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Numerical analysis of the geometrical and material criteria of acceleration of shear crack to supershear velocity in brittle nanoporous solids

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Abstract

The paper is devoted to the study of dynamic propagation of mode II cracks in porous brittle materials with nanoscale pore size. We compared static (shear strength) and dynamic parameters of crack growth in dry and fluid saturated nanoporous brittle materials at different degrees of confinement. We have shown that pore fluid in nanoporous brittle materials influences mainly the dynamics of crack propagation. This leads in particular to pronounced peculiarities of the dependence of the critical value of dimensionless geometrical parameter of the initial crack (it majorizes the interval of the ratios of length to thickness for the cracks that are capable to accelerate to intersonic velocity) on applied crack normal stress. The results of the study are relevant for understanding the conditions of supershear regime of propagation of mode II cracks as well as for assessment of the ability of mode II cracks in brittle materials (including nanoporous fluid-saturated solids) to develop in supershear regime.

Keywords: brittle solid; mode II crack; sub-Rayleigh-to-supershear transition; fluid; pore pressure; modeling; hybrid cellular automata method

1. Introduction

The conditions defining the regime and, in particular, the velocity of dynamic propagation of longitudinal shear (mode II) cracks in brittle materials are widely studied and analyzed over the past few decades. Considerable interest in this subject is concerned with its close connection with the problems of fracture of multiphase materials, the

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dynamics of earthquakes and seismic radiation, as well as a common problem of initiation and possible regimes of dynamic slip of contact surfaces (Barras et al. (2014), Svetlizky et al. (2016)). An important feature of dynamic propagation of mode II cracks is shear stress concentration in the vicinity of the crack tip (Broberg (2006)).

Beginning with the classical papers of works Burridge (1973) and Andrews (1976), we know that the initial stage of dynamic crack growth is accompanied by shear stress concentration in a compact area ahead of the crack tip (this is a so-called stress peak). In recent decades, the evolution of the stress peak became a subject of a number of studies, mainly due to the fact that it is supposed to be responsible for the formation of supershear (another name is intersonic) secondary cracks that are capable to propagate at velocities V above the shear elastic wave speed V_S and below the P-wave speed V_P. In particular, it has been shown in Shilko and Psakhie (2014) and Psakhie et al. (2015) that the physical mechanism for the formation of a compact area with high shear stresses ahead of the tip of dynamically growing mode II crack is the nucleation and development of the collective elastic vortex-like motion (hereinafter called the elastic vortex). These studies have shown that the elastic vortex is scale-invariant dynamic object, an important feature of which is the concentration of shear stress. The maximum attainable magnitude of the shear stress in the elastic vortex is the unequivocal function of the dimensionless geometrical parameter P of the initial crack. There is a critical value (P_{crit}) of this parameter, such that if $P<P_{crit}$, the initial interface crack is able to propagate at supershear velocity ($V>V_S$). Otherwise, it is able to distribute only in conventional sub-Rayleigh regime ($V<V_R$). Shilko et al. (2015) have shown that the specific value of P_{crit} is determined by the material parameters. Note that stress concentration in elastic vortices is able to promote not only crack acceleration but inelastic deformation including dynamic migration of grain boundaries (Psakh'e and Zol'nikov (1997)).

The results obtained in Shilko and Psakhie (2014), Psakhie et al. (2015) and Shilko et al. (2015) refer to the conditions of simple shearing of brittle materials including porous and fissured brittle materials of natural and artificial origins (ceramics, rocks). Pronounced features of the mechanical response of such materials are a significant influence of the value of normal load on shear strength (this feature is inherent to all brittle solids) as well as an important role of fluid pressure and redistribution in the pore space. Among porous materials a subclass of materials with nanoscale pore structure can be distinguished. An important feature of the nanoporous permeable materials is a determining role of adsorption effects, manifested, in particular, in the existence of a threshold (minimum) value of the pore pressure at which the liquid can filtrate in the pore space of the material. The estimates with use of the typical values of parameters for «sandstone-water» system with nanoscopic characteristic pore size in sandstone (<0.01 μm) show that threshold pore pressure of fluid may reach several tens of megapascals, that in many cases comparable to the strength of porous materials themselves. Therefore, at relatively low mean stresses mechanical deformation of fluid saturated nanoporous materials is not accompanied by fluid redistribution in the pore space (or filtration power is negligibly slow). In this case the material with interconnected nanoscopic pores and channels behaves in much the same way as materials with isolated pores.

Influence of pore fluid pressure on the mechanical properties and fracture of brittle porous materials is the subject of extensive theoretical and experimental studies carried out by various authors (Bidgoli and Jing (2014), Ougier-Simonin and Zhu (2015)). Due to relatively low values of cohesion in brittle materials the special emphasize is laid on the study of the shear strength and dynamics of growth of longitudinal shear cracks as well as their relationship with the magnitude of the applied crack normal load and pore pressure (Radi and Loret (2007), Brantut and James (2011)). This problem was the subject of the present research as it applied to nanoporous materials.

2. Problem statement

The study was carried out on the basis of numerical modeling using hybrid cellular automata method. The formalism is this method couples mathematical formalisms of movable cellular automata method, which belongs to a group of discrete element methods, and finite difference method (Psakhie et al. (2016)). The study of the dynamic growth of mode II cracks was carried out in the framework of the macroscopic consideration of the material. The pore structure of materials and interstitial fluid (liquid) were implicitly taken into account through the parameters of the models of mechanical response of fluid saturated porous solid and interstitial fluid. The influence of pore fluid pressure on the stress state of the solid skeleton was described using Biot's model of poroelasticity. We considered a model nanoporous macroscopically isotropic linear-elastic (brittle) material with porosity 10% and characteristic pore size d_{ch} < 0.01 μm. Two-parametric criterion of Drucker and Prager was used as a fracture criterion.