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Crack tip behavior in near-surface fluid-driven fracture experiments

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Abstract

This Note presents experimental results for the near-tip fracture opening of fluid-driven fractures. The effect of fluid viscosity, quantified by a dimensionless parameter, was varied between tests. The tip region closely followed the classical square-root behavior from linear elastic fracture mechanics when the viscosity parameter was small. Conversely, when the viscosity parameter was of order one and the lag between the fluid-filled region and the fracture front accounted for less than 30% of the fracture, the tip region behaved according to a known intermediate asymptotic solution which results from the solid/fluid coupling. ***To cite this article: A.P. Bunger et al., C. R. Mecanique 333 (2005).***

Résumé

Étude expérimentale du comportement en bout d'une fracture hydraulique se propageant près d'une surface libre. Cette Note présente les résultats d'une campagne expérimentale visant évaluer l'effet de la viscosité du fluide, quantifiée à l'aide d'un paramètre adimensionnel, sur l'ouverture en bout d'une fracture hydraulique. Les résultats expérimentaux confirment que la région en tête de fissure est conforme au comportement en racine carrée predit par la mécanique de la rupture fragile, tant que le paramètre viscosité est petit. Au contraire, lorsque ce paramètre est d'ordre 1, et que la cavité entre le front fluide et l'extrémité de la fracture couvre moins de 30 % du rayon de la fracture, l'ouverture en bout de fissure vérifie une solution asymptotique intermédiaire, résultant du couplage fluide/solide. ***Pour citer cet article : A.P. Bunger et al., C. R. Mecanique 333 (2005).***

Keywords: Rupture; Hydraulic fracture; Fracture mechanics

Mots-clés : Rupture ; Fracturation hydraulique ; Mécanique de la rupture fragile

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Le problème d'une fracture se propageant dans un milieu élastique imperméable par injection d'un fluide visqueux est gouverné par un système d'équations issus de la mécanique de la rupture fragile d'une part et de la théorie de la lubrification d'autre part [1]. Les considérations théoriques font apparaître l'existence de deux échelles de longueur en bout de fissure, $\ell_k = (K_{Ic}/E')^2$ liée à la singularité en racine carrée de la mécanique de la fracture [5] et l'autre $\ell_m = \mu V/E'$ résultant du couplage entre l'écoulement d'un fluide visqueux et la déformation élastique du solide [6,4]. (Le symbole K_{Ic} représente la tenacité du solide, E' le module d'élasticité en défomation plane, μ la viscosité du fluide d'injection, et V la vitesse de propagation de la fracture.) Chacune de ces échelles est associée à une différente asymptote de l'ouverture w : ℓ_k à la loi classique $w \sim x^{1/2}$, cf. (1), et ℓ_m au comportement $w \sim x^{2/3}$, cf. (2), où x est la distance depuis le bout de la fissure.

Une analyse détaillée de la région en bout de fracture montre qu'une couche frontière d'épaisseur $\ell = \ell_k^3/\ell_m^2$ existe, pourvu que ℓ soit petit vis à vis du rayon R de la fracture hydraulique [7]. Dans ces conditions, $w(x)$ se comporte selon (1) à l'échelle ℓ de la couche frontière, mais selon (2) à l'échelle R. De plus, l'asymptote intermediaire (2) raccorde la solution intérieure et extérieure. Donc si ℓ/R est suffisament petit, la fracture se propage en régime visqueux, vu que la solution à l'échelle R est alors indépendante de la tenacité [7]. La condition sur ℓ/R fait intervenir la solution du problème d'évolution, puisque ce rapport dépend de la vitesse de propagation et de la longueur de la fracture, toute les deux fonctions du temps t. Cette condition peut en fait être interpretée en terme des paramètres du problème (y compris le débit d'injection $\langle Q\rangle$) et de t pour des fractures à géométrie simple, car les différent régimes de propagation peuvent être alors associés à des échelles de temps de caractère universel [8,9].

Une fracture radiale se propageant parallèlement à une surface libre évolue suivant deux échelles de temps [9] : $t_{\bar{m}\bar{k}}$, cf. (3), mesurant le temps de propagation en régime visqueux (ℓ/R est donc suffisamment petit si $t < t_{\bar{m}\bar{k}}$) ; $t_{k\bar{k}}$, cf. (4), donnant une mesure du temps nécessaire pour que R soit du même ordre que la profondeur H. Dès lors, la condition de propagation en régime visqueux est remplie tant que R/H est d'ordre $\mathrm{O}(1)$ ou plus petit (ce qui correspond aux conditions experimentales) pourvu que la viscosité adimensionelle $\bar{\mathcal{M}} = t_{\bar{m}\bar{k}}/t_{k\bar{k}}$, cf. (4) soit $\mathrm{O}(1)$ ou plus grand. Au contraire, si $\bar{\mathcal{M}} \ll 1$, la dissipation d'énergie est dominée par la tenacité et le comportement asymptotique en bout de fracture, à l'échelle R, est donné par (1).

Plusieurs essais de fracturation hydraulique ont été réalisés au laboratoire en changeant les conditions expérimentales de manière à faire varier le paramètre $\bar{\mathcal{M}}$. Une séries d'essais a été réalisée dans du Polymethylmethacrylate ($\bar{\mathcal{M}} \ll 1$, une autre dans du verre en borosilicate ($E' = 65\,000$ MPa, $K_{Ic} = 0{,}7$ MPa m$^{1/2}$) pour atteindre $\bar{\mathcal{M}} = \mathrm{O}(1)$. Le fluide d'injection utilisé est une solution aqueuse de glycerine dont la viscosité peut-être facilement modifiée entre 10^{-3} et 2,5 Pa s en changeant la dilution et/ou la température. Le montage experimental comprend une source lumineuse diffuse à l'arrière de la fracture et une caméra video pour enregistrer la lumière transmise par la fracture lors de sa croissance. Avec l'addition d'un agent colorant bleu dans le fluide d'injection, l'atténuation de l'intensité lumineuse par la fracture peut être interpretée en terme de w en faisant appel à la loi de Beer–Lambert (6). Deux profils d'ouverture représentatifs de $\bar{\mathcal{M}} \simeq 0{,}01$ et 0,7 (Fig. 2) illustrent le bon accord entre l'ouverture en bout de fracture mesurée expérimentalement et les asymptotes (1) et (2). L'intensité de l'asymptote (2) représentée en Fig. 2 est calculée en identifiant la vitesse V avec celle du front du fluide, déduite de sa position en deux instants successifs. Un dépouillement des images vidéo confirme que les résultats expérimentaux s'accordent avec une marge d'erreur de moins de 20 % au comportements asymptotiques (1) et (2) si $\bar{\mathcal{M}} \ll 1$ et $\bar{\mathcal{M}} = \mathrm{O}(1)$, respectivement. Les seules exceptions concernent les résultats à petit temps lorsque le rayon du trou d'injection ne peut pas être négligé par rapport à R, et lorsque la cavité en bout de fracture dépasse de 30 % le rayon de la fracture.

1. Introduction

The mathematical model of fluid-driven fracture consists of a coupled system of equations resulting from simultaneous consideration of linear elastic fracture mechanics (LEFM) and lubrication theory [1], based on a series of assumptions that include neglecting effects related both to two-dimensional flow near the tip [2] and to the surface tension of the fluid [3]. The behavior of the solution near the fracture tip has been shown to be multiply-scaled, where the length scales associated with different tip asymptotes are related to the problem parameters [4]. Consequently, while the classical square-root tip asymptote from LEFM [5] may describe tip behavior well under certain conditions, it is often the case that its associated length scale becomes vanishingly small relative to the length scale associated with an intermediate asymptote. Appropriately accounting for this unique crack-tip behavior is an important part of solving fluid-driven fracture problems (e.g. [1]).

This Note presents the results of an experimental investigation of the near-tip behavior for fractures driven by Newtonian fluids in transparent materials which are assumed to be linear elastic and impermeable. These fractures, circular and initially parallel to a nearby traction-free surface, curve towards the surface to become bowl-shaped, day-lighting when the radius is 3 to 3.5 times the initial depth (Fig. 1(a)). The main contribution of this work comes via an experimental technique based on the Beer–Lambert law of optical absorption which enables measurement of the fracture opening over the entire fluid-filled region of the fracture. In this way, theoretical predictions about the variation of the fracture aperture in the tip region may be scrutinized by direct comparison with experimental results.

2. Theoretical background

Linear elastic fracture mechanics gives the following asymptotic form for w, the crack opening [5]

$$w \sim 4\left(\frac{2}{\pi}\right)^{1/2} \frac{K_{Ic}}{E'} x^{1/2}, \quad \frac{x}{R} \ll 1 \tag{1}$$

where K_{Ic} is the fracture toughness, $E' = E/(1-\nu^2)$ is the plane strain modulus with E denoting Young's modulus and ν Poisson's ratio, x is the distance from the crack tip, and R is the fracture radius (or length). However, when the fracture is driven by a Newtonian fluid with viscosity μ, the coupling between linear elasticity and lubrication theory leads under certain conditions to an intermediate asymptote [6,4]

$$w \sim 2\, 3^{7/6}\left(\frac{\mu}{E'}\right)^{1/3} V^{1/3} x^{2/3}, \qquad \frac{x}{R} \ll 1 \tag{2}$$

where V is the mean fluid velocity in the tip region, which is strictly equal to the fracture tip velocity if the lag between the fluid front and the crack tip is negligible. Because there are two asymptotic forms, the question arises as to when a particular form dominates the tip behavior at a length scale important to fracture modelling.

Detailed analysis of the tip region [7] indicates that the emergence of the intermediate asymptote (2) is linked to the existence of a boundary layer structure with thickness $\ell = \ell_k^3/\ell_m^2$, where $\ell_k = \left(K_{Ic}/E'\right)^2$ is the length scale associated with LEFM and $\ell_m = \mu V/E'$ is the length scale associated with viscous dissipation. This boundary layer is characterized by the LEFM asymptote (1) at the tip and by the viscous dissipation asymptote (2) far away from the tip (in terms of the layer coordinate), with the intermediate asymptote (2) also matching the inner and outer solution. In other words, the existence of this boundary layer implies both dominance of the intermediate asymptote (2) in the tip region when viewed at the scale of the fracture and propagation of the fracture in the viscosity-dominated regime [7]. Along with this comes strong fluid/solid coupling, large fluid pressure gradients, and the potential for significant fluid lag under small confining stress.

Propagation in the viscosity-dominated regime simply requires that ℓ is small compared with the fracture length scale. However, for fractures with simple, invariant shapes, the various regimes of fracture propagation may be associated with universal timescales [8,9]. Because of this, the general requirement on the ratio of length scales may be translated for some cases to a requirement that a certain dimensionless viscosity, which depends on a characteristic time, is of order one or larger. For radial fractures this dimensionless viscosity has the form of a negative power of time divided by a characteristic time, which is given for a fracture growing parallel to a free surface at depth H by [9]

$$t_{\bar{m}\bar{k}} = \frac{\mu H^{3/2} E'^2}{K_{Ic}^3} \tag{3}$$

Hence, the viscosity-dominated regime corresponds to $t/t_{\bar{m}\bar{k}} < 1$. Beyond this threshold, the problem evolves to the toughness-dominated regime, in which fluid/solid coupling vanishes and the LEFM asymptote dominates tip behavior at the length scale of R. Near-surface fractures grow relative to depth H on a second independent timescale [9]

$$t_{k\bar{k}} = \frac{K_{Ic} H^{5/2}}{\langle Q \rangle E'} \tag{4}$$

where $\langle Q \rangle$ is the mean injection rate up to time t. Provided that the fractures grow only to some order one multiple of the depth, timescale $t_{k\bar{k}}$ gives an estimate of the time required for a particular fracture to grow. It follows that the ratio of time scales $\bar{\mathcal{M}}$

$$\bar{\mathcal{M}} = \frac{t_{\bar{m}\bar{k}}}{t_{k\bar{k}}} = \mu \frac{E'^3 \langle Q \rangle}{H K_{Ic}^4} \tag{5}$$

can be used to identify the dominant regime in which the fracture will grow when $R/H \leqslant \mathrm{O}(1)$. Thus the fracture propagates mostly in the viscosity-dominated regime when $\bar{\mathcal{M}} \geqslant \mathrm{O}(1)$. Conversely, when $\bar{\mathcal{M}} \ll 1$ the fracture grows almost entirely in an essentially uncoupled (toughness-dominated) regime and the tip behavior would not be expected to reflect the fluid-driven fracture asymptote.

3. Experimental technique

We have developed experiments to explore hydraulic fracture behavior for varying values of the parameter $\bar{\mathcal{M}}$. One series of tests, performed in Polymethylmethacrylate (PMMA) ($E' = 3900$ MPa, $K_{Ic} = 1.4$ MPa m$^{1/2}$), was designed such that $\bar{\mathcal{M}} \ll 1$. A second series, designed such that $\bar{\mathcal{M}} = \mathrm{O}(1)$, was performed in borosilicate glass ($E' = 65\,000$ MPa, $K_{Ic} = 0.7$ MPa m$^{1/2}$). Fractures were driven by aqueous glycerin, a Newtonian fluid with a viscosity which may be easily varied from 0.001 to 2.5 Pa s depending on water content and temperature. Initiation occurred from a pre-existing manufactured flaw with initial radius of 10 mm and initial depth of 12 to 15 mm.

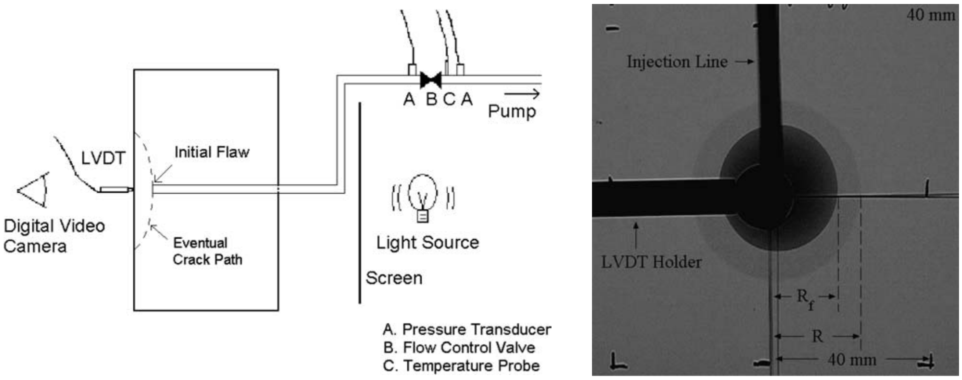
Injection fluids contained a proportion of aqueous blue dye and a video camera recorded the intensity of light transmitted through the growing fracture from a back-light source (Fig. 1(a)). In this way, opening was determined from the optical absorbance A of the fluid-filled portion of the fracture according to the well-known Beer–Lambert law

$$A \equiv \log \frac{I_o}{I} = \frac{w}{k} \tag{6}$$

where k is a constant determined by calibrating with fluid-filled wedges of known geometry. Additionally, pressure was measured using analog transducers, injection rate was estimated from the pressure drop across a needle-type flow control valve, and fracture radius R and fluid radius R_f were determined directly from video images of the growing fracture (Fig. 1(b)).

4. Results

We present the results of two representative tests in which the radius to depth ratio grew in the approximate range $0.5 < R/H < 3.5$. The dimensionless viscosity parameter was $\bar{\mathcal{M}} \approx 0.03$ for the first and $\bar{\mathcal{M}} \approx 0.7$ for



(a) (b)

Fig. 1. (a) Sketch of experimental setup; (b) image of growing hydraulic fracture.

Fig. 1. (a) Principe du montage expérimental ; (b) image d'une fracture hydraulique en propagation.

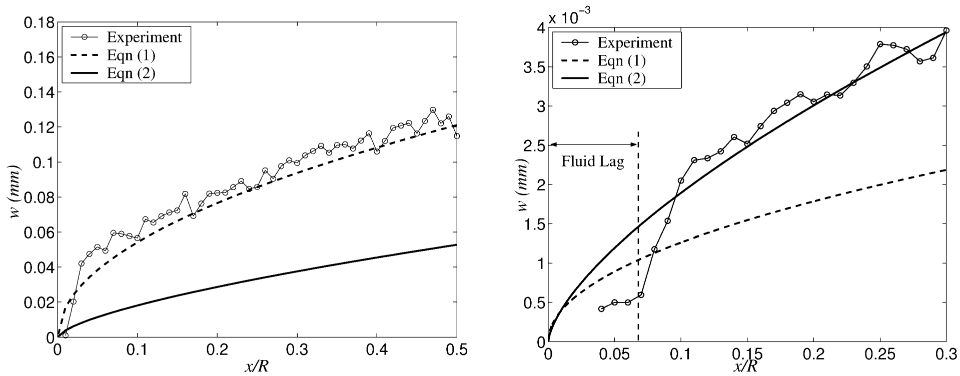


Fig. 2. Fracture opening, valid in the fluid-filled region, versus normalized distance from fracture tip for dimensionless viscosity parameter $\bar{\mathcal{M}} \approx 0.03$ (left) and $\bar{\mathcal{M}} \approx 0.7$ (right).

Fig. 2. Ouverture de la fracture, valide dans la région occupée par le fluide, en fonction de la distance normalisée du bout de la fracture pour le paramètre viscosité $\bar{\mathcal{M}} \approx 0{,}03$ (à gauche) et $\bar{\mathcal{M}} \approx 0{,}7$ (à droite).

the second. Examples of the crack tip opening for each test are shown in Fig. 2, which illustrates the agreement between the theoretical tip asymptotics and experimental results. Fig. 2 also shows that the parameter $\bar{\mathcal{M}}$ plays the crucial role in determining the tip behavior. While this figure shows only one snapshot in time from each test, it was found that for $\bar{\mathcal{M}} \ll 1$ and $\bar{\mathcal{M}} = \mathrm{O}(1)$ respectively, (1) and (2) consistently match the opening in the crack tip region ($x/R < 0.6$) within about 20 percent. The fluid lag observed in these experiments supports some previous findings [10].

The two notable exceptions where this match between theory and experiment breaks down are at early and large time. At early time, the fracture radius is on the order of the size of the injection tube, thus we suggest that the stress field, and thus the fracture behavior, is significantly effected by the presence of the borehole. At large time, poorer agreement between experiment and theory is observed only in the tests with significant fluid viscosity effects, and hence, significant fluid lag. Specifically, it appears from the experiments that (2) holds only for $R_f/R > 0.7$. When fluid fraction is smaller than 70 percent, it is likely that there is not sufficient overlap between the fluid-filled region and the tip region for the intermediate asymptotic solution to hold.

5. Conclusions

The hydraulic fracture tip solutions [6,4] which are shown here to be in congruity with the experimental data, assume that the size of the fluid lag region is very small relative to the crack length. This assumption guarantees the existence of an overlap between the fluid-filled and the near-tip regions in which the intermediate asymptote (2) holds. These experimental results suggest that an overlap region may exist even when the fluid lag accounts for nearly $1/3$ of the fracture radius. We are thus pushed into new theoretical territory and therefore a word of caution is in order. While these results provide direct experimental evidence supporting the existence of an intermediate tip solution associated with the two-thirds asymptotic behavior, they will not be fully understood until the theoretical aspects of the tip region of a fluid-driven fracture with significant fluid lag are more thoroughly explored.

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