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Examination of two regularized damage-plasticity models for concrete with regard to crack closing

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ABSTRACT

Continuum models of fracture should be equipped with a localization limiter to prevent pathological discretization sensitivity of finite element simulations. Moreover, stiffness recovery, called also crack closing effect, should be reproduced in the modelling of quasi-brittle materials when reversed loading is applied. In this paper the efficiency of two different established damage-plasticity models for concrete is assessed from the viewpoint of the two above-mentioned aspects. The first description is the so-called concrete damaged plasticity model, available in the ABAQUS package. In this model the plasticity theory is not only augmented with stiffness degradation and recovery, but also with the crack band approach and viscoplastic regularization. The gradient-enhanced damage description, which is the second one considered, can also be coupled to plasticity. In this model additional averaging equation prevents the pathological discretization sensitivity of fracture simulations. Two fields, displacements and averaged strain measure, are interpolated and suitable finite elements are programmed by the authors in the FEAP package. Basic concepts of the numerical analysis of the crack closing phenomenon are reviewed. Both models are capable of avoiding mesh-sensitivity, but it is achieved in a different manner and it is shown in the paper that the users of ABAQUS should employ the crack band options with particular care. Representative examples in the context of the examined issues are demonstrated: uniaxial tension of a bar and a cantilever beam. The results obtained using both the models are compared and the effects of regularization and crack closing are illustrated.

1. Introduction

Models of quasi-brittle materials like concrete should reproduce not only the cracking phenomenon, but also the crack closing effect when reversed static (cyclic) or dynamic loading is applied. If a phenomenological model is considered, the damage component with its unilateral character is relevant, see [1]. A measure of damage can only grow or its development can be stopped, while any changes of deformation and stress are possible. When for instance uniaxial tensile loading process takes place (see Fig. 1), a reduction of stiffness consequently proceeds. In unloading the deterioration is frozen. A stiffness recovery in nonlinear analysis is then observed for compression and the initial elasticity should be at least partly restored. This is because microcracks and microvoids close in the microstructure of the material. Fig. 1 shows an example of equilibrium path in uniaxial loading scenario together with two possible

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Nomenclature

α	parameter of residual stress in exponential law
$\bar{\epsilon}$	averaged strain measure
$\boldsymbol{D}$	elastic stiffness operator (in matrix form)
$\boldsymbol{D}^{ep}$	elasto-plastic stiffness operator
$\boldsymbol{\epsilon}$	strain tensor (in vector form)
$\boldsymbol{\epsilon}^{e}$	elastic strain tensor
$\boldsymbol{\epsilon}^{p}$	plastic strain tensor
$\boldsymbol{\epsilon}^{e+}$	tensile part of elastic strain
$\boldsymbol{\epsilon}^{e'}$	principal elastic strains
$\boldsymbol{\epsilon}^{vp}$	viscoplastic strain tensor
$\boldsymbol{m}$	plastic flow direction
$\boldsymbol{H}$	selection matrix in crack closing model
$\boldsymbol{P}^{+}$	projection operator
$\boldsymbol{s}$	derivative of strain measure
$\boldsymbol{\sigma}$	stress tensor (in vector form)
$\boldsymbol{\sigma}^{d}$	damage stress tensor
$\boldsymbol{T}$	transformation matrix
$\dot{\lambda}$	plastic multiplier
η	material ductility in exponential law
$\hat{\boldsymbol{\sigma}}$	effective stress tensor
$\hat{\boldsymbol{\sigma}}^{+}$	tensile part of effective stress tensor
$\hat{p}$	effective hydrostatic pressure
$\hat{q}$	Mises equivalent effective stress
κ^{d}	damage history parameter
κ^{p}	plastic history parameter
κ_o	initial damage threshold
κ_u	ultimate value of damage parameter
κ_c	history parameter for compression
κ_t	history parameter for tension
$\mathscr{L}$	derivative of damage function
μ	relaxation time parameter
ν	Poisson's ratio
ω	scalar damage measure
ω_c, ω_t	damage measures for compression and tension
σ_y	yield strength
$\tilde{\epsilon}$	equivalent strain measure
$\tilde{\sigma}$	equivalent stress function
c	coefficient related to internal length scale
E	Young's modulus
F^{d}	damage activation (loading) function
F^{p}	yield function
G^{p}	plastic potential function
k	ratio of compressive and tensile strengths
r	effective stress ratio for multiaxial stiffness recovery
s_c, s_t	stiffness recovery functions for compression and tension
w_c, w_t	weight factors for stiffness recovery for compression and tension

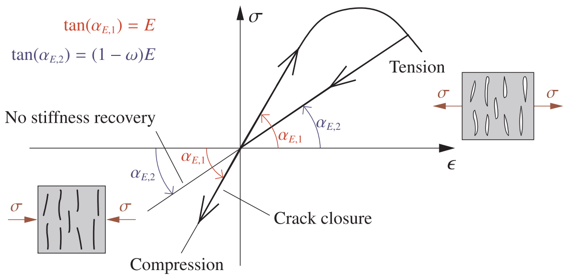

Fig. 1. Stiffness change in uniaxial behaviour – crack closing phenomenon for pure damage model (without irreversible strains).

diagrams for compression – with or without the crack closing effect. The stress–strain relationship for the pure damage model gives a return to the origin during unloading, while the presence of some irreversible strains is more adequate for the description of failure in quasi-brittle materials. Hence, a combination of continuum damage mechanics with the plasticity theory seems necessary.

Moreover, a phenomenological model which can simulate smeared cracking should be enhanced with regularization (localization limiter) to avoid pathological mesh sensitivity and numerical instabilities in the nonlinear analysis. During softening without regularization localized deformation tends to narrow down to a discrete crack (curve in 2D or surface in 3D). In finite-element solutions weak discontinuities (jumps of displacement gradient) are admitted and strain localization manifests itself in a one-element wide band, so the response is governed by the discretization. The volume of material which softens is dictated by the numerics and not the physics of a given problem [2], which in consequence leads to an infinite number of possible solutions. The issues connected with the loss of well-posedness of the boundary value problem and preservation of objectivity in the numerical analysis when strains localize are explained e.g. in [3,4]. The effects of regularization are the following: ellipticity for a static boundary value problem is guaranteed, discretization does not govern the solution, i.e. mesh-independent results are achieved (for all meshes close load-displacement diagrams and similar distributions of considered quantities, e.g. strains), divergence of softening simulations does not easily happen.

In this paper two isotropic coupled damage-plasticity models equipped with regularization and used to simulate cracking and crack closing phenomena in concrete are discussed. An idealized continuum is considered to represent smeared cracking. Hence, strong discontinuity simulations are out of the range of the paper.

The first model, called concrete damaged plasticity (CDP), comes from [5] and was adjusted in [6] to reproduce the effects of reversed (cyclic) loading in quasi-brittle materials. It is accessible in [7]. Two methods of reducing the discretization sensitivity are available in the model. One is based on the idea of fracture energy and the characteristic width of a band where the energy is