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Shear banding modelling in cross-anisotropic rocks

B. Pardoen [a,*,1], D.M. Seyedi [b], F. Collin [a]

[a] ArGEnCo Department, University of Liège, Allée de la Découverte 9, 4000 Liège, Belgium

[b] Fluid and Solid Mechanics Department, Research and Development Division, Andra, Rue Jean Monnet 1-7, 92298 Châtenay-Malabry, France

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ABSTRACT

Sedimentary geomaterials such as rocks frequently exhibit cross-anisotropic properties and their behaviour depends on the direction of loading with respect to their microstructure. As far as material rupture is concerned, localised deformation in shear band mode appears generally before cracks and material failure. The influence of cross-anisotropy on the shear strain localisation remains an important issue and is investigated in the present study. To do so, a constitutive elastoplastic cross-anisotropic model that includes anisotropy both on the elastic and plastic characteristics is defined. For the plastic part of the model, the anisotropy of a strength parameter is introduced with a microstructure fabric tensor. Then, the fractures are modelled with finite element methods by considering the development of shear strain localisation bands and an enriched model is used to properly reproduce the shear banding. The cross-anisotropy influence on shear banding is studied through numerical applications of small and large-scale geotechnical problems that engender fractures. The two considered applications are a plane-strain biaxial compression test and an underground gallery excavation. The numerical results provide information about the influence of cross-anisotropy on the appearance and development of shear bands. It has been noticed, among other observations, that the material strength vary with the loading direction and that the development and the shape of the excavation fractured zone that develops around a gallery is strongly influenced by the material anisotropy.

1. Introduction

Geomaterials frequently feature an anisotropic behaviour related to their original fabric (Casagrande and Carillo, 1944). Among them, sedimentary materials are vertically deposited in a succession of layers and their structures are composed of bedding planes. Due to this structural arrangement, the anisotropic properties of such materials often exhibit a certain type of symmetry with isotropic properties in the bedding planes. These materials are said to be transversely isotropic or cross-anisotropic (Amadei, 1983) and their behaviour and response to external solicitations depend on the loading direction with respect to their microstructure.

Since the material behaviour and failure constitute crucial issues in many geotechnical problems, various theories and failure criteria have been developed (Graham and Houlsby, 1983; Duveau et al., 1998; Abelev and Lade, 2004; Lade, 2007). Concerning the material rupture, it is commonly accepted that damage and localised deformation appear before the failure in many cases. Under a compressive regime when the rupture is essentially governed by shear failure, strain can accumulate in limited zones, generally in shear band mode (Desrues, 2005), and this accumulation can lead to material damage, to the development of macro-cracks (fractures) and to material rupture (Diederichs, 2003).

The influence of cross-anisotropy on the material behaviour and on the shear strain localisation has been investigated by different authors (Abelev and Lade, 2003; Tejchman et al., 2007; Lade et al., 2008). They concluded that the material strength as well as the shear band pattern on small-scale specimens may vary with the direction of loading or with the orientation of the bedding planes. On a large scale, the material cross-anisotropy may also influence the development of fractures around underground galleries as indicated by Armand et al. (2014) and Marschall et al. (2008).

The main objective of this study is to analyse the influence of the material cross-anisotropic features on the fracturing modelled with shear strain localisation bands. It will be investigated with finite element methods for a cross-anisotropic rock, both on a small and on a large scales. Firstly, evidences of the material anisotropy influence on the fracturing is discussed in Section 2. Secondly, the theoretical models are detailed in Section 3 where

* Corresponding author. Tel.: +32 4366 2033.
E-mail address: b.pardoen@ulg.ac.be (B. Pardoen).

[1] FRIA, F.R.S.-FNRS scholarship holder.

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List of symbols

General notations
$\dot{a}$ time derivative of quantity a s^{-1}
$a^{e/p}$ elastic/plastic component of quantity a –
$^{\sharp}a$ quantity a in orthotropic axes –
$a_{\parallel/\perp}$ quantity a in parallel/perpendicular direction related to the isotropic planes –
$a_{0/f}$ initial/final value of quantity a –
a^t current configuration of quantity a at a given time t –
a^* virtual quantity a –
$a^{0/1}$ quantity a outside/inside a shear band –

Greek letters
α Euler's rotation angle for isotropic planes orientation °
β Lode angle °
Γ porous material boundary m^2
Γ_σ part of Γ on which $\bar{t}_i$ and $\bar{T}_i$ are applied m^2
Γ_q part of Γ on which $\bar{q}$ is prescribed m^2
δ_{ij} Kronecker symbol –
ϵ_{ij} total strain field –
$\hat{\epsilon}_{ij}$ deviatoric total strain field –
$\hat{\epsilon}_{eq}$ Von Mises' equivalent deviatoric total strain (total deviatoric strain) –
ϵ_z vertical strain for biaxial compression test –
ζ stress deconfinement rate for gallery excavation –
ζ_w pore water pressure deconfinement rate for gallery excavation –
η yield surface convexity parameter –
ϑ tangential coordinate m
Θ shear band orientation °
$\Theta_{A/C/R}$ Arthur's, Coulomb's and Roscoe's angles for Θ °
κ deviatoric strain increment –
λ_{ij} Lagrange multipliers field Pa
Λ plastic multiplier –
μ_w water dynamic viscosity Pa s
$\nu_{\parallel\perp/\parallel\parallel/\perp\parallel}$ Poisson's ratios –
ξ cohesion softening ratio –
ρ_s solid grains density kg/m^3
ρ_w water density kg/m^3
σ_{ij} Cauchy total stress field Pa
σ'_{ij} Biot's effective stress field Pa
$\tilde{\sigma}'_{ij}$ Jaumann effective stress rate Pa/s
$\hat{\sigma}_{ij}$ deviatoric total stress field Pa
σ_i principal total stresses Pa
σ'_i principal effective stresses Pa
$\sigma_{H/h/v}$ Callovo-Oxfodian claystone *in situ* principal stresses Pa
σ_c uniaxial compressive strength Pa
σ_x confinement pressure for biaxial compression test Pa
σ_z vertical total stress for biaxial compression test Pa
$\sigma_{r,0}$ initial pressure on gallery wall Pa
σ_r^Γ fictive pressure on gallery wall Pa
Σ_{ijk} double stress dual of h_{ijk} Pa m
$\tilde{\Sigma}_{ijk}$ Jaumann double stress rate Pa m/s
τ_{ij} microstructure stress field (microstress) Pa
υ_{ij} microkinematic gradient field –
φ friction angle °
φ_{bif} friction angle at bifurcation °
φ_c compression friction angle °
φ_e extension friction angle °
Φ porosity –
ψ dilatancy angle °
ψ_{bif} dilatancy angle at bifurcation °
ψ_c compression dilatancy angle °
ψ_e extension dilatancy angle °
ω_{ij} spin rate tensor s^{-1}
Ω porous material configuration (volume) m^3

Roman letters
$I_{\sigma'}$ first stress invariant Pa
$II_{\hat{\sigma}}$ second deviatoric stress invariant Pa
$II^p_{\hat{\sigma}}$ second deviatoric stress invariant at plastic state Pa
$III_{\hat{\sigma}}$ third deviatoric stress invariant Pa
a_{ij} microstructure fabric tensor for cohesion Pa
$\hat{a}_{ij}$ deviatoric microstructure fabric tensor for cohesion Pa
A_{ij} reduced deviatoric microstructure fabric tensor for cohesion –
$A_\parallel$ component of A_{ij} in the isotropic planes –
$\mathcal{A}_{ijkl}$ elastoplastic constitutive tangent tensor for large strain and rotations Pa
A^J_{ijkl} Jaumann's correction tensor for large strain and rotations Pa
b_{ij} Biot's tensor –
$b_{\parallel/\perp}$ Biot's coefficients –
b generalised Biot's coefficient –
$b_{1/2}$ cohesion evolution parameters –
B_φ friction angle hardening coefficient –
B_c cohesion softening coefficient –
c cohesion Pa
$\bar{c}$ cohesion under isotropic loading Pa
C_{ijkl} elastoplastic constitutive tangent tensor for small strain and rotations Pa
$d_{1/2}$ yield surface parameters –
D second gradient elastic modulus N
D^e_{ijkl} compliance elastic tensor Pa^{-1}
dec_c cohesion softening shifting –
dec_φ friction angle hardening shifting –
Du_i normal derivative of u_i –
e_i orthotropic coordinate axes m
$E_{\parallel/\perp}$ young's moduli Pa
F yield surface Pa
F_{ij} macrodeformation gradient field –
g_i shear band velocity gradient field s^{-1}
G plastic potential Pa
$G_{\parallel\perp/\parallel\parallel/\perp\parallel}$ shear moduli Pa
h_{ijk} microkinematic second gradient field m^{-1}
k_{ij} intrinsic water permeability tensor m^2
$k_{\parallel/\perp}$ intrinsic water permeabilities m^2
K generalised bulk modulus of the poroelastic material Pa
K_s isotropic bulk modulus of the solid grains Pa
l_i generalised loading vector –
L_{ij} velocity gradient field s^{-1}
m yield surface parameter –
m_G plastic potential parameter –
$m_{w,i}$ water mass flow kg/m^2 s
M_w water mass inside unit volume Ω kg/m^3
n_i normal unit vector –
p_w pore water pressure Pa
p_w^Γ pore water pressure on gallery wall Pa
q global deviatoric stress for biaxial compression test Pa
$\bar{q}$ input water mass per unit area kg/m^2 s
$q_{w,i}$ average speed of water relative to the solid grains m/s
Q water sink term kg/m^3 s
r gallery radius m
r_c compression reduced radius of the yield surface –
$r_{c,G}$ compression reduced radius of the plastic potential –
r_e extension reduced radius of the yield surface –