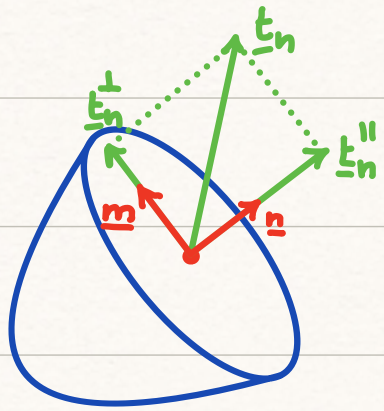
Normal and Shear Stresses



Consider an arbitrary surface in B with normal $\underline{n}$. Then we have the two projection matrices

$$\underline{\underline{P}}^{\parallel} = \underline{n} \otimes \underline{n} \quad \text{and} \quad \underline{\underline{P}}^{\perp} = \underline{\underline{I}} - \underline{n} \otimes \underline{n} = \underline{m} \otimes \underline{m}$$

that define the

normal stress: $\underline{t}_n^{\parallel} = \underline{\underline{P}}^{\parallel}\, \underline{t}_n = (\underline{n} \cdot \underline{t}_n)\, \underline{n} = \sigma_n \underline{n}$

shear stress: $\underline{t}_n^{\perp} = \underline{\underline{P}}^{\perp}\, \underline{t}_n = (\underline{m} \cdot \underline{t}_n)\, \underline{m} = \tau\, \underline{m}$

The magnitudes of these stresses are

$$\sigma_n = \underline{n} \cdot \underline{t}_n = \underline{n} \cdot \underline{\underline{\sigma}}\, \underline{n} \quad \text{or} \quad \sigma_n = n_i \sigma_{ij} n_j$$

$$\tau = \underline{m} \cdot \underline{t}_n = \underline{m} \cdot \sigma\, \underline{n} \quad \text{or} \quad \tau = m_i \sigma_{ij} n_j$$

If $\sigma_n > 0$ the normal stresses are tensile if $\sigma_n < 0$ the normal stresses are compressive.

From geometry: $\underline{t}_n = \underline{t}_n^{\parallel} + \underline{t}_n^{\perp}$

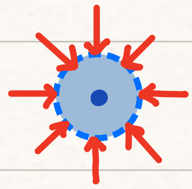
$$|\underline{t}_n|^2 = |\sigma_n \underline{n}|^2 + |\tau \underline{n}|^2 = \sigma_n^2 + \tau_n^2$$

Simple states of stress

I) Hydrostatic stress

$$\boxed{\underline{\underline{\sigma}} = -p\,\underline{\underline{I}}} = \begin{bmatrix} -p & 0 & 0 \\ 0 & -p & 0 \\ 0 & 0 & -p \end{bmatrix}$$

$$\Rightarrow \underline{t}_n = \underline{\underline{\sigma}}\,\underline{n} = -p\,\underline{n} \quad \text{for all } \underline{n}$$



$$\underline{t}_n^{\parallel} = \underline{\underline{P}}_n^{\parallel}\,\underline{t} = (\underline{n}\otimes\underline{n})(-p\,\underline{n}) = -p\,(\underline{n}\cdot\underline{n})\,\underline{n} = -p\,\underline{n}$$

$$\Rightarrow \underline{t}_n = \underline{t}_n^{\parallel} \qquad \underline{t}_n^{\perp} = 0$$

normal stress: $\sigma_n = -p$
shear stress: $\tau = 0$

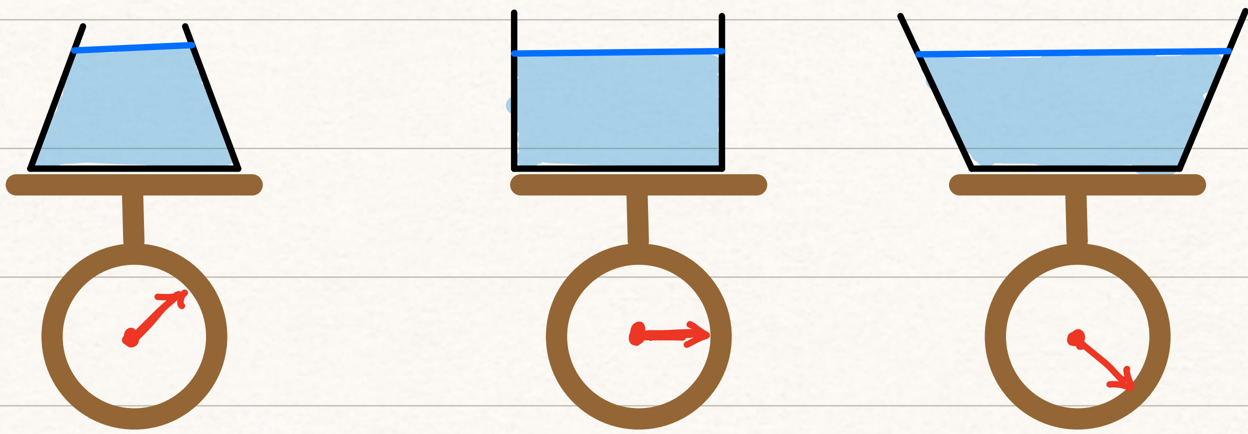
$\Big\}$ on all planes

Pascal's law:

The pressure in a fluid at rest is independent of the direction of a surface. Pressure is a scalar!

Hydrostatic paradox: (Blaise Pascal)

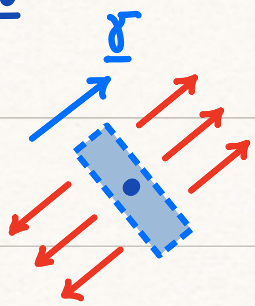
Weight different but the force on base is same $f = pA$



II) Uniaxial stress

$$\boxed{\underline{\underline{\sigma}} = \sigma \; \underline{\gamma} \otimes \underline{\gamma}} \quad \Rightarrow \quad \underline{t}_n = \underline{\underline{\sigma}}\,\underline{n} = \sigma\,(\underline{\gamma}\cdot\underline{n})\,\underline{\gamma}$$

($\underline{\gamma}$ is unit vector)



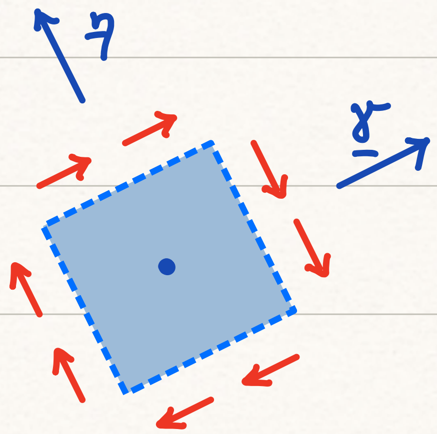
Traction is always parallel to $\underline{\gamma}$ and vanishes on surfaces with normal perpendicular to $\underline{\gamma}$.

$\sigma > 0$: pure tension

$\sigma < 0$: pure compression

III, Pure shear stress $\quad \underline{\gamma} \cdot \underline{\eta} = 0$

$$\boxed{\underline{\underline{\sigma}} = \tau\,(\underline{\gamma} \otimes \underline{\eta} + \underline{\eta} \otimes \underline{\gamma})} \Rightarrow \underline{t}_n = \underline{\underline{\sigma}}\,\underline{n} = \tau(\underline{\eta}\cdot\underline{n})\,\underline{\gamma} + \tau(\underline{\gamma}\cdot\underline{n})\,\underline{\eta}$$



$\underline{n} = \underline{\eta}: \quad \underline{t}_n = \tau\,\underline{\gamma}$

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IV, Plane stress

If there exists a pair of orthogonal vectors $\underline{\gamma}$ and $\underline{\eta}$ such that the matrix representation of $\underline{\underline{\sigma}}$ in the frame $\{\underline{\gamma}, \underline{\eta}, \underline{\gamma} \times \underline{\eta}\}$ is of the form

$$[\underline{\underline{\sigma}}] = \begin{pmatrix} \sigma_{11} & \sigma_{12} & 0 \\ \sigma_{21} & \sigma_{22} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

then a state of plane stress exists.

Q: Is uniaxial stress a plane stress?

$\underline{\underline{\sigma}} = \sigma\, \underline{a} \otimes \underline{a}$

Pick a frame $\{\underline{e}_i\}$ and evaluate $[\underline{\underline{\sigma}}]$.

What frame $\underline{e}_1 = \underline{a}$ know $\underline{e}_2 \cdot \underline{a} = \underline{e}_3 \cdot \underline{a} = \underline{0}$

$\sigma_{ij} = \underline{e}_i \cdot \underline{\underline{\sigma}}\, \underline{e}_j$

substitute with $\underline{a} = \underline{e}_1$

$\sigma_{ij} = \underline{e}_i \cdot (\sigma\, \underline{a} \otimes \underline{e}_1)\, \underline{e}_j$

$= \sigma\, \underline{e}_i \cdot (\underline{a} \cdot \underline{e}_j)\, \underline{e}_1 = \sigma (\underline{e}_i \cdot \underline{e}_1)(\underline{e}_j \cdot \underline{e}_1)$

$\sigma_{11} = \sigma\, (\underline{e}_1 \cdot \underline{e}_1)(\underline{e}_1 \cdot \underline{e}_1) = \sigma$

$\sigma_{12} = \sigma (\underline{e}_1 \cdot \underline{e}_1)\cancelto{0}{(\underline{e}_1 \cdot \underline{e}_2)} = 0$

$\sigma_{22} = \sigma (\underline{e}_2 \cdot \underline{e}_1)(\underline{e}_1 \cdot \underline{e}_2) = 0$

...

$\Rightarrow \quad [\underline{\underline{\sigma}}] = \begin{bmatrix} \sigma & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$ ✓ plane stress

Extremal Stress Values

I) Maximum and Minimum Normal Stresses

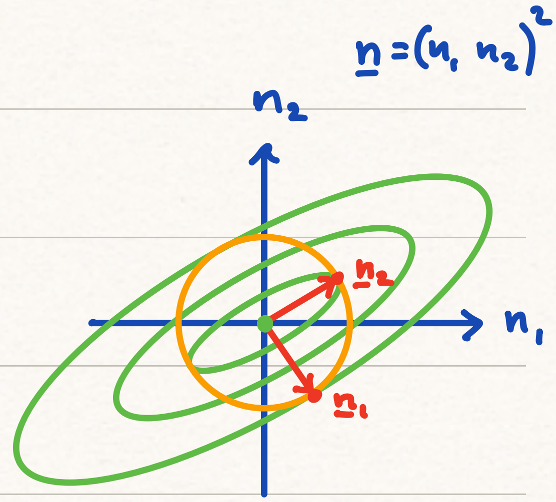
Given a state of stress $\underline{\underline{\sigma}}$ at point $\underline{x}$, what are the unit normals $\underline{n}$ corresponding to min. and max. normal stress σ_n.

This is a constrained optimization problem, because we want to find extrema of the function $\sigma_n = \sigma_n(\underline{n})$ with the constraint that $|\underline{n}| = 1$.

Lagrange multiplier method

$$\boxed{\begin{aligned} \mathcal{L}(\underline{n}, \lambda) &= \underline{n} \cdot \underline{\underline{\sigma}}\, \underline{n} - \lambda(\underline{n} \cdot \underline{n} - 1) \\ \mathcal{L}(n_i, \lambda) &= n_i \sigma_{ij} n_j - \lambda(n_i n_i - 1) \end{aligned}}$$

$$\underbrace{n_i \sigma_{ij} n_j}_{\text{function}} - \underset{\substack{\uparrow \\ \text{Lagrange multiplier}}}{\lambda} \underbrace{(n_i n_i - 1)}_{\text{constraint}}$$



$f(\underline{n}) = \underline{n} \cdot \underline{\underline{\sigma}}\, n$ is quadratic

Function $f(\underline{n}) = \underline{n} \cdot \underline{\underline{\sigma}}\, \underline{n}$ is quadratic in components of $\underline{n}$.

If eigenvalues of $\underline{\underline{\sigma}}$ are positive then the level sets of $f(\underline{n})$ are ellipsoids as shown.

The extremal values are the stationary points of $\mathcal{L}(\underline{n},\lambda)$

$$\frac{\partial \mathcal{L}}{\partial \lambda} = n_i n_i - 1 = 0$$

$$\frac{\partial \mathcal{L}}{\partial n_k} = \sigma_{ij}\,(n_{i,k}\, n_j + n_i\, n_{j,k}) - \lambda\,(2\, n_i\, n_{i,k}) = 0$$

where $n_{i,k} = \delta_{ik}$ $\quad n_{j,k} = \delta_{jk}$

$$= \sigma_{ij}\,(\delta_{ik}\, n_j + \delta_{jk}\, n_i) - \lambda\,(2\, n_i\, \delta_{ik})$$

$$= \sigma_{kj} n_j + \sigma_{ik} n_i - 2\lambda n_k \overset{\sigma_{ik} = \sigma_{ki}}{=} \sigma_{kj} n_j + \sigma_{ki} n_i - 2\lambda n_k$$

$$= 2\,(\sigma_{ik}\, n_k - \lambda n_k) = 0$$

In symbolic notation: $\boxed{(\underline{\underline{\sigma}} - \lambda \underline{\underline{I}})\underline{n} = \underline{0} \quad \text{and} \quad |\underline{n}| = 1}$

The Lagrange multiplier method leads to an eigenproblem, where the Lagrange multiplier, λ, is the eigenvalue and the normal, $\underline{n}$, the eigenvalue.

We can see that λ is the magnitude of the normal stress by taking the dot product of eigenproblem with $\underline{n}$.

$$\underline{n} \cdot (\underline{\underline{\sigma}} - \lambda \underline{\underline{I}})\underline{n} = 0 \implies \underline{n} \cdot \underline{\underline{\sigma}}\,\underline{n} = \lambda\, \underline{n} \cdot \underline{n} \implies \boxed{\sigma_N = \lambda}$$

Hence to find the extremal stress values we must find the eigenvalues λ_i and eigenvectors $\underline{n}_i$.

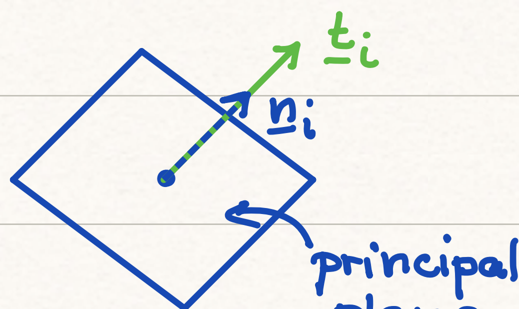
λ_i's are the principal normal stresses $\Rightarrow \lambda_i = \sigma_i$

$\underline{n}$'s are the principal directions of $\underline{\underline{\sigma}}$

Since $\underline{\underline{\sigma}} = \underline{\underline{\sigma}}^T$ all λ_i are real and the set $\{\underline{n}_i\}$ form a mutually orthogonal basis, so that $\underline{\underline{\sigma}}$ can be represented as $\underline{\underline{\sigma}} = \sum_{i=1}^{3} \sigma_i \, \underline{n}_i \otimes \underline{n}_i$

The tractions in the principal directions are

$$\underline{t}_{\underline{n}_i} = \underline{\underline{\sigma}} \, \underline{n}_i = \sigma_i \underline{n}_i$$



since $\underline{t}_i \parallel \underline{n}_i$ there is no shear stress on the principal planes, $\underline{t}_i^{\perp} = 0$.

If the σ_i's are distinct and ordered $\sigma_1 > \sigma_2 > \sigma_3$ then σ_1 and σ_3 are the max. and min. normal stresses.

II. Maximum and minimum shear stresses

Given the principal directions $\underline{n}_1$, $\underline{n}_2$ and $\underline{n}_3$ at $\underline{x}$ what is the unit vector $\underline{s} = [s_1 \; s_2 \; s_3]$ that gives the max. and min. values of the shear stresses τ?

In the frame of the principal directions $\{\underline{n}_i\}$

$$\underline{s} = s_i \underline{n}_i \qquad \text{where} \qquad s_i = \underline{s} \cdot \underline{n}_i$$

so that the traction vector in direction $\underline{s}$ is

$$\underline{t}_s = \underline{\underline{\sigma}}\, \underline{s} = \sum_{i=1}^{3} \sigma_i\, \underline{n}_i \otimes \underline{n}_i \quad s_j \underline{n}_j$$

$$= \sum_{i=1}^{3} \sigma_i s_j\, (\underline{n}_i \otimes \underline{n}_i)\, \underline{n}_j = \sum_{i=1}^{3} \sigma_i s_j\, \underbrace{(\underline{n}_i \cdot \underline{n}_j)}_{\delta_{ij}} \underline{n}_i$$

$$= \sum_{i=1}^{3} \sigma_i s_i \underline{n}_i$$

traction vector associated with $\underline{s}$ is

$$\underline{t}_s = \sigma_1 s_1 \underline{n}_1 + \sigma_2 s_2 \underline{n}_2 + \sigma_3 s_3 \underline{n}_3$$

The magnitudes of normal, σ_N, and shear stress, τ, are

$$\sigma_n = \underline{s} \cdot \underline{t}_s = \sigma_1 s_1^2 + \sigma_2 s_2^2 + \sigma_3 s_3^2$$

$$\tau^2 = |\underline{t}_s|^2 - \sigma_n^2 = \sigma_1^2 s_1^2 + \sigma_2^2 s_2^2 + \sigma_3^2 s_3^2 - (\sigma_1 s_1^2 + \sigma_2 s_2^2 + \sigma_3 s_3^2)^2$$

Hence we have the following expression for the shear stress

$$\boxed{\tau^2 = \sum_{i=1}^{3} \sigma_i^2 s_i^2 - \left(\sum_{i=1}^{3} \sigma_i s_i^2\right)^2}$$

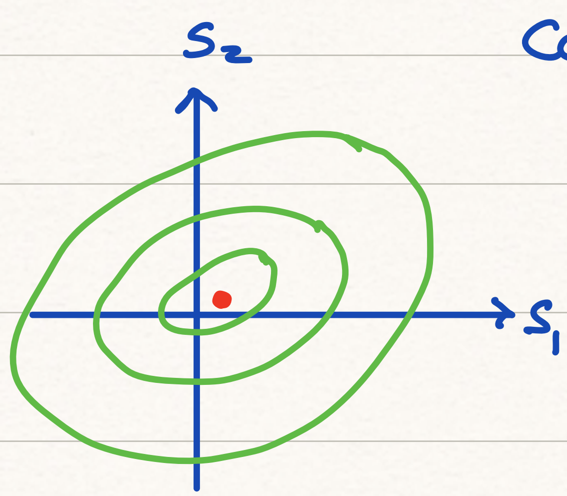
we are looking for the extremal values of τ^2 under the constraint $|\underline{s}|^2 = 1 \rightarrow s_1^2 + s_2^2 + s_3^2 = 1$

$\Rightarrow$ Solve using Lagrange mult. or direct elimination.

I) Eliminate $s_3^2 = 1 - s_1^2 - s_2^2 \Rightarrow \tau^2 = \tau^2(s_1, s_2)$.

$$\tau^2 = \sigma_1^2 s_1^2 + \sigma_2^2 s_2^2 + \sigma_3^2 s_3^2 - (\sigma_1 s_1^2 + \sigma_2 s_2^2 + \sigma_3 s_3^2)^2$$

$$= \sigma_1^2 s_1^2 + \sigma_2^2 s_2^2 + \sigma_3^2 (1 - s_1^2 - s_2^2) - (\sigma_1 s_1^2 + \sigma_2 s_2^2 + \sigma_3 (1 - s_1^2 - s_2^2))$$



Constraint $|\underline{s}| = 1$ is incorporated

To find extremum partial derivatives need to vanish.

We just need to find $\frac{\partial \tau^2}{\partial s_1} = \frac{\partial \tau^2}{\partial s_2} = 0$.

$$\frac{\partial \tau^2}{\partial s_1} = 2 s_1 (\sigma_1 - \sigma_3)\left\{\sigma_1 - \sigma_3 - 2\left[(\sigma_1 - \sigma_3) s_1^2 + (\sigma_2 - \sigma_3) s_2^2\right]\right\} = 0$$

$$\frac{\partial \tau^2}{\partial s_2} = 2 s_2 (\sigma_2 - \sigma_3)\left\{\sigma_2 - \sigma_3 - 2\left[(\sigma_1 - \sigma_3) s_1^2 + (\sigma_2 - \sigma_3) s_2^2\right]\right\} = 0$$

First solution: $s_1 = s_2 = 0 \Rightarrow s_3 = 1 \quad \underline{s} = \pm \underline{n}_3$

$$\tau^2 = \sigma_3^2 \cdot 1 - (\sigma_3 \cdot 1)^2 = 0$$

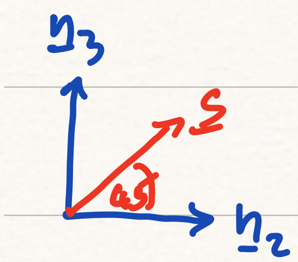
$\Rightarrow$ minimum in the shear stress

which vanishes on principal plane

Second solution: $s_1 = 0$

$$\frac{\partial \tau^2}{\partial n_2} = \sigma_2 - \sigma_3 - 2\left[(\sigma_2 - \sigma_3) s_2^2\right] = 0$$

$$(\sigma_2 - \sigma_3)(1 - 2 s_2^2) = 0 \quad \Rightarrow \quad s_2 = \pm \frac{1}{\sqrt{2}}$$



from $s_2^2 + s_3^2 = 1 \quad \Rightarrow \quad s_3 = \pm \frac{1}{\sqrt{2}}$

$$\Rightarrow \underline{s} = \pm \frac{1}{\sqrt{2}} \underline{n}_2 \pm \frac{1}{\sqrt{2}} \underline{n}_3$$

$$\tau^2 = \frac{\sigma_2^2}{2} + \frac{\sigma_3^2}{2} - \left(\frac{\sigma_2}{2} + \frac{\sigma_3}{2}\right)^2$$

$$= \frac{\sigma_2^2}{2} + \frac{\sigma_3^2}{2} - \left(\frac{\sigma_2^2}{4} + 2\frac{\sigma_2}{2}\frac{\sigma_3}{2} + \frac{\sigma_3^2}{4}\right)$$

$$\tau^2 = \left(\frac{\sigma_2}{2}\right)^2 - 2\,\frac{\sigma_2}{2}\,\frac{\sigma_3}{2} + \left(\frac{\sigma_3}{2}\right)^2 = \left(\frac{\sigma_2 - \sigma_3}{2}\right)^2$$

We have the following two solutions:

min. $\tau = 0$ for $\underline{s} = \pm \underline{n}_3$

max. $\tau = \frac{1}{2}(\sigma_2 - \sigma_3)$ for $\underline{s} = \pm \frac{\underline{n}_2}{\sqrt{2}} \pm \frac{\underline{n}_3}{\sqrt{2}}$

Two additional pairs of solutions can be obtained by eliminating $\underline{n}_1$ or $\underline{n}_2$ from τ^2 and folling similar steps. So that we have

Minimum shear stresses:

$\tau = 0$ on $\underline{s} = \pm \underline{n}_1$ $\quad \underline{s} = \pm \underline{n}_2$ $\quad \underline{s} = \pm \underline{n}_3$

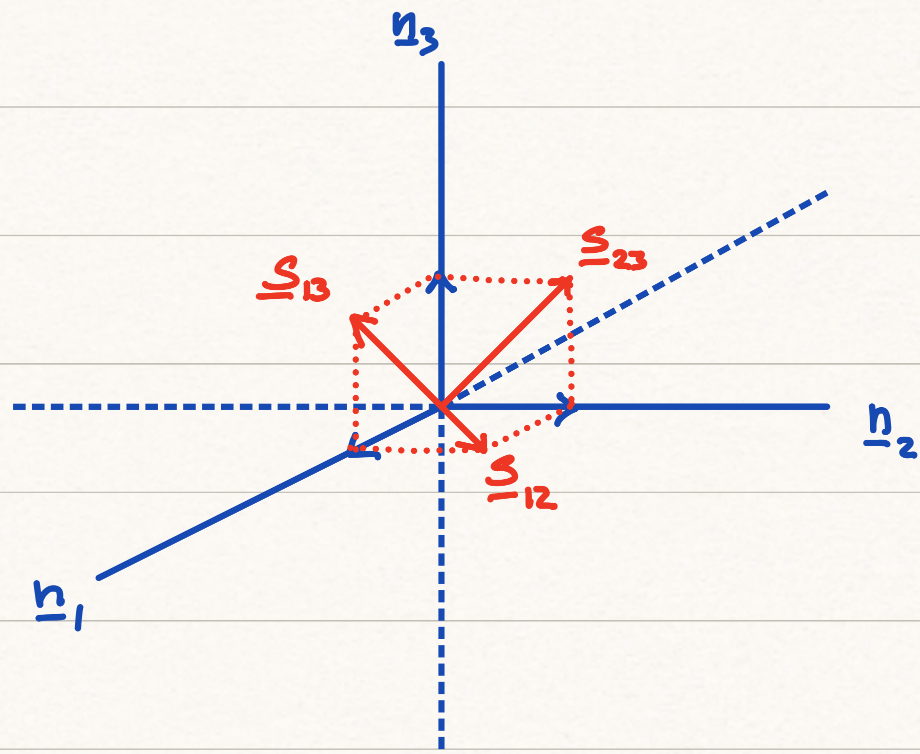
Maximum shear stresses:

$$\tau_{23} = \frac{1}{2}(\sigma_2 - \sigma_3) \quad \text{on} \quad \underline{s}_{23} = \frac{1}{\sqrt{2}}(\pm \underline{n}_2 \pm \underline{n}_3)$$

$$\tau_{13} = \frac{1}{2}(\sigma_1 - \sigma_3) \quad \text{on} \quad \underline{s}_{13} = \frac{1}{\sqrt{2}}(\pm \underline{n}_1 \pm \underline{n}_3)$$

$$\tau_{12} = \frac{1}{2}(\sigma_1 - \sigma_2) \quad \text{on} \quad \underline{s}_{12} = \frac{1}{\sqrt{2}}(\pm \underline{n}_1 \pm \underline{n}_2)$$

where we assume $\sigma_1 \geq \sigma_2 \geq \sigma_3$



Note: G&S do this with Lagrange multipliers but it leads to odd expressions in index notation, such as

$$4\left(\sum_{j=1}^{3} n_j^2 \sigma_j\right) n_i \sigma_i = 2\lambda n_i \quad ?$$

where 'i' seems to be a dummy on the l.h.s. but a free index on the r.h.s.

$\Rightarrow$ we did it the pedestrian way.