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Discrete crack path prediction by an adaptive cohesive crack model

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ABSTRACT

In this contribution, an enhancement of the numerical simulation methods for cohesive crack propagation within the finite element framework is introduced. Motivated by some fundamental drawbacks of the standard procedure, which is characterised by an initial implementation of cohesive surfaces, a novel algorithmic approach is presented which allows an adaptive incorporation of the cohesive elements depending on a crack growth criterion for structures with low crack growth rates. A new adaptive modification of the nodal coordinates and element boundaries on basis of the anticipated crack propagation direction defined by failure criteria enables furthermore the representation of arbitrary crack patterns. Following a detailed description of implementation and formulation aspects, the applicability of different fracture criteria with respect to a reliable prediction of the crack growth direction is investigated. Exemplary computations show the capabilities of the proposed methods in relation to conventional approaches and in comparison with experimental results.

1. Introduction

The discrete crack model on basis of cohesive finite elements dates back to investigations on steel sheets by Dugdale [1] and theoretical considerations on an atomistic scale by Barenblatt [2]. The development of an appropriate numerical incorporation of cohesive zones into the finite element method started with investigations of a concrete bending beam with symmetric boundary conditions by Hillerborg et al. [3] who used a staggered substitution of the symmetric supports with crack opening displacement related equilibrium forces to simulate the localised failure of the structure. The first introduction of an adapted finite element formulation with coincident nodal points in the initial configuration can be found in the work of Needleman [4]. He also stated the common representation of the cohesive constitutive relations between the strength of the cohesive phase T_0 and the relative displacement of the traction free crack faces δ_0 in terms of a traction separation law. Some further relevant aspects of finite element formulations of the cohesive crack tip model were provided by Tvergaard [5] who investigated fibre reinforced composites. His modification of Needleman's polynomial shaped traction separation law by a dimensionless parameter

$$D = \sqrt{\left(\frac{\delta_N}{\delta_{N0}}\right)^2 + \left(\frac{\delta_T}{\delta_{T0}}\right)^2} \qquad (1)$$

led to a model which is capable to consider both normal and tangential separation modes δ_N and δ_T, respectively. The parameter D accounts for the interface damage by considering no damage at the initial state, i.e. $D = 0$, and full damage at complete decohesion ($D = 1$). Taking furthermore into account that the crack opening process has to be irreversible, Tvergaard pro-

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Nomenclature

Operators

$\langle\bullet\rangle$	McCauly bracket
$\dot{\bullet}$	derivation with respect to time
$\int\bullet$	integration

Indices

0	initial value
c	critical value
n, N	normal components
t, T	tangential components

Fracture mechanics

E	Young's modulus
E_{eff}	effective stiffness
f_t	tensile strength
G	energy release rate
$\mathcal{G}_c$	fracture toughness
C^n_{eff}	value of the failure criterion at node n
C_{crit}	critical value of the failure criterion
A_s	fracture surface area

Cohesive material

Γ	cohesive fracture energy
Γ_0	work of separation
T_0	maximum traction value, strength of the cohesive surface
$\mathbf{T}$	traction vector
T_N, T_T	normal and tangential traction components
T_{eff}	effective traction
$\boldsymbol{\delta}$	separation vector, displacement jump vector
δ_N, δ_T	normal and tangential separation components
δ_0	maximum separation value, relative displacement of traction free surfaces
δ_{N0}, δ_{T0}	normal and tangential components of δ_0
D	damage parameter, interaction criterion
β	relation between tangential and normal strength of the material
K_0	initial stiffness of the initially elastic traction separation law
Γ_c	interface
l_c	cohesive length

Finite element method

n_e	number of finite elements
n_1	number of degrees of freedom before insertion of cohesive elements
n_2	number of degrees of freedom after insertion of cohesive elements
h_e	cohesive element length
$\mathbf{K}$	element stiffness matrix
$\mathbf{u}$	displacement vector
$\mathbf{N}$	matrix of shape functions
F	nodal forces
$\boldsymbol{\sigma}$	stress tensor
Ω	element domain

posed a formulation with $D = D_{max}$ for the unloading state ($\dot{D} < 0$). He considered additionally a specific formulation for negative normal separations, i.e. in case of interpenetration of cohesive surfaces, and for the situation after complete failure by applying a contact and friction law.

Despite these contributions, the application of cohesive surfaces within the finite element method is still a subject of intensive research, regarding the method itself or its application for discrete crack propagation. The strong interest in the cohesive element model can be attributed to the following key feature: In contrast to smeared approaches, which use continuum elements and a softening material formulation, the cohesive model provides a mesh independent framework to