Engineering Fracture Mechanics 150 (2015) 96–114

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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

A crack-tracking technique for localized cohesive–frictional damage

Savvas Saloustros *, Luca Pelà, Miguel Cervera

International Center for Numerical Methods in Engineering (CIMNE), Universitat Politècnica de Catalunya (UPC-BarcelonaTech), Jordi Girona 1-3, 08034 Barcelona, Spain

ARTICLE INFO

Article history:
Received 15 May 2015
Received in revised form 14 September 2015
Accepted 26 October 2015
Available online 29 October 2015

Keywords:
Continuum damage model
Crack-propagation
Cracking
Strain localization
Mohr–Coulomb

ABSTRACT

This paper extends the use of crack-tracking techniques within the smeared crack approach for the numerical simulation of cohesive–frictional damage on quasi-brittle materials. The mechanical behaviour is described by an isotropic damage model with a Mohr–Coulomb failure surface. The correct crack propagation among the two alternative fracture planes proposed by the Mohr–Coulomb theory is selected with the use of an energy criterion based on the total elastic strain energy. The simulation of three benchmark problems of mixed-mode fracture in concrete demonstrates that the proposed methodology can reproduce the material's frictional characteristics, showing robustness, as well as mesh-size and mesh-bias independence.

1. Introduction

The accurate structural assessment of existing structures and the efficient design of new ones necessitate, apart from the comprehensive knowledge of the construction materials' characteristics, the realistic simulation of fracture phenomena, potentially leading to structural failure. Geomaterials, such as concrete, mortar and bricks, are typically found in the existing buildings. Owing to their high competence under compressive loading, the critical state in such materials is usually determined by their shear or tensile capacity. Under these two stress states, fracture initiates upon reaching the material's ultimate capacity and propagates exhibiting a drop in the stress (i.e. stress softening) for increasing strain. It is for this reason that these materials are termed as *quasi-brittle materials*.

Simulation of fracture in quasi-brittle materials within the computational failure mechanics is possible by means of two alternative ways: the discrete and the smeared crack approaches. In the discrete crack approach, cracking is modelled as an actual discontinuity within the discretized finite element domain. In most of the numerical strategies of the discrete crack approach the onset and the propagation of the modelled crack bases on energy criteria. On the contrary, in the smeared crack approach the fracture is initiated by a stress/strain criterion and is modelled as smeared within the area of a finite element by modifying its mechanical properties (stiffness and strength). For a comprehensive review of discrete and smeared crack approaches the reader is referred to [13,19,20,5,6,35].

Independently of the approach chosen to simulate fracture, it was soon realised that the numerical solution was strongly dependent on the discretization characteristics of the analysed domain, i.e. there was a strong mesh-bias dependence. To overcome this drawback, the aforementioned numerical strategies are usually enhanced by means of an integrated

---

* Corresponding author.

E-mail addresses: savvas.saloustros@upc.edu (S. Saloustros), luca.pela@upc.edu (L. Pelà), miguel.cervera@upc.edu (M. Cervera).

http://dx.doi.org/10.1016/j.engfracmech.2015.10.039
0013-7944/© 2015 Elsevier Ltd. All rights reserved.

Nomenclature

Symbols

c	cohesion
$\mathbf{C}$	isotropic linear-elastic constitutive tensor
d	damage index
D	specific dissipated energy
E	Young's modulus
f_t	tensile strength
f_c	compressive strength
G_f	tensile fracture energy
h_e	average element size
H_d	discrete softening parameter
H_{mat}	material softening parameter
l_{dis}	discrete characteristic width
l_{mat}	material characteristic length
l_e	finite element size
r	damage threshold internal variable
r_{excl}	exclusion radius defined by the user
r_{neigh}	radius of the neighbourhood where $\vec{V}_c$ is computed
r_{crack}	radius for the application of the energetic criterion
r_{crit}	radius defined by the user used for the selection of r_{crack}
r_0	initial value of the damage threshold internal variable
ν	Poisson's ratio
V^e	the volume of element e
$\vec{V}_e$	crack direction for the current element
$\vec{V}_c$	crack average direction vector
$\vec{V}_{c,max}$	vector which forms an angle α_{max} with vector $\vec{V}_c$
$V_1,\ V_2$	the volume of the potential cracks in the directions θ_1 and θ_2
$w_1,\ w_2$	the elastic strain energy per volume crack for crack propagation θ_1 and θ_2
W^e	the elastic strain energy of element e
α	angle between $\vec{V}_c$ and $\vec{V}_e$
α_{max}	maximum curvature angle
β	angle between a potential failure surface and the direction of the minimum principal stresses
δ_κ	distance between *new potential* and *crack tip/root* element
$\theta_{1,2}$	direction of the two potential fracture planes according to the Mohr–Coulomb theory
Σ	equivalent stress
σ	normal stress
$\boldsymbol{\sigma}$	stress tensor
$\bar{\boldsymbol{\sigma}}$	effective stress tensor
τ	shear stress
$\boldsymbol{\varepsilon}$	strain tensor
ψ^e	the selected crack propagation angle of element e
φ	internal friction angle
Φ	damage criterion
ω^e	direction of the minimum principal stresses of element e
$:$	double contraction

Abbreviations

DEN	double edge notched
XFEM	Extended Finite Element Method
EFEM	Embedded Finite Element Method

crack-tracking procedure. The use of crack-tracking techniques permits to identify the path for the crack propagation and allow in this way the application of the selected numerical strategy on a restricted part of the mesh. This necessity for the prediction of the crack propagation has triggered the research on the methodology to identify the correct crack path. Within the discrete crack method, a variety of procedures have been proposed. These include on one hand the use of local criteria, where the crack propagates towards the direction of the maximum circumferential stress at the vicinity of the crack tip [2,40,23,44] or perpendicular to the direction of the maximum principal stress of an averaged stress/strain tensor at the