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Modelling mixed-mode fracture in poly(methylmethacrylate) using peridynamics

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Abstract

Peridynamics (Silling (2000)) is a non-local continuum theory that is particularly suited to handle discontinuities in the displacement field, such as those arising during fracture. Peridynamics prescribes that each material point interacts with all its neighbors contained in a sphere of given radius; this assumption introduces a characteristic length scale in the continuum description. In a nutshell, the interactions between material points depend on their relative distance; in the peridynamics framework this distance is called the “bond length”. The equations of motion, holding at each material point, link the material point acceleration to the integral over the point neighborhood of a force density field, whose strength depend on bond-stretches, i.e. the ratio of the actual bond-length over the initial one. In these equations the displacement gradient does not appear, thus naturally allowing for discontinuities in the displacement field to occur. As to failure, the simplest possible damage description is provided by an interaction law prescribing the force to vanish when a critical bond-stretch threshold is crossed; this parameter can be related to the Mode I critical strain energy release rate. A single parameter is needed to describe failure, in principle under every possible loading condition.
In this work the predictive abilities of peridynamics were checked against experimental results in the case of mixed-mode failure of brittle polymers. Pre-cracked poly(methylmethacrylate) (PMMA) samples were tested using different specimens, in order to obtain Mode I, Mixed-Mode and Mode II loading conditions. The material was assumed to behave according to a peridynamics brittle elastic material model; the parameters needed to calibrate the elastic behavior were determined from Mode I tests, as was the critical stretch.The peridynamics simulations of mixed-mode tests were able to catch the correct fracture initiation load and to provide a fair description of the crack path under different conditions. The peridynamics model was also able to qualitatively capture the typical “nail” shape assumed by the crack front during propagation.

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1. Introduction

Peridynamics is a non-local theory that describes the mechanical behavior of continua; it was originally introduced by Silling (2000) with the explicit objective of tackling fracture problems. The primary feature allowing peridynamics to deal with the nucleation and the evolutions of cracks, and generally with discontinuous displacement fields, is its representation of the equation of motion in an integro-differential form rather than by the partial differential equation form which is common in classical continuum theories. Using such a formulation the constraints on the smoothness of the displacement field which are typical of the classical continuum models can be significantly relaxed, as long as the integral appearing in the motion equations (see Sec.2) can be evaluated. The non-local character of peridynamics arises from the fact that each material point (sometimes called a "particle" in peridynamics) is allowed interacting, via a force field, with all the other material points within a given distance; the latter is called the horizon and is assumed to be a material property. This formulation allows dealing with problems involving an intrinsic length scale.

Different peridynamics formulations are available; they differ mostly for the type of interactions that are allowed between material points. In the so called bond-based formulation, see Silling (2000), the material points interact in a pairwise fashion as if they were connected by a spring network; the force exchanged between two particles is always directed as the line joining the material points themselves. Bond-based formulations are somewhat limited and to overcome their limitations the so called state-based formulations were introduced by Silling et al. (2007); in these formulations the force exchanged by two particles depends on the collective deformation of the material inside the horizon of a given material particle.

The first peridynamics models were initially developed for homogenous isotropic elastic materials but nowadays there are peridynamics constitutive models to mimic the behavior of fiber reinforced composites (see for example Oterkus and Madenci (2012)), of plastic (Mitchell (2011)) and of viscoplastic materials (Foster et al. (2010)); it has been shown that classical material models can be used within the peridynamics framework following a standard adaptation procedure (see Silling et al. (2007) for a thorough discussion of this issue). Initially developed only to model the mechanical behavior of continua, peridynamics has been extended to include the thermal behavior (see Madenci and Oterkus (2013) for a discussion) and also to be used in multiphysics settings, as for example in the work by Oterkus et al. (2013).

Irrespective of the material model used, peridynamics easily allows a representation of cracks initiation and propagation by adding a fracture criterion, which is usually specified as a critical event that suppresses the interactions between neighboring material points. The most commonly used criteria are strain based, similarly to what was proposed by Silling and Askari (2005) for their bond-based formulation, and usually depend on single parameter. Peridynamics has been applied to model failure in engineering applications: for instance, it was used to model failure of concrete slabs under impact, to study crack branching under dynamic conditions by Ha and Bobaru (2010) and to study the failure of microelectronics packaging by Agwai et al. (2008). However, most of the technical literature deals with the development of material models and with the development of numerical techniques to solve peridynamics problems—which are very important as the complexity of peridynamics equations makes analytical solutions nearly impossible to find—and relatively little attention has been devoted to the quantitative evaluation of the predictive capabilities of peridynamics fracture models. Madenci and Oterkus (2013, chapter 6) checked the predictions of a simple failure model against the data generated with the mixed mode specimen proposed by Ayatollahi and Aliha (2009), finding fair agreement as to the fracture load and a good agreement with respect to the predicted fracture paths.

To contribute to the validation of peridynamics predictions, in this work we use peridynamics to model failure of PMMA using different specimens to generate different mixed mode conditions; after a brief review of the basics of