for peridynamics and obtained uniform convergence to the classical solutions of static and dynamic problems in one dimension in the limit of the horizon going to zero.

Even though bond-based peridynamics shows remarkable ability to deal with discontinuities in material like crack propagation, fracture and damage, its weak relationship with classical mechanics restricts its application on complicated material. As a result, Silling et al. (2007) proposed a more general form of peridynamics, called *state-based peridynamics*, which can adopt the constitutive model directly and reinforce the relationship between peridynamics and classical mechanics. Warren et al. (2009) applied state-based peridynamics to solve deformation and fracture problems in solid materials. Foster et al. (2010) proposed a method to implement a rate-dependent viscoplastic material within this peridynamic model.

The peridynamic theory overcomes weaknesses of existing methods and can simultaneously and spontaneously simulate all failure modes without simplifying assumptions. The efficiency and convenience of this numerical method facilitate its application in deformation and discontinuities of materials.

In this paper, we applied state-based peridynamics, which is a nonlocal theory that uses integration rather than differentiation to calculate material deformation and requires no need for a predefined crack propagation path, to simulate the interaction between level ice and a cylindrical, vertical, rigid structure at different velocities. The basic theory of state-based peridynamics and numerical methods as implemented in the simulation, such as discretization and time-integration stability, were introduced briefly. To implement a two-body interaction in the peridynamic model, an interaction force density in terms of relative positions in the current configuration was applied to prevent material particles that belong to different bodies from sharing the same position. To verify the feasibility and accuracy of applying the peridynamic method to ice—structure interactions, the peridynamic simulation results were compared with small-scale experiments. The results from numerical simulation, including the ice force values, repetitive nature of ice forces, phenomenon of damaged ice, damage zone length and characteristics of ice loading cycle were presented and analyzed.



Local

Peridynamics

Molecular dynamics

Fig. 1. Comparison of local method, peridynamics and molecular dynamics.

2. Theory of peridynamics

The peridynamic theory divides continuum into discrete material points, see Fig. 3. Therefore, the deformation of body can be described by displacements of points. Each material point interacts with its neighbors by nonlocal forces, see Fig. 2. Integrating the forces acting on a material point leads to its acceleration and velocity with help of Newton's law and avoids the mathematical problems faced in partial differential methods when addressing discontinuities (Silling, 2000). Furthermore, when the relative displacement of material points reaches a critical value, nonlocal force vanishes. This process means appearance of material failure. Additional criteria are not required for determining crack growth and branching, which allows crack growth and branching to proceed spontaneously.

Peridynamics introduces a “horizon” for each material point, in which the material points interact with each other by

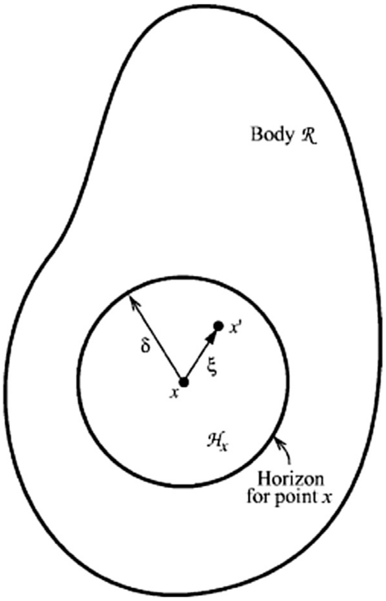


Fig. 2. Each point x in the body interacts with points in its horizon, δ is radius of horizon.

Please cite this article in press as: Liu, M., et al., Peridynamic simulation of brittle-ice crushed by a vertical structure, International Journal of Naval Architecture and Ocean Engineering (2016), http://dx.doi.org/10.1016/j.ijnaoe.2016.10.003