ARMA19-103: Propagation of a plane-strain hydraulic fracture accounting for the presence of a cohesive zone and a fluid lag

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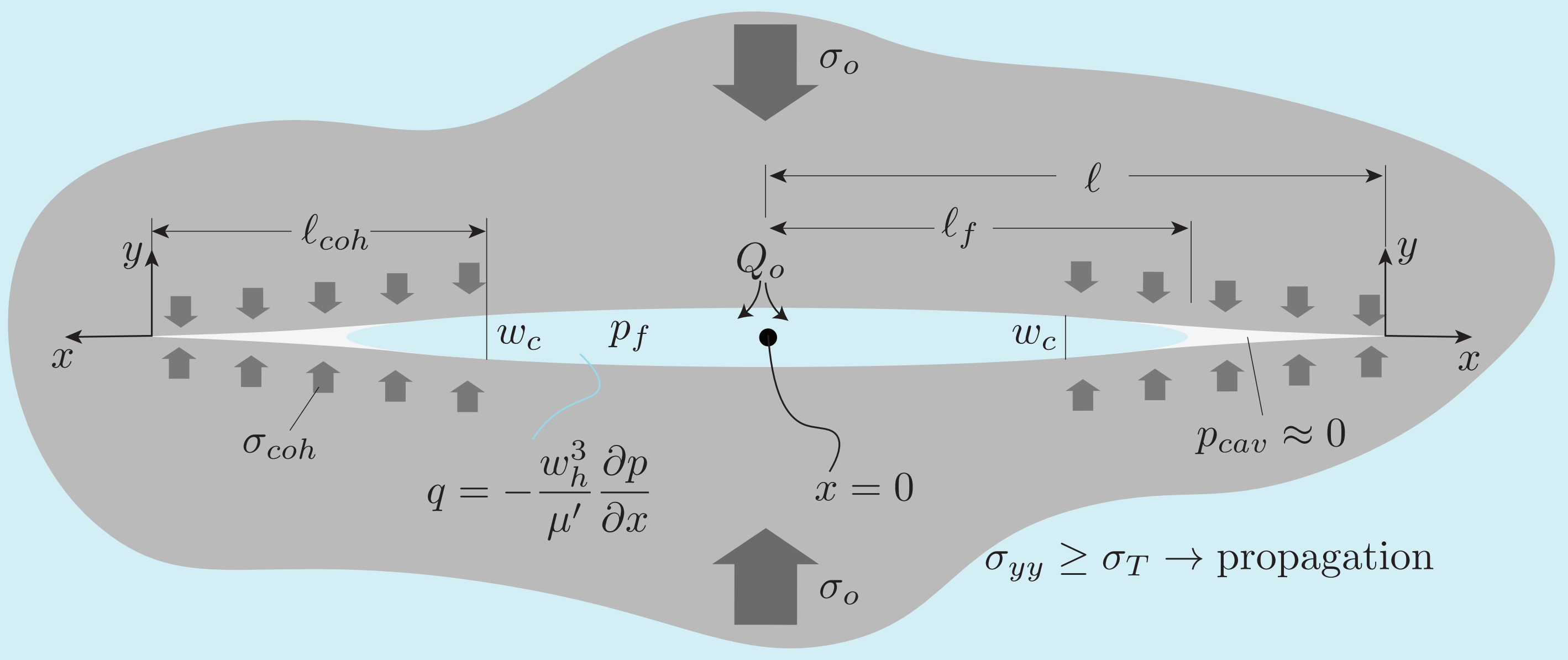
1. Highlights

We study the growth of a plane-strain hydraulic fracture in an impermeable quasi-brittle material. The evolution of the fluid lag differs from the purely brittle case as the fluid penetrates into the cohesive zone. As a result, besides (i) a dimensionless toughness and (ii) a timescale t_{om} governing the disapperance of the fluid lag, the fracture propagation also depends on (iii) the ratio between the in-situ confining stress and the tensile strength σ_o/σ_T.

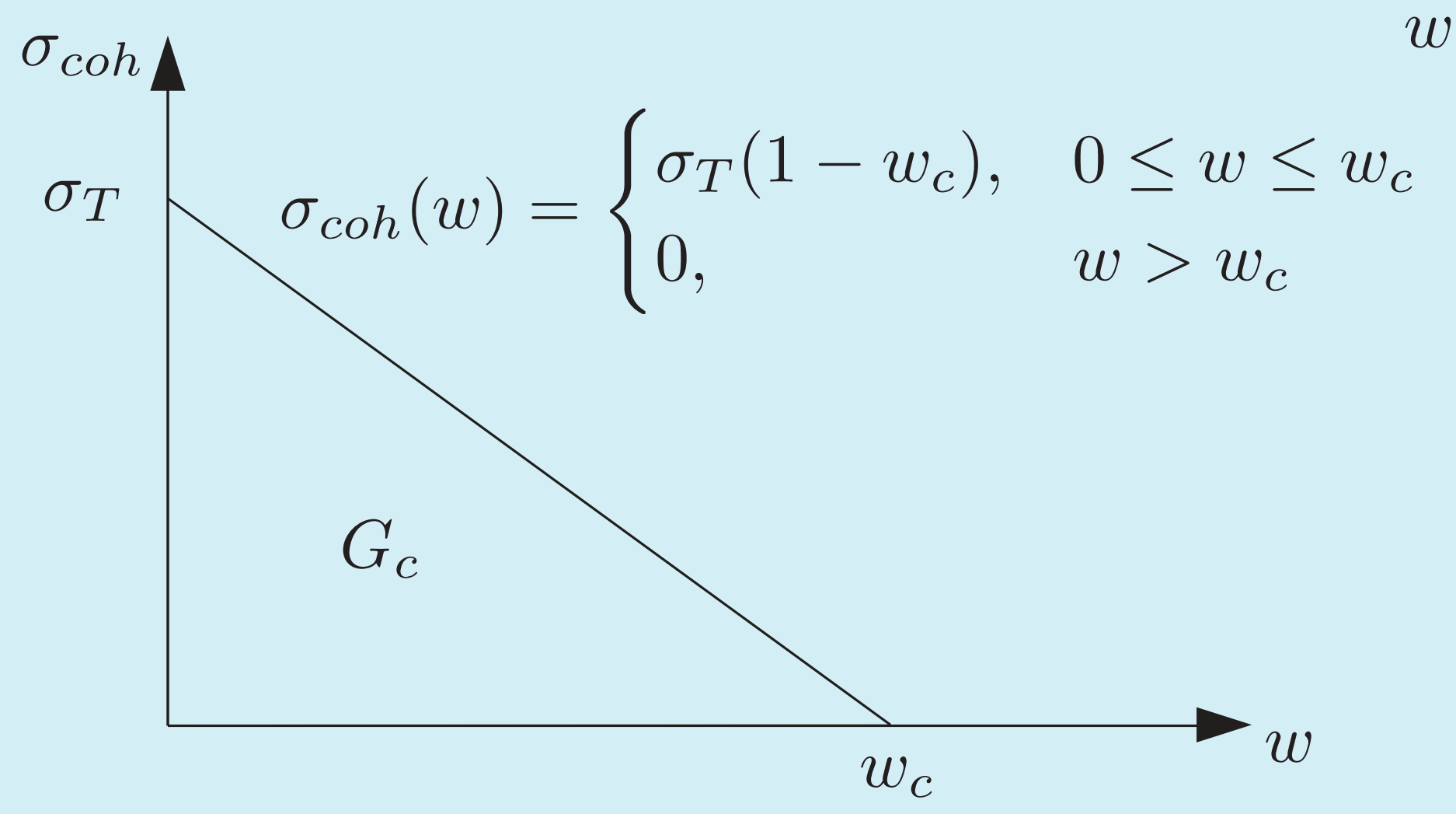
The cohesive forces clamp the fracture tip and further enhance the elasto-hydrodynamics suction effect. The effect becomes prominent when the fluid front lies within the cohesive zone. As a result, the fluid pressure drop is further localized near the tip and the fracture growth deviates from the known solutions for a linear elastic medium. A slightly wider opening and higher net pressure are obtained. The length of the cohesive zone increases with time, eventually reaching a plateau at very large time (not observed in our early-time simulations). This development is strongly influenced by σ_o/σ_T.

2. Problem description

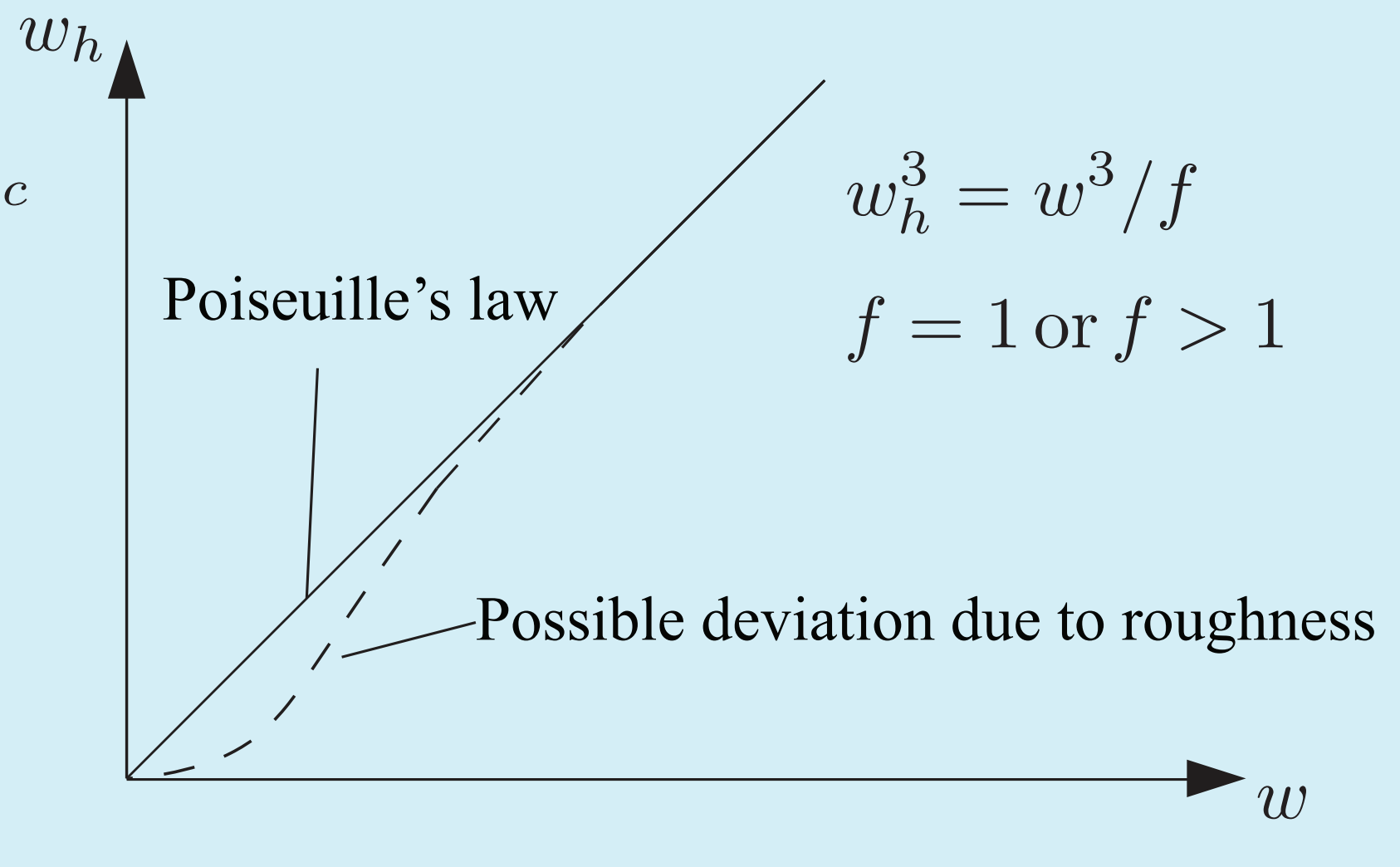


Hypothesis:
Homogeneous
Newtonian fluid
Constant injection rate

Isotropic
Incompressible fluid
Zero leak-off



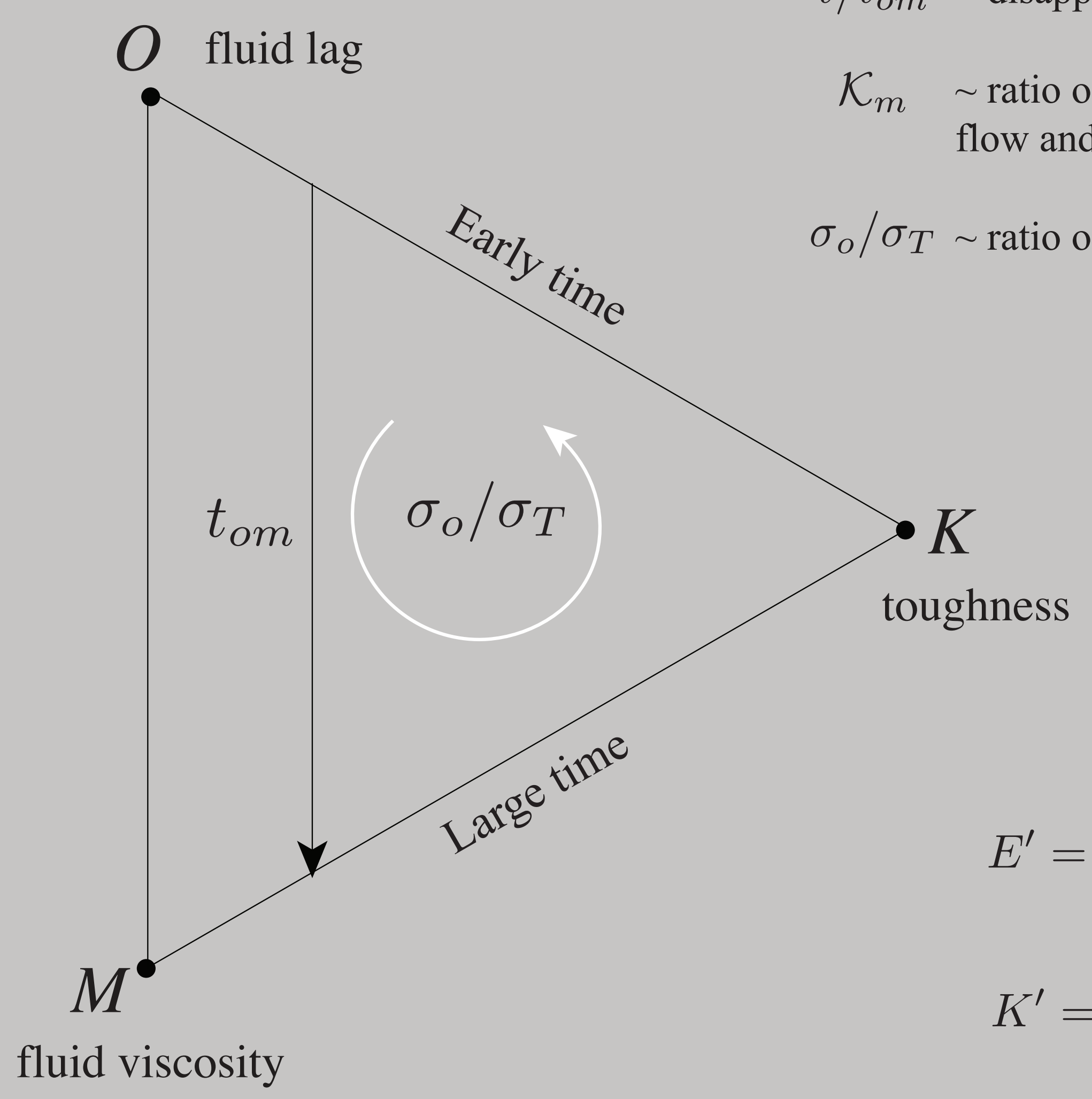
$$\sigma_{coh}(w) = \begin{cases} \sigma_T(1-w_c), & 0 \leq w \leq w_c \\ 0, & w > w_c \end{cases}$$



$$w_h^3 = w^3/f$$

$$f = 1 \text{ or } f > 1$$

3. Dimensional analysis



t/t_{om} ~ disappearance of the fluid lag

$\mathcal{K}_m$ ~ ratio of energy dissipated by viscous fluid flow and that of fracture surface creation

σ_o/σ_T ~ ratio of confining stress and the rock tensile strength

$$t_{om} = \frac{E'^2\mu'}{\sigma_o^3}$$

$$\mathcal{K}_m = \frac{K'}{E'}\left(\frac{E'}{\mu' Q_o}\right)^{1/4}$$

$$E' = \frac{E}{1-\nu^2} \qquad \mu' = 12\mu$$

$$K' = \sqrt{\frac{32}{\pi}}K_{Ic} = \sqrt{\frac{16}{\pi}E'\sigma_T w_c}$$

Characteristic scales:

$$L_m = \frac{Q_o^{1/2}E'^{1/6}t^{2/3}}{\mu'^{1/6}} \qquad W_m = \frac{\mu'^{1/6}Q_o^{1/2}t^{1/3}}{E'^{1/6}}$$

$$P_m = \frac{\mu'^{1/3}E'^{2/3}}{t^{1/3}} \qquad L_{coh} = \frac{E' w_c}{\sigma_T}$$

4. Numerical Scheme

We adopt a fixed regular grid and discretize elasticity using the displacement discontinuity method with piece-wise constant elements. The fluid mass conservation is discretized by finite difference. We use a fully implicit scheme to solve for fluid pressure, fracture opening and fracture increment. To model the appearance of the fluid lag during fracture initiation, we adopt an Elrod-Adams based method. After the appearance of the fluid lag, we use the previously obtained results to initialize a scheme tracking the fluid front position via the introduction of a filling fraction variable as in (Gordeliy and Detournay, 2011). This allows us to to perform simulations with a larger span of dimensionless time at a reduced computational cost. We choose the same element size in both algorithms, and solve iteratively for the time-step increment corresponding to a given increment of fracture length.

5. Results

$\mathcal{K}_m = 1.009$

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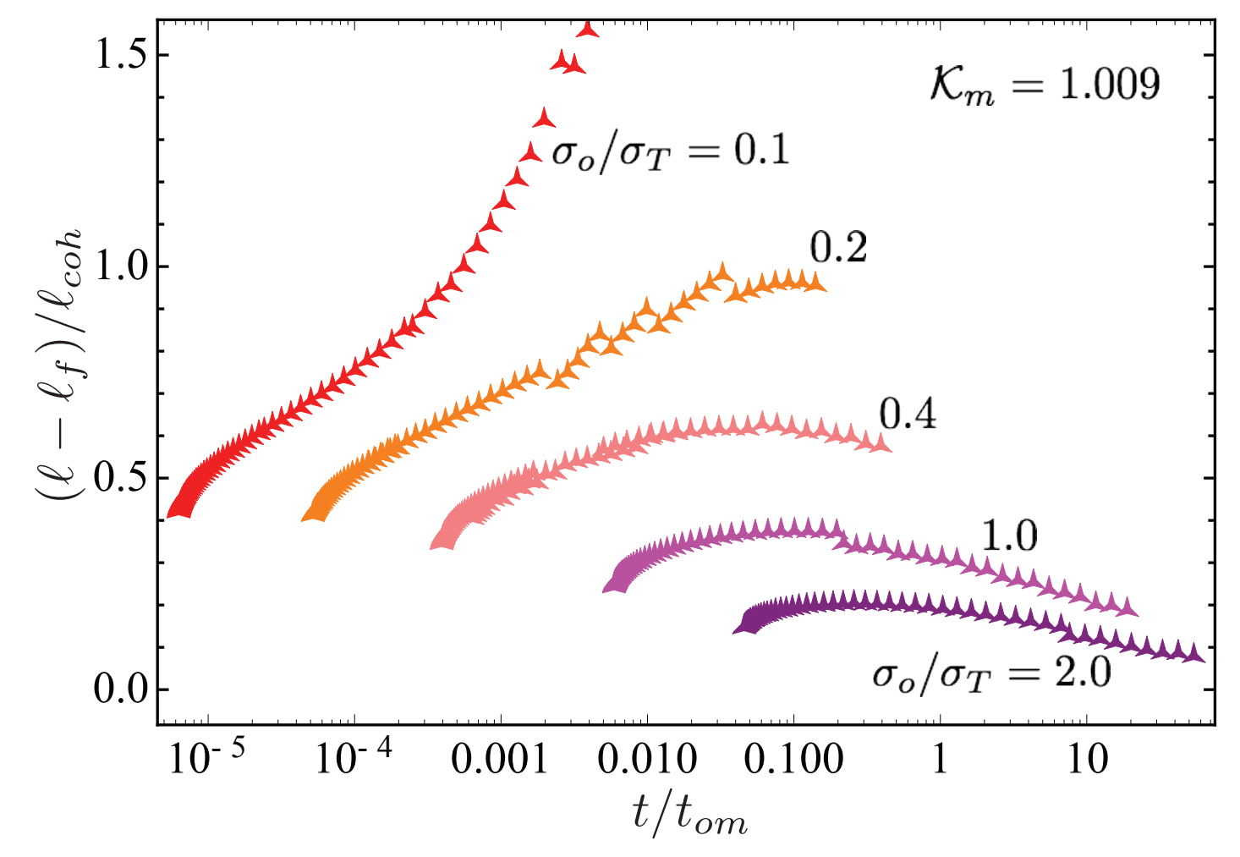
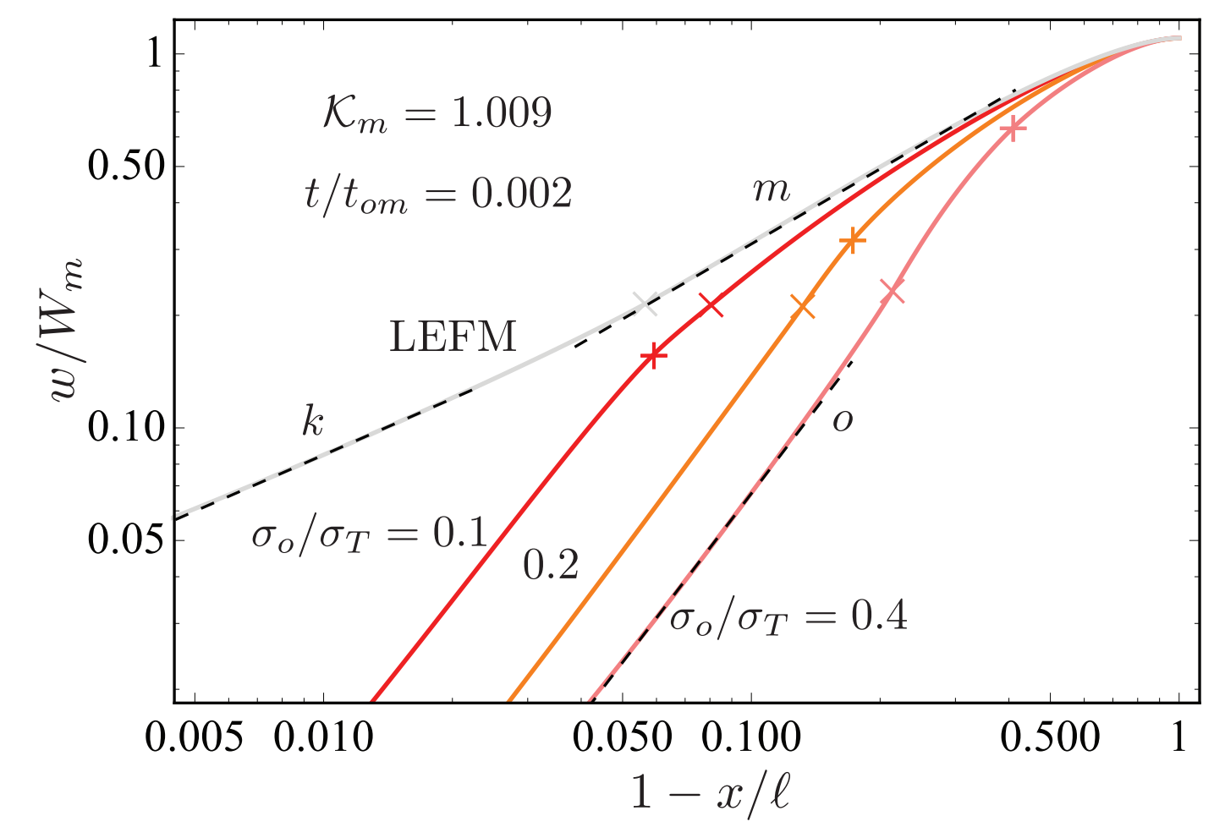
$\sigma_o/\sigma_T =$	0.1	0.2	0.4	1.0	2.0	0.

× fluid front + cohesive zone

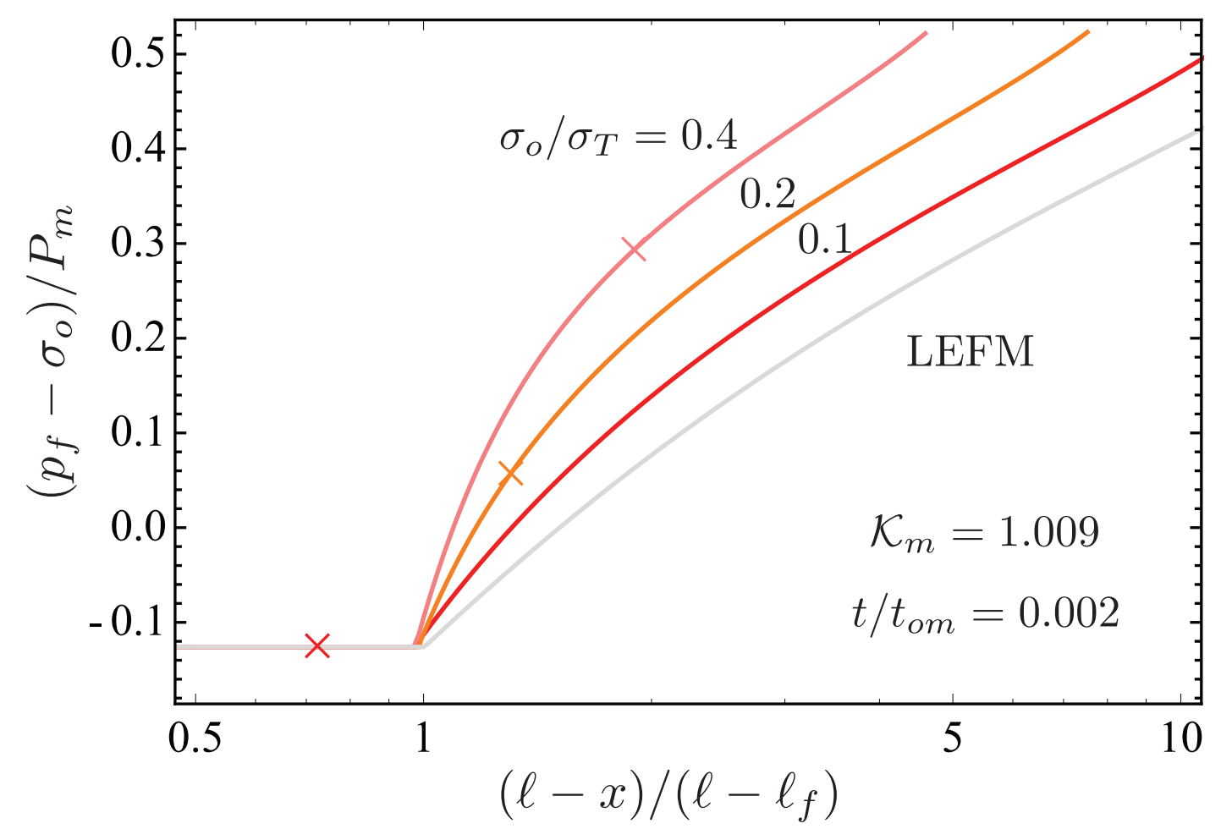
Fluid lag scaled by the cohesive zone length



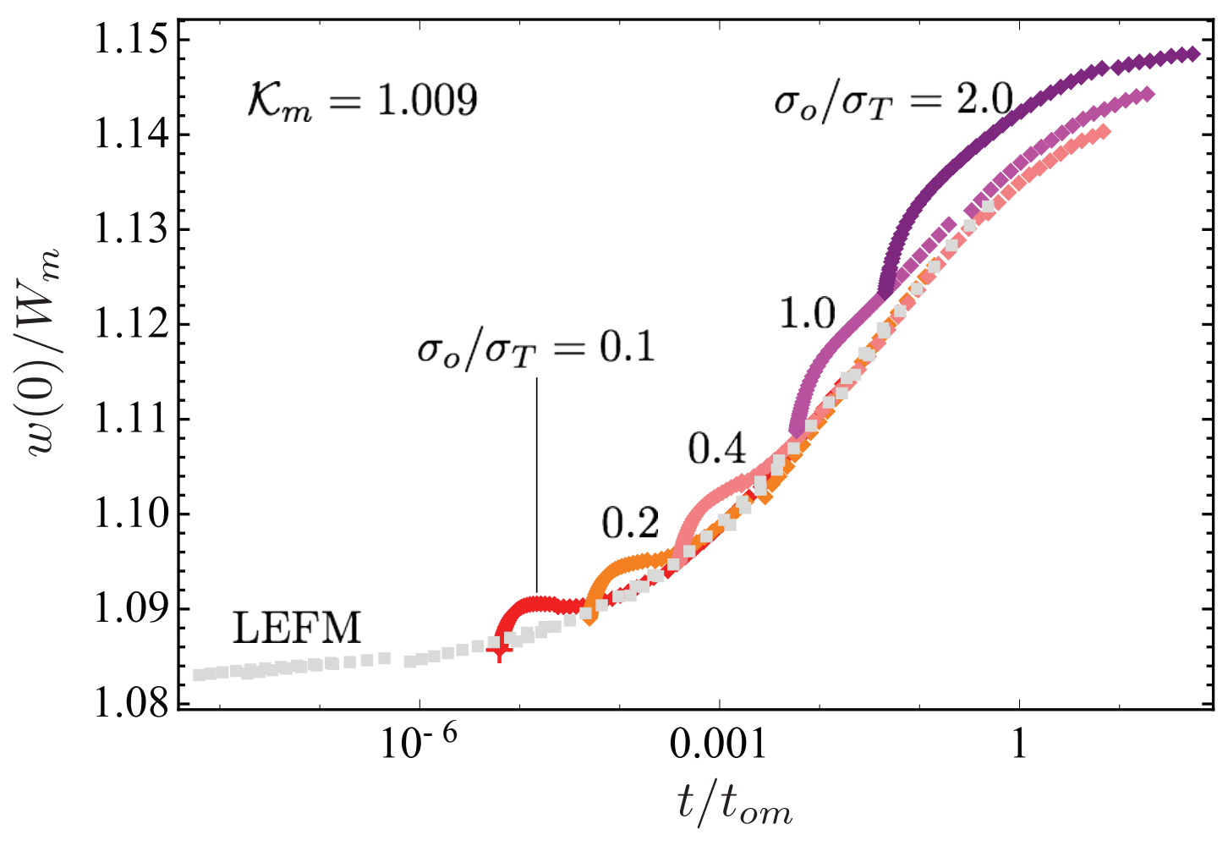
Change of the fracture tip-asymptote



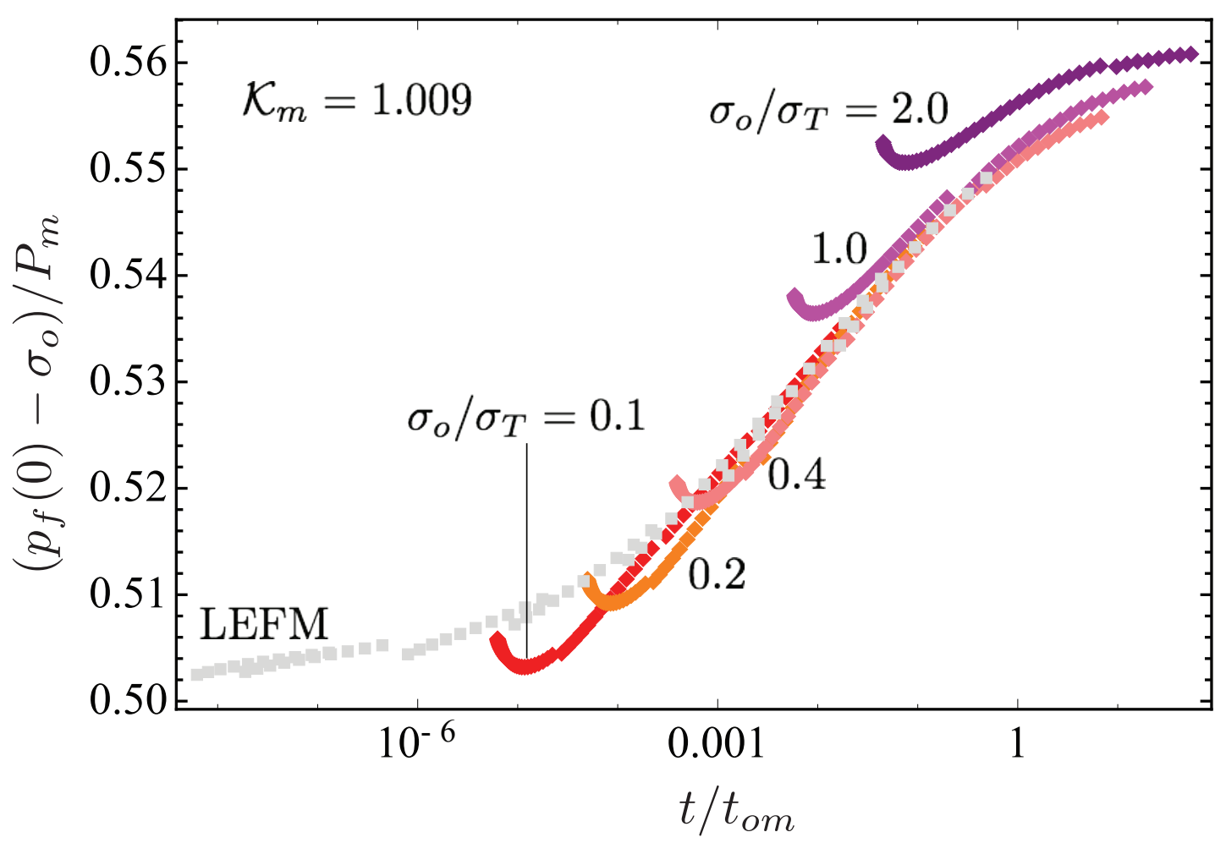
Localization of the pressure drop



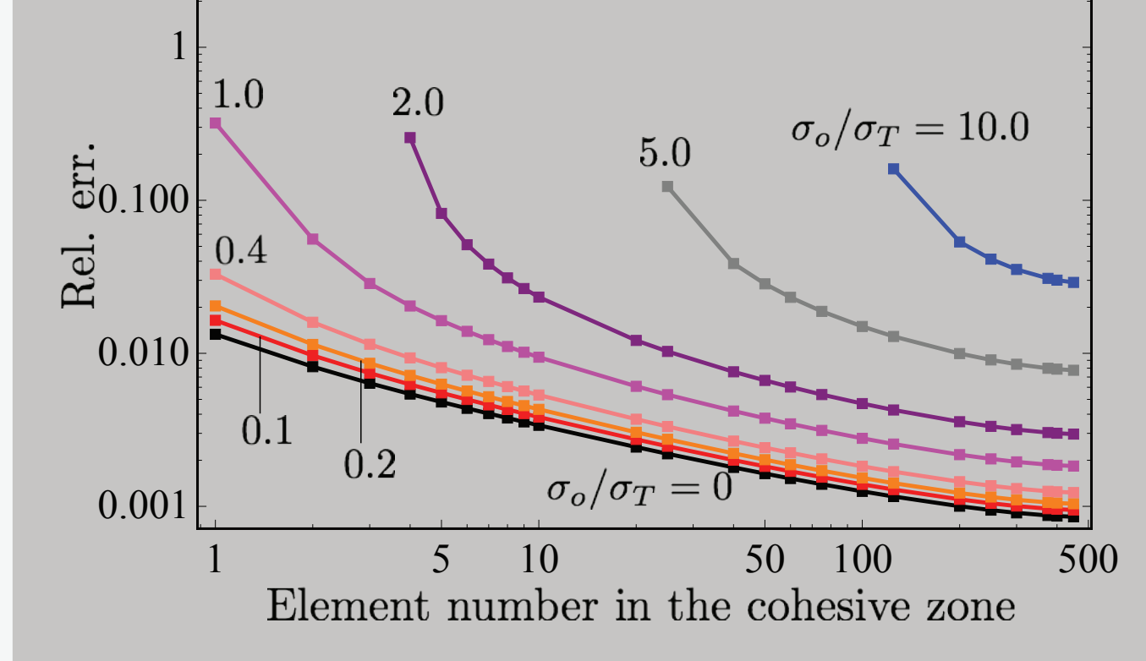
Inlet opening vs time



Inlet net pressure vs time



6. Discussions



Mesh dependency of the stress accuracy ahead of the fracture tip (stress component of the element nearest to the fracture tip) for a uniformly-pressurized fracture with an impermeable cohesive zone.

The mesh size has a significant effect on the stress accuracy ahead of the tip. A larger σ_o/σ_T requires a finer mesh (e.g. more elements inside the cohesive zone) to capture the shrinking tensile zone ahead of the fracture tip. In order to study cases which are closer to the field condition (σ_o/σ_T~10) with a small fraction of the cohesive zone compared to the whole fracture length, a large number of elements are required (up to 10^4 1D elements).

The critical opening in the cohesive zone model can be very small of the order of the aperture roughness. Fluid flow in small rough apertures may deviate from Poiseuille's law which assumes a smooth channel flow. As a result, an increased resistance to fluid flow will occur inside the cohesive zone. This will further localize the pressure drop inside the cohesive zone. Wider inlet opening and higher pressure are anticipated. Such effect would only play a role when the fluid front penetrates into the cohesive zone, corresponding usually to the later stage of propagation where the fluid lag becomes smaller.

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