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Radial fracture in a three-phase composite: Application to wellbore cement liners at early ages

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ABSTRACT

Little understanding exists between the early-age stress developments in a wellbore cement sheath and its risk of impairment. During hydration, the cement morphology and pore-pressure changes induce eigenstresses in the solid and pore volumes. Utilizing these stresses as the driving mechanism of fracture, this paper formalizes the inspection of a radial crack in an elastic cement sheath constrained by an inner steel casing and an outer rock formation. The solution is constructed in the framework of analytic function theory and seeks the Green's function for an edge dislocation in the intermediate cement phase. A dislocation pile-up along the line of fracture constructs a singular integral equation for the crack opening displacement derivative, from which the energy release rate is readily deduced.

Under the uniform development of eigenstresses, the stiffness ratios of steel-to-cement and rock-to-cement generally predict the crack to initiate along the steel-cement interface. Here, the impacts of (i) a rigid bond and (ii) a sliding interface with no shear are assessed. This leads to the primary result of the paper: the potential for radial fracture is substantially mitigated by ensuring the shear connection between the steel casing and the cement sheath.

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1. Problem statement

In the construction of an oil or natural gas well, the cement sheath is placed between the geologic formation and the steel casing to seal reservoir fluids from overlying and underlying strata. Loss of the sealing function carries harmful environmental consequences, creates potential hazards in rig and oil well operations, and assumes loss of revenue due to decreased production capacity and expensive repair operations [1,2]. Nonetheless, recent evidence suggests that current design practices are insufficient in safeguarding against interzonal flow. For instance, studies have indicated that leakages of methane into groundwater aquifers during unconventional gas production (*i.e.*, gas production by hydraulic fracturing) are the result of impaired cement casings [3–5]. Though the debonding of the interfaces and the cracking of the sheath provide the most ostensible pathways for fluid migration, failure criteria have yet to be defined in the context of fracture criteria. Moreover, it is known that early-age shrinkage phenomena and pore-pressure developments are primary contributors to sheath failure [6], yet contemporary modeling efforts rarely and inadequately incorporate their physics. In this work, a framework is developed to connect the chemo-poro-elastic nature of cement to the risk of radial fracture in a wellbore cement sheath.

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Nomenclature

$\boldsymbol{\Sigma}$	effective stress tensor
$\boldsymbol{\sigma}$	stress tensor
κ	$3-4\nu$; elastic constant specific to the assumption of plane strain
$\mathbf{E}$	strain tensor
$\mathbf{Q}$	$Q_x + iQ_y$; contour integral of the traction vector normal to the integration path
$\mathbf{u}$	$u_x + iu_y$; displacement vector
$\mathcal{E}$	elastic potential energy
$\mathcal{G}$	fracture energy release rate
$\mathcal{K}$	stress intensity factor
μ	dislocation density
Φ	first complex potential defining the Airy stress function
Ψ	second complex potential defining the Airy stress function
σ^*	eigenstress in the solid-phase
ξ	hydration degree; mass fraction of cement undergone reaction
p	eigenstress in the fluid-phase; pore-pressure
R_0	inner radius of the steel casing
R_1	outer radius of the steel casing; inner radius of the cement sheath
R_2	outer radius of the cement sheath; borehole radius
C	cement domain
R	rock domain
RC	rock-cement interface
S	steel domain
SC	steel-cement interface

Cement shrinkage causes tensile hoop stresses that concentrate along the steel-cement boundary (SC) [7]. As formation fluid accumulates in open fractures, it acts to propagate cracks upward, and by extension, radially outward [8]. In our analysis, we calculate the energy release rate for a unit depth of the sheath due to a single crack emanating along SC. Several other studies have solved similar problems. Bowie and Freese provided the stress intensity factor for an edge crack in a circular ring with a uniform tension applied along the external boundary [9]. Delale and Erdogan produced the stress intensity factor for a radial crack in a hollow cylinder [10]. The solutions closest to the problem at hand were given by Luo and Chen [11] and Ardakani and Ulm [12], who solved for the energy release rate of a crack in the intermediate matrix of a three-phase composite cylinder. The analysis outlined in the following synthesizes and amends elements of the aforementioned works, integrates the sheath as a chemo-poro-mechanics material, and expands upon the boundary conditions posed along the cement interfaces. The result is a low-input model that respects the constitutive behavior of cement and draws upon analytic function theory to assess the risk of radial fracture.

2. Fracture mechanics in chemo-porous media

It is now generally agreed that the mechanical behavior of cement is well described by elastic poromechanics models [13–15]. More recent models capture the couplings between the eigenstress in the calcium-silicate-hydrate gel (the primary constituent of the solid cement phase) $\sigma^*(\xi)$, the pore-pressure development $p(\xi)$, and the deformation of the porous skeleton [16]. At early ages, the cement has a solid-to-pore volume fraction that varies in function of the hydration degree, ξ. This means that the growth of the solid matter requires the loading of the system to be assessed *incrementally* and at *constant hydration degree*. That is, the incremental loading due to the eigenstresses, $\delta\sigma^*(\xi)$ and $\delta p(\xi)$, and at an instant ξ in the reaction process is applied to an instantaneous system volume $V(\xi)$. A subsequent increment in loading $(\delta\sigma^*(\xi+\delta\xi); \delta p(\xi+\delta\xi))$ must be framed as a new boundary value problem whose solid volume has increased to $V(\xi+\delta\xi)$. As such, the risk of fracture is specific to the hydration degree and eigenstresses prevailing at the time of evaluation.

The energy release rate,

$$\mathcal{G}(\Gamma)|_{\xi,\sigma^*,p} = \frac{\partial \mathcal{W}}{\partial \Gamma}\bigg|_{\xi,\sigma^*,p} = \frac{1}{2}\int_{\Gamma} [(\boldsymbol{\sigma} + p\mathbf{I})\cdot\mathbf{n}]\cdot\frac{\partial [\![\mathbf{u}]\!]}{\partial \Gamma}\mathrm{d}\Gamma \tag{1}$$

is inspected by holding ξ, σ^*, and p constant and measures the work $\partial\mathcal{W}$ required to create an additional unit of crack surface area $\partial\Gamma$. A drained fracture process will reduce the traction vector normal the surface of the crack from its initial value $\boldsymbol{\sigma}\cdot\mathbf{n}$ to its progressed value $-p\mathbf{I}\cdot\mathbf{n}$, causing a jump in displacement $[\![\mathbf{u}]\!]$. Comparing $\mathcal{G}$ to the evolution of the fracture toughness

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