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Research Paper

Finite element modelling of fracture propagation in saturated media using quasi-zero-thickness interface elements

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A R T I C L E I N F O

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A B S T R A C T

A new computational technique for the simulation of 2D and 3D fracture propagation processes in saturated porous media is presented. A non-local damage model is conveniently used in conjunction with interface elements to predict the degradation pattern of the domain and insert new fractures followed by remeshing. FIC-stabilized elements of equal order interpolation in the displacement and the pore pressure have been successfully used under complex conditions near the undrained-incompressible limit. A bilinear cohesive fracture model describes the mechanical behaviour of the joints. A formulation derived from the cubic law models the fluid flow through the crack. Examples in 2D and 3D, using 3-noded triangles and 4-noded tetrahedra respectively, are presented to illustrate the accuracy and robustness of the proposed methodology.

1. Introduction

Modelling the fluid flow in a multi-fractured porous domain implies taking into account that the cracks in the solid skeleton introduce preferential flow paths as well as jumps in the displacement field. A proper understanding of discontinuities is crucial not only because they influence the behaviour of the local surroundings of the cracks, but also because they modify the global permeability and the mechanical response of the medium, specially whenever it undergoes a crack growth process.

Numerical methods that allow analysing and understanding the complexity of a multi-fractured porous domain are of major interest in various fields, but probably the most widely known is the petroleum industry. Here, the oil-gas-soil interaction takes the leading role along with the hydraulic fracturing as a common technique to enhance reservoir permeability and well efficiency [1,2]. Other possible applications can be found in the geothermal energy production, where the solid-pore fluid formulation is coupled with the thermal problem [3], the underground storage of carbon dioxide [4], and even the study of fractures in epithelial cell sheets [5,6].

In the last decades, important efforts have been made to develop numerical models for the accurate analysis of discontinuities in solids and porous media.

The extended finite element method (XFEM) has obtained notable attention in the past years [7–10]. The discontinuity is captured by means of enrichment functions that introduce the jumps in the displacement field. The most noticeable advantage of the method is that there is no need to explicitly represent cracks in a mesh, provided that enriched nodes are considered. This avoids the necessity of remeshing during crack growth, but in return it demands a higher computational cost in terms of number of degrees of freedom and numerical integration.

The present work focuses on the numerical techniques purely based on the finite element method (FEM). In this category, numerous methods can be found in the literature, but two main subgroups can be distinguished: the "smeared crack" and the "discrete crack" approaches. The former can be classed as continuum based methods in which the influence of developing fractures is incorporated into the constitutive stress-strain law [11–14]. In discrete crack models, however, each single discontinuity is represented explicitly [15–18]. In this paper, the heterogeneity of materials is considered through the combination of standard elements governed by a smeared crack model, with interface elements governed by a discrete crack model.

Since Goodman et al. proposed the "zero-thickness" interface element to describe the mechanical behaviour of pre-existing joints in rock masses [19] many authors have developed strategies to adapt this element for the solution of fracture processes in coupled solid-pore fluid problems.

Three different types of zero-thickness interface elements can be found in the literature concerning the way the fluid is modelled: single, double and triple noded elements. The single-noded element is the simplest one and only considers longitudinal conductivity with no pressure drop across the interface [20]. The triple-noded element was

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Nomenclature

Symbols

α	Biot's coefficient
$\boldsymbol{\delta}$	relative displacements of the interface
$\boldsymbol{\lambda}$	rotation matrix
$\boldsymbol{\sigma}$	total stress vector
$\boldsymbol{\sigma}'$	effective stress vector
$\boldsymbol{\varepsilon}$	strain vector
$\boldsymbol{k}$	intrinsic permeability matrix
$\boldsymbol{u}$	displacement vector
$\breve{\varepsilon}_{eq}$	non-local equivalent strain
δ_c	critical relative displacement of the interface
ϵ	volumetric strain of the solid skeleton
$\varkappa$	compressive to tensile strength ratio
$\mathbb{d}$	damage
$\mathbb{d}_p$	fracture propagation damage
$\mathscr{D}$	distance
μ	dynamic viscosity
μ_F	friction coefficient of the interface
ν	Poisson's ratio
ϕ	porosity
ρ	density of the solid-fluid mixture
ρ_f	fluid density
ρ_s	solid density
σ_y	yield stress of the interface
$\varepsilon_{eq,I}$	equivalent strain of the interface
ε_{eq}	local equivalent strain
ϱ	internal historical variable of the interface
ϱ_y	damage threshold of the interface
ζ	fluid mass content per unit volume
E	Young's modulus
K	bulk modulus of the porous medium
K_f	fluid bulk modulus
k_n	transversal permeability of the interface
K_s	solid bulk modulus
l_c	non-local characteristic length
l_p	fracture propagation length
p	pore pressure
Q	Biot's modulus
R	residual strength
r	internal historical variable
r_y	damage threshold
S	softening slope
t_I	joint width
t_{min}	minimum joint width
w	integration coefficient
Z	non-local weighting function

meant to include the effect of the transversal conductivity through the discontinuity [21]. The two nodes at each side of the interface represent the potentials in the pore pressure, while the third node, placed at the middle of the interface, stores the average potential of the longitudinal fluid through the fracture. Finally, the double-noded elements take into account both types of conductivity but the external nodes variables substitute the middle node. Ng and Small [22] used this double-noded zero-thickness interface element to model flow problems with pre-existing discontinuities, but did not consider hydraulic potential drop between the two interface walls. Segura and Carol [23] introduced the transversal conductivity in double-noded zero-thickness elements to account for the exchange of fluid between the discontinuity and the porous media.

Regarding the mechanical behaviour of fractures, there are basically two different approaches: those based on linear elastic fracture mechanics (LEFM), and those based on non-linear fracture mechanics (NLFM). LEFM techniques were first proposed to solve fracture propagation problems by means of remeshing without considering a fracture process zone (FPZ) before the crack tip. This approach is applicable in large structures where the size of the FPZ is negligible. However, for quasi-brittle analyses, the consideration of a non-linear fracture process zone where the energy is dissipated before it completely fails was found to be essential. In those cases the NLFM technique is usually applied and a softening law relates the cohesive stress to the crack opening in the FPZ. The first procedure based on the cohesive fracture model was originally introduced by Barenblatt [24,25] for brittle materials and by Dugdale [26] for plastic materials. Hillerborg et al. [27] developed the first fictitious crack model for Mode I fracture. It was extended later for the mixed mode fracture, from which Camacho and Ortiz [28] proposed a suitable fracture criterion that is widely used in the literature.

One of the most important parts in the modelling of fracture propagation is the criterion for determining the direction of the crack growth. Some methodologies are based on the local evaluation of the stress field at the crack tip, such as the maximum circumferential stress [29] and the maximum principal stress criteria [30,31]. Others measure the energy distribution at the fractured zone, e.g. the minimum strain energy density criterion [32] or the maximum strain energy release rate criterion [33]. Finally, some authors have developed crack growth criteria based on continuum damage mechanics [34] and, more recently, combined with level set procedures [35,36].

In order to reduce mesh-induced directional bias, in this work we use a non-local damage model in combination with a discrete crack approach in which discontinuities are represented by quasi-zero-thickness interface elements. A special remeshing technique allows us introducing new joint elements according to the damage map obtained with the damage model. The low permeability and high compressibility of this kind of problems makes the pressure field oscillate spuriously if equal order interpolation elements are used without stabilization. Here we solve the solid-pore fluid interaction problem with a FIC-FEM stabilized formulation presented in a recent work by the authors [37].

The paper is organized as follows. First, we present the coupled FIC-FEM formulation derived from the second-order FIC form of the mass balance equation in space. Next, the developed methodology for fracture propagation is introduced, explaining the fundamental theory behind the non-local damage model, and describing the quasi-zero-thickness interface elements. Finally, two academic plane-strain examples are solved to test the accuracy of the proposed methodology. Finally, one additional three-dimensional case is included to show the performance of the generalized 3D formulation.

2. Solid-pore fluid FIC-FEM formulation

In 1941 Biot [38] found a relation between the fluid mass content per unit volume ζ, the volumetric strain of the solid skeleton ϵ and the pore pressure p as

$$\zeta = \alpha\,\epsilon + \frac{p}{Q} \tag{1}$$

In the above relation, α is the Biot's coefficient and Q is a combined compressibility of the fluid-solid phases, also called Biot's modulus [39]:

$$\alpha = 1 - \frac{K}{K_s} \leqslant 1; \quad \frac{1}{Q} = \frac{\alpha - \phi}{K_s} + \frac{\phi}{K_f} \tag{2}$$

being ϕ the porosity of the soil, K_s the bulk modulus of the solid phase, K_f the bulk modulus of the fluid phase, and K the bulk modulus of the