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On the modeling of mixed-mode discrete fracture: Part II – Inclusion of dilatancy

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A B S T R A C T

This manuscript contains the continuation of the work presented in "On the modeling of mixed-mode discrete fracture: part I – damage models". After the introduction of several damage models within the scope of a discrete crack approach, dilatancy is included herein as an additional compliance of both deformation-based and traction based models. Due to the nature of the damage formulation, the total-secant stiffness is explicitly derived. As a consequence, this feature allows for the use of this model with non-iterative numerical methods, which are built upon the assumption of damage evolution. Several elementary results are presented together with the simulation of some experimental tests.

1. Introduction

In part I of this manuscript, energy-based, deformation-based and traction-based localised damage models were derived within the scope of a discrete crack approach. In this manuscript, the possibility of modelling dilatancy is added to both deformation-based and traction-based damage models.

In all cases, the total/secant relationship is explicitly derived, which allows for the use of non-iterative methods, such as the ones presented in Rots [22]; Rots and Belletti [23]; Invernizzi et al. [14]; Costa et al. [5,6].

First, both the deformation-based model and the traction-based model presented in Alfaiate and Sluys [3] are briefly reviewed. Next, dilatancy is included in both models. Due to the limitations inherent to the deformation-based models, some tests are performed with the traction-based model only. Besides some elementary examples, experimental tests from Paulay and Lobber [21] as well as from Hassanzadeh [13,11,12] are also simulated. A comparative analysis is performed and some refinements are made to the original model with the purpose of better approximating the experimental results.

2. Damage models

In this Section, a review of both the deformation-based and the stress-based discrete damage models presented in Alfaiate and Sluys [3], and Alfaiate [1] are performed.

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Nomenclature

σ	stress component
$\boldsymbol{\sigma}$	stress tensor
d	scalar damage variable
$\mathbf{d}$	second order damage tensor
d_n	normal damage variable component
d_s	shear damage variable component
$\mathbf{I}$	identity tensor
$\mathbf{w}$	displacement jump vector
w_n	normal component of the jump displacement vector
w_s	shear component of the jump displacement vector
$\mathbf{t}$	traction vector acting at the discontinuity
t_n	normal component of the traction vector
t_n	normal traction corresponding to the maximum shear strength
t_s	shear component of the traction vector
$\mathbf{D}^{el}_{\Gamma_d}$	second order elastic constitutive tensor corresponding to discontinuity Γ_d
$\mathbf{C}^{el}_{\Gamma_d}$	elastic compliance constitutive tensor/matrix corresponding to discontinuity Γ_d
D^{el}_{nn}	normal diagonal component of tensor $\mathbf{D}^{el}_{\Gamma_d}$
D^{el}_{ss}	shear diagonal component of tensor $\mathbf{D}^{el}_{\Gamma_d}$
f, f_1, f_2, f_3	limit surfaces defined in the traction space
f_{t0}	initial tensile strength
f_t	tensile strength
f_c	compressive strength
c_0	initial cohesion: shear strength under the absence of normal traction
c	cohesion
G_F	fracture energy
G_F^{II}	fracture energy under mode-II fracture
κ	monotonic increasing function of the displacement jump components
β	scalar function which enables transition between mode-I and modeII fracture
g	loading function defined in the displacement jump space
g_n	normal damage evolution law
g_s	shear damage evolution law
ϕ	internal friction angle
ψ	dilatancy angle
ξ_n	w_n/κ_n
ξ_s	$\lvert w_s\rvert/\kappa_s$
G	c/f_t
ρ	κ_s/κ_n

2.1. Deformation-based model

In a general, non-isotropic, discrete damage framework we can write:

$$\begin{aligned} t_n &= (1-d_n)D^{el}_{nn}w_n \\ t_s &= (1-d_s)D^{el}_{ss}w_s, \end{aligned} \tag{1}$$

where t_n is the traction normal to the discontinuity, t_s is the traction tangent to the discontinuity, w_n is the normal jump displacement, w_s is the sliding jump displacement, d_n is the damage under normal traction, d_s is the damage variable under shear traction and D^{el}_{nn}, D^{el}_{ss} are the normal and shear stiffness coefficients, respectively. Assume the following definition of the non-isotropic damage variables under exponential softening:

$$\begin{cases} d_n^+ = d_s & (t_n \geqslant 0) \quad \text{mixed-mode fracture}, \\ d_n^- = 0 & (t_n < 0) \quad \text{mode-II}, \\ d_s(\kappa,\beta) = 1 - \frac{\kappa_0}{\kappa}\exp\left[-\frac{f_{t0}}{G_F}\beta(\kappa-\kappa_0)\right]. \end{cases} \tag{2}$$