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Initiation of a secondary crack across a frictional interface

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ABSTRACT

The propagating crack interacts with an inclined frictional interface. The experiments focus on how a crack reaching the interface would further form a secondary crack on the opposite side after traveling down some distance along the interface. This distance increases with the inclination angle of the interface. This effect is related to an influence of shear along the contact plane caused by the initial crack approaching the contact plane. A simplified model explains the secondary crack development as a result of slip zone propagation along the contact plane, which induces stress concentration at the end of the slip zone.

1. Introduction

Propagation of a crack through the interface between two dissimilar media is an important problem for investigation of fracture processes in layered media as well as for studying hydraulic fracture development in a structured medium. The former problem is related to morphology of layered media where tensile deformation occurs along the layers due to the action of external loads. Such deformation can result in formation of transverse faults. In the case of hydrofracture, the main interest is in understanding of possible technological implications of the process of the fluid penetration into crumbling rocks.

According to numerous field observations, in layered crumbling rocks, transverse faults can cross the interfaces to form a stepwise structure [1–3]. A fault crossing an interface initiates local slippage along the plane of contact with possible debonding on the interface [4]. Although the types of interaction of the fault with the contact plane are readily determined in field studies, the mechanisms that control their development are not yet fully understood [5]. In particular, insufficient attention is given to the development of the models that would be capable to explain the formation of discontinuities with the planes of contact inclined at certain angle to the direction of the principal stress, which affects the energy parameters of the system [6].

Experiments on compression of cylindrical composite samples consisting of the layers with different deformation properties, show that discontinuities are initiated in the layers of more brittle materials. Then, they can progress into the plastic layers where their propagation is prevented by increase in layer's thickness and material ductility. If compression acts along the normal to the plane of the contact, then a shift of the secondary crack axis relative to the initial crack axis was negligible [7]. On the other hand, at tension of planar layered sample along the layers [8], it was observed that the fault initiates certain shift of the interface faces. The shift is accompanied by a local shear along the interface between the cracks. In this zone the

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Nomenclature

a	size of the cube sample edge
b	size of the part sample edge
d	size of the slip zone
t	thickness of the sample
h	thickness of the slipping zone
M	overturning moment
N	total load normal to the slipping surface
T	rolling force on the slipping plane
P_n, P_t	projections of forces created by a wedge
α	angle of the contact plane orientation
β	angle of the wedge
r	distance
R	characteristic distance
Δf_{fr}	difference between the coefficients of static and slipping friction
σ	stress level
σ_1, σ_2	principal stresses
σ_n	normal pressure at the contact
σ_t^*	limit stress
σ_θ	hoop stress
$\tau_{\max}$	maximal shear stress at the contact
K_{II}	stress intensity factor for the transverse shear crack
K_{II}^*	stress intensity factor for the transverse shear crack at the initiation of the secondary crack
σ_t	tensile strength
σ^*	stresses in the sample along the slipping plane in the cross section of the secondary crack

normal displacements of crack surfaces are replaced by tangential displacements of the contacting surfaces. This leads to reduction in flow passage cross-section of a discontinuity. The effect may be important, for instance, for estimation of the fluid flow inside the crack.

Structures of fracture in layered media are controlled by local shear along interfaces. If longitudinal strain in the layer increases then the proportional decrease of the distance between the transverse cracks in it can be replaced by an opening of the existing cracks due to microshears at interfaces. Numerical analysis of the three-layer model of the layered medium has confirmed this concept [9].

Considerable amount of experimental studies is devoted to modeling of the interaction of a hydraulic fracture with interfaces and/or other discontinuities. This is due to complexity of observation of such processes in natural conditions and their technological significance. Most experiments were carried out on blocks of rocks or model materials on testing systems that provide mechanical loading of a sample in 3-D. Hydraulic fracture is initiated by fluid injected into a well in the block. In experiments with blocks containing also a joint (discontinuity of natural origin) it was shown [10] that horizontal differential stresses and the angle of the crack orientation with respect to the contact zone have a significant impact on hydrofracture propagation. At a small intercept angle (30°) and stresses (~9 MPa), the crack opens a discontinuity while sliding occurs along it at higher stresses. At larger angle (60°), the intersection of the hydrofracture with the natural joint occurs at high differential stresses (~15 MPa), while its opening takes place at lower stresses (~2 MPa). If the crack approaches an orthogonal joint, then the crossing has always been observed. The significance of the friction coefficient at the discontinuity surfaces for the conditions of natural joint (fault) crossed by a hydraulic fracture was shown in experiments on sandstone blocks with artificial fault [11]. Similar conclusions were obtained in [12]. Cracks in layered media, as in other variants of brittle fracture, are propagated along the trajectories providing maximal release rate of deformation energy. In experiments for modeling of the conditions of hydraulic fracture propagation in blocks containing a system of artificial parallel discontinuities it has been observed that the hydrofracture tends to be oriented perpendicular to the discontinuities. Crack trajectories are not always co-axial with to the direction of maximum principal stresses [13]. It is also shown that the fluid penetration into the discontinuity being crossed leads to shifting of the secondary cracks and splitting of the hydraulic fracturing front.

An experimentally verified criterion for crack propagation across perpendicular frictional interfaces has been proposed in [8]. Initiation of a secondary crack on the opposite side of the interface when the initial crack approaches the interface is related to the asymptotic behavior of the stresses in a small neighborhood of a crack tip of the initial crack. The maximum tensile stresses in the vicinity of the crack tip are observed at an angle to its direction. A secondary crack occurs when the stresses near the initial crack tip are sufficient to initiate a crack on the opposite side of the interface, and if the compression stresses at the interface are sufficient to prevent slip along the interface. The analytical criterion was later extended for the case of an arbitrary angle of the initial crack inclination to the interface [14], as well as for modeling of a stepwise crack formation in a block medium [15].