

Problem Sheet 4

1. In a two-dimensional granular material, show that the normal stress N and shear stress F on a line element with unit normal $\mathbf{n} = (\cos \theta, \sin \theta)^T$ lie on the *Mohr circle*

$$F^2 + \left(N - \frac{1}{2}(\tau_{xx} + \tau_{yy}) \right)^2 = \frac{(\tau_{xx} - \tau_{yy})^2}{4} + \tau_{xy}^2.$$

Sketch the Mohr circle in the (N, F) -plane and explain why the Coulomb yield condition $|F| = -N \tan \phi$ is satisfied at exactly one value of θ if and only if

$$-(\tau_{xx} + \tau_{yy}) \sin \phi = \sqrt{(\tau_{xx} - \tau_{yy})^2 + 4\tau_{xy}^2}.$$

If there is no body force and negligible inertia, deduce that the Airy stress function satisfies

$$\frac{\partial^2 \mathfrak{A}}{\partial x^2} \frac{\partial^2 \mathfrak{A}}{\partial y^2} - \left(\frac{\partial^2 \mathfrak{A}}{\partial x \partial y} \right)^2 = \frac{\cos^2 \phi}{4} (\nabla^2 \mathfrak{A})^2. \quad (*)$$

By differentiating with respect to x and y , write $(*)$ as a first-order system for $p = \partial^2 \mathfrak{A} / \partial x^2$ and $q = \partial^2 \mathfrak{A} / \partial y^2$. Show that the system is hyperbolic.

2. Show that

$$w = \frac{b\theta}{2\pi} = \frac{b}{2\pi} \tan^{-1} \left(\frac{y}{x} \right) \quad (\dagger)$$

is a possible displacement in equilibrium antiplane strain, and evaluate the corresponding stress components. What would you have to do to a cylinder of metal for it to adopt this configuration?

3. Show that the Tresca yield criterion in plane strain leads to the condition

$$\sqrt{\frac{1}{4}(\tau_{xx} - \tau_{yy})^2 + \tau_{xy}^2} \leq \tau_Y,$$

where τ_Y is the yield stress. Assuming that inertia and gravity are negligible, deduce that the Airy stress function in a yielding material satisfies the equation

$$(\nabla^2 \mathfrak{A})^2 + 4 \left\{ \left(\frac{\partial^2 \mathfrak{A}}{\partial x \partial y} \right)^2 - \frac{\partial^2 \mathfrak{A}}{\partial x^2} \frac{\partial^2 \mathfrak{A}}{\partial y^2} \right\} = 4\tau_Y^2. \quad (\ddagger)$$

By differentiating with respect to x and y (or otherwise), show that (\ddagger) is hyperbolic, with characteristics satisfying

$$\frac{dy}{dx} = 2 \left(\frac{\partial^2 \mathfrak{A}}{\partial x \partial y} \pm \tau_Y \right) / \left(\frac{\partial^2 \mathfrak{A}}{\partial x^2} - \frac{\partial^2 \mathfrak{A}}{\partial y^2} \right).$$

4. Consider a circular torsion bar of radius a and shear modulus μ subject to a twist $\Omega > \Omega_c = \tau_Y/\mu a$, where τ_Y is the yield stress. Show that the bar yields in a region $s < r < a$, where $s = \tau_Y/\mu\Omega$, and that the stress components in the bar are given by

$$\tau_{xz} = \begin{cases} -\mu\Omega y & 0 \leq r < s, \\ -\mu\Omega y s/r & s < r < a, \end{cases} \quad \tau_{yz} = \begin{cases} \mu\Omega x & 0 \leq r < s, \\ \mu\Omega x s/r & s < r < a. \end{cases}$$

Hence show that the torque M exerted on the bar satisfies

$$\frac{2M}{\pi a^3 \tau_Y} = \frac{1}{3} \left(4 - \frac{\Omega_c^3}{\Omega^3} \right).$$

Now suppose that, after a maximum twist Ω_M has been applied, the torque is gradually released. Assuming that the material instantaneously reverts to being elastic, show that the stress components are now given by

$$\begin{aligned} \tau_{xz} &= \begin{cases} -\mu\Omega y & 0 \leq r < s_M, \\ \mu(\Omega_M - \Omega)y - \mu\Omega_M s_M y/r & s_M < r < a, \end{cases} \\ \tau_{yz} &= \begin{cases} \mu\Omega x & 0 \leq r < s_M, \\ -\mu(\Omega_M - \Omega)x + \mu\Omega_M s_M x/r & s_M < r < a, \end{cases} \end{aligned} \quad (\S)$$

where $s_M = \tau_Y/\Omega_M\mu$ is the maximum radius of the yielded region. Hence show that the corresponding torque is given by

$$\frac{2M}{\pi a^3 \tau_Y} = \frac{\Omega - \Omega_M}{\Omega_c} + \frac{1}{3} \left(4 - \frac{\Omega_c^3}{\Omega_M^3} \right),$$

and evaluate the residual twist Ω_0 that remains when the torque is completely released.

Suppose we now twist the bar in the opposite direction, so that M is negative. Use (§) to show that the bar yields again at $r = a$ when

$$\Omega = \Omega_M - 2\Omega_c, \quad \frac{2M}{\pi a^3 \tau_Y} = -\frac{2}{3} - \frac{\Omega_c^3}{3\Omega_M^3} > -1.$$

[Thus, after the bar has yielded in one direction, a smaller torque is required to make it yield in the opposite direction. This is known as the Bauschinger effect.]

5. Consider plane strain outside a circular hole $r = a$ which is inflated to a pressure P that is greater than the yield stress τ_Y . Show that the material yields in a region $a < r < s$, where

$$s(P) = a \exp \left(\frac{P}{2\tau_Y} - \frac{1}{2} \right).$$

Now suppose that P increases to a maximum value P_M before decreasing back to zero. Assuming that the material instantaneously becomes elastic when $P < P_M$, show that there is a residual stress field

$$\begin{aligned} \tau_{rr} &= \begin{cases} -P_M + 2\tau_Y \log \left(\frac{r}{a} \right) + \frac{a^2 P_M}{r^2} & a < r < s_M, \\ -\frac{\tau_Y s_M^2}{r^2} + \frac{a^2 P_M}{r^2} & s_M < r < \infty, \end{cases}, \\ \tau_{\theta\theta} &= \begin{cases} -P_M + 2\tau_Y + 2\tau_Y \log \left(\frac{r}{a} \right) - \frac{a^2 P_M}{r^2} & a < r < s_M, \\ \frac{\tau_Y s_M^2}{r^2} - \frac{a^2 P_M}{r^2} & s_M < r < \infty, \end{cases} \end{aligned}$$

where $s_M = s(P_M)$. Deduce that the material will yield again at $r = a$ as the pressure is released if $P_M > 2\tau_Y$.