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A homogenized localizing gradient damage model with micro inertia effect

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The conventional gradient enhancement regularizes structural responses during material failure. However, it induces a spurious damage growth phenomenon, which is shown here to persist in dynamics. Similar issues were reported with the integral averaging approach. Consequently, the conventional nonlocal enhancement cannot adequately describe the dynamic fracture of quasi-brittle materials, particularly in the high strain rate regime, where a diffused damage profile precludes the development of closely spaced macrocracks. To this end, a homogenization theory is proposed to translate the micro processes onto the macro scale. Starting with simple elementary models at the micro scale to describe the fracture mechanisms, an additional kinematic field is introduced to capture the variations in deformation and velocity within a unit cell. An energetic equivalence between micro and macro is next imposed to ensure consistency at the two scales. The ensuing homogenized microforce balance resembles closely the conventional gradient expression, albeit with an interaction domain that decreases with damage, complemented by a micro inertia effect. Considering a direct single pressure bar example, the homogenized model is shown to resolve the non-physical responses obtained with conventional nonlocal enhancement. The predictive capability of the homogenized model is furthermore demonstrated by considering the spall tests of concrete, with good predictions on failure characteristics such as fragmentation profiles and dynamic tensile strengths, at three different loading rates.

1. Introduction

There are two major challenges when developing a continuous model at the macro scale for dynamic fracture: (i) the material responses and failure characteristics are rate dependent; (ii) standard continuum models become mesh sensitive during strain softening. In this contribution, we focus on the development of a homogenized gradient damage model that is energetically consistent with a higher resolution formulation at the micro scale. Predictions by the homogenized model are regularized, with sharp localized damage profiles corresponding to the development of macro cracks. Furthermore, the predicted fragmentation profiles and dynamic tensile strengths compare well against experimental data.

The dynamic fracture of a quasi-brittle material typically involves: (i) nucleation and propagation of inherent micro cracks; (ii) interactions between micro cracks to form new cracks; (iii) development of fragments; and (iv) elastic unloading of surrounding bulk materials during crack propagation (Meyers et al., 1994; Shockey et al., 1974). Failure characteristics

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such as the dynamic tensile strength, fragmentation profile and average fragment size, at various loading rates and with different material properties, are important issues in dynamic applications. The analysis of a fragmentation process, however, is a challenging topic, since it involves several mechanisms of different length and time-scales.

One popular strategy is to adopt cohesive interfaces to describe the development of micro cracks. This approach captures directly the interactions between bulk materials and micro cracks, and has been utilized in literature to study the dynamic fragmentation characteristics of quasi-brittle materials (Cereceda et al., 2017; Espinosa et al., 1998; Levy and Molinari, 2010; Levy et al., 2012; Zhou et al., 2005). Although the physical mechanisms underlying a fragmentation event are well described, such a high resolution approach may not be suitable for practical engineering applications.

At the lower end of the resolution spectrum, continuum damage models smear out the discrete micro cracks underlying a fracture process. This approach provides the overall material response, and is thus computationally more amenable. Standard continuum models, however, are mesh sensitive during strain softening (Bažant, 1975). One popular remedy is to adopt nonlocal enhancements to regularize the softening response. Broadly speaking, the spatial average of a damage driving variable over an interaction domain, is incorporated into the constitutive law. This is first formulated in the integral form (Bažant et al., 1984; Bažant and Jirásek, 2002; Bažant and Pijaudier-Cabot, 1988; Jirásek, 1998; Pijaudier-Cabot and Bažant, 1987), and later rewritten as a differential equation, commonly known as the implicit gradient approach (Pamin, 2005; Pamin and Wosatko, 2012; Peerlings et al., 1996; 1998; 2004). Alternatively, the implicit gradient equation can be understood as a balance law in a generalized micromorphic continuum (Dillard et al., 2006; Forest, 2009; 2016).

Whereas the structural responses are made mesh independent, the conventional nonlocal enhancement induces a non-physical evolution of damage. With the gradient approach, a spurious damage growth leading to a diffused damaged region was observed in quasi-static analyses (Geers et al., 1998; Saroukhani et al., 2013; Sun and Poh, 2016). Deficiencies such as wrong crack initiation and propagation processes were also reported (Poh and Sun, 2017; Simone et al., 2004). These limitations may lead to a wrong prediction of failure mode, e.g. in the presence of a diffused damage profile, Wosatko et al. (2015) highlighted the difficulty for an expected punching cone profile to develop in a reinforced concrete slab. Similar issues concerning spurious damage growth have been reported with the integral approach for quasi-static (Nguyen, 2011; Simone et al., 2004) and dynamic problems (Giry et al., 2011; Pereira et al., 2016).

The need for accurate predictions of failure characteristics at different loading rates, e.g. dynamic tensile strength and fragmentation profiles, poses another challenge in the development of a damage model for dynamic fracture. In literature, strain rate dependent constitutive laws are commonly adopted (e.g. Das, 2016; Ožbolt et al., 2015; Ožbolt et al., 2006; Pereira et al., 2016; Pereira et al., 2017). In general, however, the postulation of suitable relations and calibration of parameters can be difficult.

At this juncture, it is highlighted that a phenomenological, stress-based nonlocal enhancement with the integral formulation has been proposed by Giry et al. (2011), and adopted for the dynamic fracture of concrete, with predictions that compare well with experimental data (Pereira et al., 2016; 2017). Based on the asymptotic homogenization scheme, a two scale model for dynamic fracture with a viscous type damage evolution law has also been developed, for cases with moderate macro accelerations such that inertia effects at the micro scale can be neglected (Dascalu, 2016; François and Keita, 2015; Keita et al., 2014). Against this backdrop, the objective in this paper is to develop a homogenized damage model based on elementary models at the micro scale, for applications in the regime with significant micro inertia effect, at a lower computational cost compared to a high resolution modeling approach. Also, it is of interest to remedy the limitations of conventional nonlocal enhancements, by having regularized structural responses with localized damaged profiles at failure. To this end, the bottom-up homogenization theory in Sun and Poh (2016) is reformulated here for the dynamic fracture of quasi-brittle materials. For simplicity, we consider only problems in one-dimensional settings.

This paper is organized as follows. In Section 2, a brief summary of a direct single pressure bar problem is provided to establish an analytical damage initiation location. This is next solved with the conventional gradient damage model in Section 3, where a wrong damage initiation, a spurious damage growth and a free boundary effect are demonstrated. In Section 4, an empirical relation for average fragment sizes at different strain rates is highlighted, which provides the physical length scale in our framework. The bottom-up homogenization strategy is elaborated in Section 5, starting with the specific choice of a unit cell comprising of two micro cracks. At the micro scale, an elementary model with cohesive interfaces is adopted to describe the development of micro cracks. A key contribution is in the introduction of an additional damage strain kinematic field, to characterize the average displacement jumps within a unit cell. The linearization of this macro kinematic field thus enables the framework to describe the variations in deformation and velocity within a unit cell. The corresponding potential and kinetic energy densities of a unit cell are next translated consistently onto the macro scale following the Hill–Mandel condition. Finally, the macro governing equations are extracted via Hamilton's Principle. The ensuing homogenized microforce balance, discussed in Section 6, resembles the conventional gradient expression closely, albeit with a nonlocal effect that vanishes with damage, as well as a micro inertia effect that manifests itself naturally through the bottom-up strategy. The performance of the homogenized model is demonstrated numerically in Section 7, where it is shown to remedy the limitations of a conventional nonlocal enhancement in the direct single pressure bar test. Its good predictive capability is furthermore demonstrated by considering the spall test of concrete, benchmarked against experimental data at three loading rates.