Comput. Methods Appl. Mech. Engrg. 274 (2014) 289–348

Contents lists available at ScienceDirect

Comput. Methods Appl. Mech. Engrg.

journal homepage: www.elsevier.com/locate/cma

Crack-path field and strain-injection techniques in computational modeling of propagating material failure

J. Oliver [a,b,*], I.F. Dias [c], A.E. Huespe [b,d]

[a] E.T.S. d'Enginyers de Camins, Canals i Ports, Technical University of Catalonia (BarcelonaTech), Campus Nord UPC, Edifici C-1, c/Jordi Girona 1-3, 08034 Barcelona, Spain
[b] International Center for Numerical Methods in Engineering (CIMNE), Campus Nord UPC, Edifici C-1, c/Jordi Girona 1-3, 08034 Barcelona, Spain
[c] Laboratório Nacional de Engenharia Civil (LNEC), Avenida Brasil 101, 1700 Lisboa, Portugal
[d] INTEC-UNL-CONICET, Güemes 3450, Santa Fe, Argentina

ARTICLE INFO

Article history:
Received 5 August 2013
Received in revised form 3 December 2013
Accepted 7 January 2014
Available online 31 January 2014

Keywords:
Fracture
Computational material failure
Strong discontinuities
Crack-path field
Strain injection
Finite elements with embedded discontinuities

ABSTRACT

The work presents two new numerical techniques devised for modeling propagating material failure, i.e. cracks in fracture mechanics or slip-lines in soil mechanics. The first one is termed *crack-path-field* technique and is conceived for the identification of the path of those cracks, or slip-lines, represented by strain-localization based solutions of the material failure problem. The second one is termed *strain-injection*, and consists of a procedure to insert, during specific stages of the simulation and in selected areas of the domain of analysis, goal oriented specific strain fields via mixed finite element formulations. In the approach, a first injection, of elemental constant strain modes (CSM) in quadrilaterals, is used, in combination of the crack-path-field technique, for obtaining reliable information that anticipates the position of the crack-path. Based on this information, in a subsequent stage, a discontinuous displacement mode (DDM) is efficiently injected, ensuring the required continuity of the crack-path across sides of contiguous elements. Combination of both techniques results in an efficient and robust procedure based on the staggered resolution of the crack-path-field and the mechanical failure problems. It provides the classical advantages of the "intra-elemental" methods for capturing complex propagating displacement discontinuities in coarse meshes, as E-FEM or X-FEM methods, with the non-code-invasive character of the crack-path-field technique. Numerical representative simulations of a wide range of benchmarks, in terms of the type of material and the failure problem, show the broad applicability, accuracy and robustness of the proposed methodology. The finite element code used for the simulations is open-source and available at http://www.cimne.com/compdesmat/.

1. Introduction

In the context of this work, the concept *material failure* refers to the process of deterioration of the mechanical behavior in solids, produced by the reduction of the strength of the constituent material in localized domains, which, from a macroscopic view, constitute a manifold one-dimension smaller than the domain of analysis. Cracks, in fracture mechanics, and shear

---

[*] Corresponding author at: E.T.S. d'Enginyers de Camins, Canals i Ports, Technical University of Catalonia (BarcelonaTech), Campus Nord UPC, Edifici C-1, c/Jordi Girona 1-3, 08034 Barcelona, Spain. Tel.: +34 934016490.

E-mail addresses: xavier.oliver@upc.edu (J. Oliver), idias@lnec.pt (I.F. Dias), ahuespe@intec.unl.edu.ar (A.E. Huespe).

http://dx.doi.org/10.1016/j.cma.2014.01.008

bands (or slip-lines), in soil mechanics, are examples of names given, in different areas of mechanics, to these *failure manifolds*. In addition, it is accepted that, at the macroscopic observation scale, that deterioration of the mechanical strength translates into discontinuities of the displacement field across those failure manifolds. These discontinuities in the displacement field will be technically termed *strong discontinuities*, in contrast with discontinuities in the strain field that are termed *weak discontinuities* [41]. Moreover, it will be assumed that those failure manifolds (cracks or slip-lines) evolve along time (the term *evolving discontinuities* has been also coined for this case) *in the sense of propagation*. Once they appear they remain in a stationary position, but they can grow (propagate) in the domain of interest from the borders of the failure manifold (the crack or slip-line tips). The term *strain localization* will be used also to indicate that scenario in which weak discontinuities appear in the form of highly intensified strains in propagating narrow bands (the *localization bands*).

Material failure mechanics is a subject of large interest in simulation based sciences, where the term *computational material failure mechanics* has been coined. This work makes some new proposals in this area, which aim at improving the performance, in front of alternative approaches, of reliability, accuracy and robustness, of computational simulations of propagating material failure.

1.1. Motivation

The aim of this work is the presentation of an approach, rather than its generalization. Therefore, for the sake of simplicity, the mechanical ingredients of the approach have been simplified in some aspects: (1) the kinematical description of the motion is simplified to *infinitesimal strains*, (2) the *dimensions of the problem*, are here reduced to the *2D cases*, (3) *dynamic effects have been neglected* and (4) *thermal effects have been discarded*. The authors are aware that the extension of the present work to account for some of those effects, typically 3D analysis and inertial effects, will open new, relevant and specific areas of application and, therefore, they will be considered in subsequent works.

During the last decades, a large number of proposals of models for propagating material failure have been done by the computational mechanics community, whose classification can be done on different grounds. In the context of the present work, two different classification criteria are chosen: (1) the kind of constitutive model at the failure manifold and (2) the procedure through which the displacement discontinuities, inherent to material failure modeling, are captured in the context of finite element methods.

1.1.1. Constitutive model description of the failure manifold

The first criterion refers to the manner that the de-cohesion process at the crack or slip-line interface is modeled:

- In the so called (de)*cohesive* (or discrete) *approaches* the mechanical behavior is described in terms of a traction-separation law relating, by means of a non-linear relationship, the traction vector and the vector of displacement jump across the interface. In this law, the introduction of the fracture energy, as a material property identified as the dissipation per unit of surface along a full decohesion process, plays a fundamental role to make these models physically meaningful [25,27,8].
- The continuum counterpart of the previous approach is the *continuum approach*, where the mechanical behavior of the interface is described in terms of a standard stress–strain constitutive model, equipped with strain softening, to account for the stress release associated to failure. The difficult point here is to relate the “interface strain” intervening in the constitutive model with the physically meaningful displacement jump. The *Continuum Strong Discontinuity Approach* (CSDA), developed by the authors, among others, in the past [60,45], provides this link by introducing the concept of *regularized strong discontinuity kinematics* (a regularized version of the description of the displacement jump at the interface in terms of a Dirac’s delta function) which allows describing the corresponding regularized interfacial strain. In the CSDA it is shown that any continuum stress–strain constitutive model, when applied to a strain field described by a regularized strong discontinuity kinematics induces an equivalent (projected) traction-separation law at the discontinuity interface. This provides a clear link between continuum and discrete approaches [49] that allows using the format of implementation considered most convenient, but keeping the physical meaning of the approach. In this sense, it can be argued in favor of the continuum approach that the same constitutive model, whenever it is equipped with strain softening, can be used for both the continuous domain and the discontinuity interface and, at a given material point, for both the undamaged and the failure stages, this leading to advantages as a less invasive implementation in commercial finite element codes or an easier identification of the material parameters.

1.1.2. Numerical approach for displacement jumps capturing

The second classification of interest here is the one in terms of the selected numerical approach for crack/slip-line capturing. Considering the capture of the propagating jump in the displacement field as the ultimate goal of the numerical simulation, the available approaches can be split into three groups.

- The *strain-localization-based methods* take advantage of the trend of continuum (stress–strain) constitutive models, equipped with strain softening, to provide solutions of the mechanical problem exhibiting strain localization in strain-localization bands. These localization-bands tend to propagate along finite element bands that, under ideal conditions, encompass just one element. In this context a strain-localization band can be interpreted as the strain field stemming