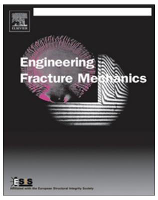
Engineering Fracture Mechanics 193 (2018) 214–247

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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



Coupling damage and cohesive zone models with the Thick Level Set approach to fracture

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ARTICLE INFO

Article history:
Received 24 November 2017
Received in revised form 22 December 2017
Accepted 22 December 2017

Keywords:
Damage mechanics
Fracture mechanics
Cohesive zone
Thick Level Set
X-FEM
Level set

ABSTRACT

This paper couples bulk damage modeling and cohesive zone modeling to get the benefits of both. Damage brings the directionality for the crack propagation as well as the possibility of crack branching while cohesive zone modeling allows for an explicit discrete crack modeling. The coupling is made easy through the Thick Level Set approach. The originality is that the coupling induces concurrent development of bulk and interface degradation.

1. Introduction

Models which allow the study of quasi-brittle failure are usually divided into two categories: continuous and discontinuous models. In the latter, macro-cracks are explicitly modeled by a discontinuity of the displacement field. Cohesive forces [13,1,17] on the crack lips allow to recover the right amount of dissipated energy and process zone length. For continuous models, micro-cracking is modeled by an internal damage variable [19,7], introducing a softening effect on the stiffness of the material. These models do not explicitly represent the displacement discontinuity.

Both continuous and discontinuous models have been widely used to study quasi-brittle materials, therefore their advantages and drawbacks are well-known. Cohesive zone models (CZM) are able to capture macro-cracks openings, which is essential when studying permeability of structures for instance. They are also particularly efficient to represent size effects [18]. However, the discontinuities of the displacement field need to be taken into account by the finite element mesh, which makes crack paths strongly dependent on finite elements orientation. Some particular numerical methods were developed to introduce displacement jumps independently from the spatial discretization, a well-known example being the eXtended Finite Element Method (X-FEM) [27,26]. Propagation is another complicated aspect, especially in case of branching and coalescence of cracks. Also, an efficient propagation criterion needs to be provided. On the other hand, continuum damage models can easily deal with initiation and complex damage patterns, but cannot represent crack opening. Furthermore, local models suffer from spurious mesh dependency [2], which requires some regularization methods. Among these numerous methods we can cite the higher order gradient models [10,8] or regularization of internal variables [38,16,21,35]. Based

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https://doi.org/10.1016/j.engfracmech.2017.12.036
0013-7944/

Nomenclature

ℓ	position of the damage front (1D case)
ℓ_c	characteristic length of the TLS
d	interfacial damage
f	traction-separation cohesive function
g	configurational force of the TLSV2
g_c	critical value of the configurational force of the TLSV2
h	interfacial softening function
h_e	mesh element size
k	reference cohesive stiffness
t	1D cohesive traction
w	1D cohesive opening
w_c	critical opening of the cohesive zone model
y	cohesive energy release rate
y_c	critical cohesive energy release rate
D	bulk damage
E	Young modulus
H	bulk softening function
Y	bulk energy release rate
Y_c	bulk critical energy release rate
$\mathbb{C}$	order 4 Hooke elasticity tensor
$\boldsymbol{\lambda}$	augmented Lagrange multiplier
ϵ	1D strain
λ, μ	Lamé coefficients
ϕ	level set field
ϕ^*	critical value of the TLSV2
ϕ_s	value of the level set field on the skeleton
ψ	free energy of the cohesive zone model
σ	1D stress
σ_c	critical stress of the cohesive zone model
u	1D displacement solution
Γ_s	skeleton of the level set field
Ψ	free energy of the bulk damage model
$(\bullet)_1$	quantity related to pure CZM or TLSV1 model
CZM	cohesive zone model
TLSV1	Thick Level Set method, first version
TLSV2	Thick Level Set, second version
TLS	Thick Level Set
$(\bullet)'$	derivative of the one variable function $(\bullet)$ with respect to its argument
$(\bullet)^n$	quantity $(\bullet)$ computed at computation step n
$(\bullet)_I$	quantity $(\bullet)$ computed at mode I
$(\bullet)_{\text{ref}}$	quantity $(\bullet)$ computed for the reference loading
$[[\bullet]]$	jump of $(\bullet)$ field
$\dot{(\bullet)}$	increment of $(\bullet)$
$\overline{(\bullet)}$	non local TLSV1 field associated to $(\bullet)$
Bold letters	order 1 or 2 tensors
$\text{tr}(\bullet)$	trace of tensor $(\bullet)$

on the variational approach to fracture [14], the phase-field approach [20,25] uses a smoothed representation of the macro-cracks to get a process zone with a finite thickness, and can deal with complex crack topologies.

Some approaches [34,45,42,41] based on continuum damage mechanics propose to introduce a traction-free discontinuity when the damage variable D becomes greater than a critical value $D_c < 1$, avoiding conditioning problems when finite elements are fully damaged. However, the amount of energy dissipated when D grows from D_c to 1 is not taken into account, and the crack orientation needs to be determined. In [15], a different way to proceed is proposed: a traction-free macro-crack is used to compute the displacement solution at a large scale, then the phase field approach is used at the tip scale to propagate this macro-crack. As many multi-scale approaches, the main drawback is that a coupling method between the different scales needs to be provided.

The Thick Level Set method was introduced in [28,43] as a new way to regularize local damage models. The implementation was further improved in [3] for quasi-static loading and time-independent damage models, in [31] for dynamics and in [40] for 3D quasi-static problems. The TLS method allows a diffuse progression of damage as well as