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Strain injection techniques in dynamic fracture modeling

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Abstract

A computationally affordable modeling of dynamic fracture phenomena is performed in this study by using strain injection techniques and Finite Elements with Embedded strong discontinuities (E-FEM). In the present research, classical strain localization and strong discontinuity approaches are considered by injecting discontinuous strain and displacement modes in the finite element formulation without an increase of the total number of degrees of freedom. Following the Continuum Strong Discontinuity Approach (CSDA), stress–strain constitutive laws can be employed in the context of fracture phenomena and, therefore, the methodology remains applicable to a wide number of continuum mechanics models. The position and orientation of the displacement discontinuity is obtained through the solution of a crack propagation problem, i.e. the crack path field, based on the distribution of localized strains. The combination of the above mentioned approaches is envisaged to avoid stress-locking and directional mesh bias phenomena.

Dynamic simulations are performed increasing the loading rate up to the appearance of crack branching, and the variation in terms of failure modes is investigated as well as the influence of the strain injection together with the crack path field algorithm. Objectivity of the presented methodology with respect to the spatial and temporal discretization is analyzed in terms of the dissipated energy during the fracture process. The dissipation at the onset of branching is studied for different loading rate conditions and is linked to the experimental maximum velocity observed before branching takes place.

Keywords: Fracture dynamics; Strong discontinuity approach; Crack path field; Strain injection techniques

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1. Introduction

Fracture phenomena in engineering structures are strongly influenced by the loading rate which has a clear effect on the strength, stiffness and ductility of the material [1]. At high strain rates, inertial forces play a dominant role over

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possible viscous behaviors in quasi-brittle and brittle materials and lead to crack curving and branching phenomena when a critical crack tip velocity is exceeded [2]. In order to account for the progressive increase of resistance at high strain rates it becomes crucial to accurately simulate materials designed to perform at such extreme loading conditions. Studies on rate dependent behavior of civil engineering materials such as concrete have been conducted by Reinhardt [1] showing that, at loading strain rates higher than 10 s^{-1}, the increase of structural resistance is mainly motivated by the inertial forces.

Experimental results on different types of brittle and quasi-brittle materials report that when a critical crack tip velocity is met, unstable crack propagation takes place and mode I fracture tends to change to mixed mode [2–5]. In general, an increase of the crack tip propagation speed is observed upon increasing loading rates until a certain fraction of the Rayleigh wave speed in the material is met. This fraction varies upon the material but the maximum crack tip velocity is always bounded by the Rayleigh surface wave speed. Once the critical velocity is reached, the crack may branch and the immediate resulting velocities of the branched cracks are found lower than the original speed although they might increase upon increasing loading rate. Indeed, there is a relation between the maximum crack velocity and the wave velocities in the medium, since those areas ahead of the crack tip that are not yet affected by the pressure waves cannot undergo any fracturing phenomena. Moreover, if one considers that a single crack cannot propagate beyond a certain velocity, the corresponding dissipation is, therefore, also bounded. In such scenario it seems reasonable that a possible mechanism to increase the dissipation rate consists of an increase of the fracture surface which is directly connected to the branching phenomena.

Dynamic fracture phenomena is in general difficult and expensive to study through experimental setups due to its fast occurrence and because the loading conditions are often not straightforward to reproduce in a laboratory. For this reason, numerical algorithms are regarded as valuable tools for its simulation and design of improved materials. Finite element methods (FEM) for solving general dynamic fracture problems show some limitations, and have not been widely adopted in the literature. In some cases, FEM fail to predict experimental tests, and according to [6], the capacity for adequately modeling this kind of problem through FE simulations is yet negative. Works involving cohesive interface elements (inter-elemental enrichment) for dynamic problems have been addressed by Falk et al. [7] and Pandolfi et al. [8]. Intra-elemental enrichments have been used in Song and Belytschko [9] and Linder and Armero [10] to model cracks intersecting the FE mesh, among other authors. Recent advances in the phase-field modeling led to impressive 2D and 3D results but at the cost of extremely fine FE discretizations [11–13]. A softening visco-elastic visco-plastic damage continuum model has been employed for dynamic fracture of concrete up to intermediate loading rates in [14,15] where the visco-plastic contribution is used to regularize the model. Erosion or element deletion models proposed by Camacho and Ortiz [16,17] have proven to be powerful methods specially for the modeling of fragmentation and spalling processes. Besides this, many alternative numerical methodologies have been addressed with some success, e.g. peridynamics [18,19], discrete methodologies such as lattice models [20] and mesh-free methodologies [21], to mention a few.

One of the main challenges when modeling these type of problems employing finite element methodologies consists in the accurate description of the strong discontinuity arising during crack nucleation and growth. The complex geometry concerning the dominant crack paths may involve branching and sudden changes of the crack propagation direction. Furthermore, successful energy convergence studies are hard to find. Besides the challenge of accurately modeling complex failure phenomena, it is the objective of the present contribution to present a computationally affordable methodology compared to those techniques (supra-elemental techniques) that model strain localization phenomena with an explicit discretization of the failure band with the corresponding increase of the number of finite elements.

The present contribution focuses on the description of a finite element method developed for analyzing a specific range of crack propagation problems in specimens undergoing rapid loading conditions with the presence of a dominant crack. Brittle or quasi-brittle fracture is considered and dynamic fracture problems involving fragmentation or spalling are left outside the scope of our study. The concept of embedded discontinuities (cf. [22,23]), utilized for the study of fracture in quasi-brittle materials and successfully applied to the study of tensile crack growth in gravity dams (cf. [24,25]), is regarded as the starting point for the technique presented in this contribution. Particularly, the formulation developed by Oliver et al. [26] and assessed for quasi-static multiscale fracture problems, is adopted together with an injection procedure which is specifically tailored for dynamic fracture propagation problems. Cracks, represented by strong discontinuities embedded into the finite elements, may intersect the mesh in arbitrary directions and, therefore, relatively coarse meshes can be employed which positively impacts the computational cost of the analyses.