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Calibration of nonlocal models for tensile fracture in quasi-brittle heterogeneous materials

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ABSTRACT

A new calibration strategy for integral-type nonlocal damage models for quasi-brittle materials is proposed. It is based on the assumption that in the fracture process zone in quasi-brittle materials the large majority of energy is dissipated in a localised rough crack. Measuring the roughness of the fracture surface allows for calibrating the interaction radius of nonlocal models by matching experimental and numerical standard deviations of spatial distributions of dissipated energy densities. Firstly, fracture analyses with a lattice model with random fields for strength and fracture energy are used to support the assumptions of the calibration process. Then, the calibration strategy is applied to an integral-type nonlocal damage model for the case of a fracture surface of a three-point bending test.

1. Introduction

Fracture in quasi-brittle heterogeneous materials, such as concrete, rock, stiff soils, wood and bones, is characterised by the formation of a finite nonlinear zone ahead of a macroscopic crack in which energy is dissipated; it is defined as the Fracture Process Zone (FPZ). The size of this zone influences the load capacity of structures and is one of the parameters which determine a size effect on the nominal strength of structural members specific for quasi-brittle materials (Bažant, 2002).

Integral-type nonlocal models are often used for describing the fracture process of quasi-brittle materials (Pijaudier-Cabot and Bažant, 1987; Bažant and Jirásek, 2002). In these models, the stress at a point is determined by a weighted spatial average of state variables in the vicinity of this point. The size of the vicinity in which the averaging is performed is determined by the nonlocal interaction radius. Integral-type nonlocal models describe localised fracture by narrow, but finite, regular strain profiles. This is the main difference to nonlinear fracture mechanics approaches, such as cohesive crack models, in which localised fracture is described by displacement jumps. Integral-type nonlocal models are popular because they provide results, which are mesh size and orientation insensitive for both tensile and compressive failure. The nonlocal averaging should describe the finite FPZ experimentally observed in heterogeneous materials.

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The FPZ in concrete was studied by acoustic emission tests by, for instance, Mihashi et al. (1991), Landis (1999), Otsuka and Date (2000), Haidar et al. (2005), Muralidhara et al. (2010), and Grégoire et al. (2015) in which acoustic signals originating from fracture events are spatially located and the strength of the signal is used to differentiate between the magnitude of energy dissipation of events. Other studies include techniques to record the displacements (Cedolin et al., 1987; Wu et al., 2011; Skarżyński et al., 2011) and fracture surface measurements (Lange et al., 1993; Mourot et al., 2006; Morel et al., 2008; Ponson et al., 2006). Despite providing important insight into fracture processes in quasi-brittle materials, these investigations have not yet resulted in calibration strategies for the interaction radius of nonlocal models. In other studies it has been suggested to determine the nonlocal radius by inverse calibration based on structural results (Bažant and Pijaudier-Cabot, 1989; Carmeliet, 1999; Bellégo et al., 2003; Jirásek et al., 2004; Iacono et al., 2006, 2008). One of the disadvantages of inverse calibration is that the parameters strongly influencing the width of the fracture process zone, such as the nonlocal radius in integral type nonlocal models, are obtained using structural results unrelated to this width. Consequently, a good fit of structural results may lead to completely unrealistic widths of fracture process zones. For instance, in Jirásek et al. (2004), simultaneous fitting of size effect data for nominal strength and nominal fracture energy, resulted in a nonlocal radius of 75 mm, which corresponds to much wider FPZs than observed in experiments.

In this work, a new, more direct calibration procedure for the nonlocal radius of integral type nonlocal models is proposed, by matching experimentally and numerically determined dissipated energy densities. Optical profiling techniques (Mourot et al., 2006) are used to measure the roughness of the crack surface obtained from a three point bending test. This crack surface profile is then used to compute the standard deviation of the distribution of the deviation of the height of the crack surface from the mean crack plane. If the final rough crack is the dominant source of dissipated energy and the, usually varying, energy per crack length can be considered, for the purpose of the calibration, to be uniform, then this standard deviation is equal to the standard deviation of the dissipated energy density profile obtained by a nonlocal model from, for instance, a uniaxial tensile test. Matching the experimentally and numerically determined standard deviations provides the link between the fracture process zone and the nonlocal radius.

One of the assumptions of this calibration procedure is that the large majority of energy dissipated in the fracture process zone originates from the crack which forms the main fracture surface, for which the roughness is measured. This assumption is supported by experimental results (Cedolin et al., 1987), and numerical and analytical modelling results (Planas et al., 1992; Nirmalendran and Horii, 1992; Bolander et al., 1998). Furthermore, it is assumed that the dissipation along the crack surface can be considered to be uniform for the purpose of the calibration. The validity of these assumptions is investigated here by qualitative two-dimensional meso-scale analyses of direct tensile tests of a periodic specimen in plane stress using a lattice model developed in Grassl and Jirásek (2010), which is conceptually similar to models reported in Zubelewicz and Bažant (1987), Herrmann et al. (1989), Schlangen and Van Mier (1992), Bolander and Saito (1998), Bolander et al. (1998), and Delaplace et al. (1996). For these lattice analyses, the heterogeneity of the material is idealised by a single isotropic autocorrelated random field for strength and fracture energy generated by a spectral representation method (Shinozuka and Jan, 1972) used previously for lattice modelling of fracture in Grassl and Bažant (2009) and Grassl and Jirásek (2010). This type of lattice analyses of tensile fracture has been shown to provide qualitatively realistic results (Grassl and Jirásek, 2010; Grassl et al., 2015) and, if calibrated appropriately, can provide a good agreement with fracture experiments (Grassl et al., 2012; Grégoire et al., 2015). In the present study, the modelling approach is only used to investigate the validity of the assumptions of the calibration procedure and a direct comparison with experiments or macroscopic nonlocal modelling results is not carried out.

The aim of this study is to propose a new calibration strategy for the interaction radius of nonlocal models based on surface roughness measured in experiments. To the authors' knowledge, this is the first time that a quantitative calibration procedure for the nonlocal radius based on local experimentally measurable results with strong physical meaning is proposed in the literature. This application of the calibration procedure is illustrated for concrete in the present work. It is anticipated that it can be applied to a wide range of other quasi-brittle heterogeneous materials.

2. Calibration procedure

In this section, the proposed calibration procedure for nonlocal approaches to modelling tensile failure in concrete is described. The objective of the calibration procedure is to determine the interaction radius which is used in nonlocal models to describe the weighted average of history variables in the vicinity of a point. The calibration procedure, illustrated in Fig. 1, is described by the following steps:

1. Perform a fracture test to obtain a crack surface. Determine the fracture energy. Measure the distribution of roughness of the fracture surface, defined as the height deviation of the crack surface from the mean plane. Evaluate the standard deviation of this roughness distribution (Fig. 1(a)).
2. Perform a numerical or analytical analysis of a 1D uniaxial tensile test with the nonlocal model to be calibrated to determine the dissipated energy density profile. Evaluate the standard deviation of this dissipated energy density profile (Fig. 1(b)). Here, the standard deviation is computed as the spatial deviation from the centre of density profile. It has, as the standard deviation of the roughness, the unit of length.