Al-Mansour University College

قسم الهندسة المدنية
المرحلة الثانية

Civil Eng. Dept
2nd. Stage

Mechanics of materials

2022 – 2023

Sheet.3

مقاومة

- Principal Stresses
- Mohr`s Circle

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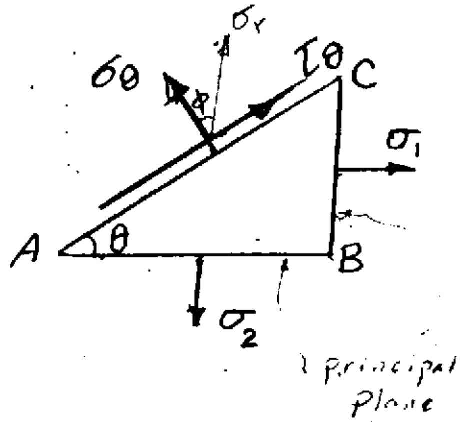
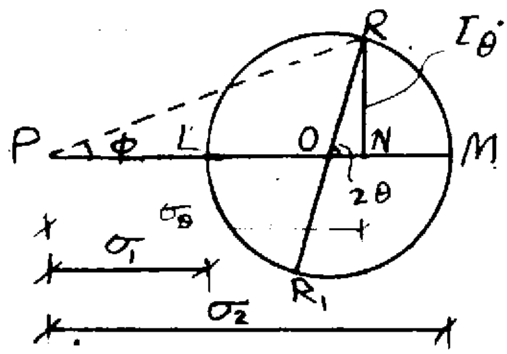
Mohr's Stress Circle



Let σ_1 & σ_2 be the principal stresses acting on principal planes 'BC' and 'AB' respectively.
The stress circle will be developed to find the stress components on any plane AC which makes an angle 'θ' with 'AB'.



In the figure to the right, ($\sigma_2 > \sigma_1$), mark off $PL = \sigma_1$ & $PM = \sigma_2$ (+ve direction → tension to the right of 'P' & vice versa).
With LM as diameter, draw a circle centre 'O' and draw (OR) at angle 2θ from OM. Draw $RN \perp PM$, then

$$PN = PO + ON$$

$$= \frac{(\sigma_1+\sigma_2)}{2} + \frac{(\sigma_2-\sigma_1)}{2}\cos 2\theta$$

$$= \sigma_1\left(\frac{1-\cos 2\theta}{2}\right) + \sigma_2\left(\frac{1+\cos 2\theta}{2}\right)$$ from eq. (1) since $\tau_{xy}=0$ on principal Plane

$$PN = \sigma_1 \sin^2\theta + \sigma_2 \cos^2\theta = \sigma_\theta$$ (Normal stress comp. on AC) +ve since to the right of P

$$\therefore\ RN = \frac{(\sigma_2-\sigma_1)}{2}\sin 2\theta$$ eq. (2), $\tau_{xy}=0$

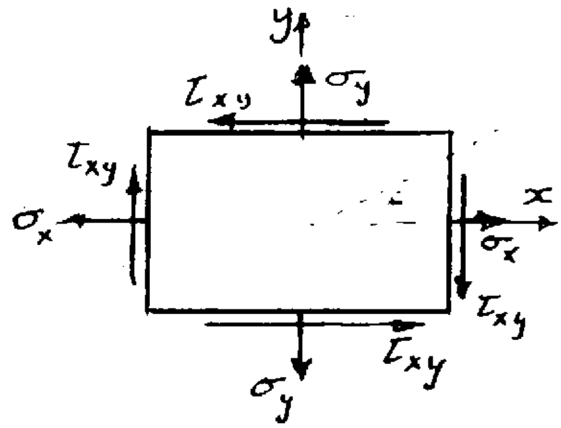
$$= \tau_\theta$$ (the shear stress component on AC) (+ve in this case because R is above PM)

The resultant stress $\sigma_r = \sqrt{\sigma_\theta^2+\tau_\theta^2} = PR$
The inclination of σ_r to the normal of the plane is given by $\phi = \angle RPN$.
R.S. Max shear stress occurs when $RN = OR$, i.e $2\theta = 90°$, $\theta = 45°$ and equal in magnitude to $OR = \frac{1}{2}(\sigma_2 - \sigma_1)$.
Maximum value of ϕ is obtained when PR is tangent to the circle.

Combined Stresses

General Case of Two-Dimensional Stress

In general if a plane element is removed from a body, it will be subject to the normal stresses σ_x and σ_y together with the shearing stress τ_{xy} as shown below.

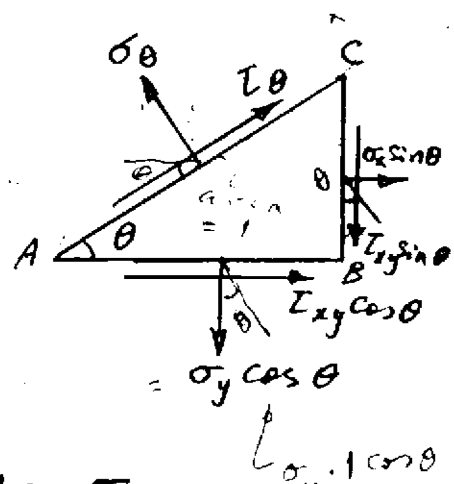


Sign Convention

For normal stresses, tensile stresses are considered to be positive, while compressive stresses are negative. For shearing stresses, the positive sense is as shown in the figure.

Stresses on Inclined plane

Consider the prism element ABC in which the area of the plane AC is assumed = unity 1



Let σ_θ & τ_θ be the normal and shear stresses acting on plane AC, and let the stresses acting on planes AB and BC be σ_x, σ_y & τ_{xy}.

The normal force acting on 'AC' $= \sigma_\theta \cdot 1 = \sigma_\theta$

The shear force acting on 'AC' $= \tau_\theta \cdot 1 = \tau_\theta$

The normal force acting on 'AB' $= \sigma_y \cdot 1 \cos\theta = \sigma_y \cos\theta$

The remaining forces acting on AB & BC are as shown.

Resolve forces in the direction of σ_θ

$$\sigma_\theta = (\sigma_y \cos\theta)\cos\theta + (\sigma_x \sin\theta)\sin\theta + (\tau_{xy}\cos\theta)\sin\theta + (\tau_{xy}\sin\theta)\cos\theta$$

$$\cancel{\sigma_\theta = \sigma_y \cos^2\theta + \sigma_x \sin^2\theta + 2\tau_{xy}\sin\theta\cos\theta} \quad \text{———} (1)$$

$$= \sigma_y\left(\frac{1+\cos 2\theta}{2}\right) + \sigma_x\left(\frac{1-\cos 2\theta}{2}\right) + \tau_{xy}\sin 2\theta$$

$$\sigma_\theta = \tfrac{1}{2}(\sigma_y+\sigma_x) + \tfrac{1}{2}(\sigma_y - \sigma_x)\cos 2\theta + \tau_{xy}\sin 2\theta \quad \text{—} (1a)$$

Resolve forces in the τ_θ direction:

$$\tau_\theta = (\sigma_y\cos\theta)\sin\theta - (\sigma_x\sin\theta)\cos\theta + (\tau_{xy}\sin\theta)\sin\theta - (\tau_{xy}\cos\theta)\cos\theta$$

$$= (\sigma_y - \sigma_x)\sin\theta\cos\theta - \tau_{xy}(\cos^2\theta - \sin^2\theta)$$

$$\tau_\theta = \tfrac{1}{2}(\sigma_y - \sigma_x)\sin 2\theta - \tau_{xy}\cos 2\theta \quad \text{———} (2)$$

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Principal Stresses

Eqs. (1) and (2) vary w.r.t. θ ← gives max. & min. stresses

For max. or min. σ_θ, $\frac{d\sigma_\theta}{d\theta} = 0$ ⇒ i.e., principal stresses

From eq. (1) above:

$$0 = \sigma_y(2\cos\theta)(-\sin\theta) + \sigma_x(2\sin\theta)(\cos\theta) + 2\tau_{xy}[\cos\theta.\cos\theta + \sin\theta(-\sin\theta)]$$

$$2(\sigma_x - \sigma_y)\sin\theta\cos\theta + 2\tau_{xy}(\cos^2\theta - \sin^2\theta) = 0$$

$$(\sigma_x - \sigma_y)\sin 2\theta + 2\tau_{xy}\cos 2\theta = 0$$

$$\therefore \tan 2\theta = \frac{2\tau_{xy}}{\sigma_y - \sigma_x} \quad \text{———} (3)$$

$\angle$ direction of
Principal planes

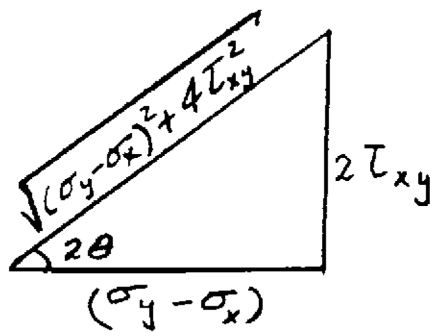
A

~~Eq.(3) gives 2-values of (2θ) differing by 180° and hence~~
2-values of (θ) differing by (90°) . i.e., two perpendicular directions are given by eq.(3) which means 2-planes perpendicular to each other which are called : <u>principal planes</u> .

The normal stresses on these 2-planes will be maximum on one plane and minimum on the other plane.

From eq.(2) , if $\tau_\theta = 0$, then eq.(3) is obtained, i.e., <u>the shear stresses on the principal planes = 0</u>

From eq.(3); we can represent the figure (on the right).



Since $\tan 2\theta$ is +ve in 1st & 2nd quadrant

$$\therefore \sin 2\theta = \pm \frac{2\tau_{xy}}{\sqrt{(\sigma_y-\sigma_x)^2+4\tau_{xy}^2}}$$

$$\cos 2\theta = \pm \frac{(\sigma_y-\sigma_x)}{\sqrt{(\sigma_y-\sigma_x)^2+4\tau_{xy}^2}}$$

Subst. into eq.(1a) :

$$\sigma_\theta = \frac{1}{2}(\sigma_y+\sigma_x) \pm \frac{(\sigma_y-\sigma_x)^2}{2\sqrt{(\sigma_y-\sigma_x)^2+4\tau_{xy}^2}} \pm \frac{2\tau_{xy}^2}{\sqrt{(\sigma_y-\sigma_x)^2+4\tau_{xy}^2}}$$

$$= \frac{1}{2}(\sigma_y+\sigma_x) \pm \frac{[(\sigma_y-\sigma_x)^2+4\tau_{xy}^2]}{2\sqrt{[(\sigma_y-\sigma_x)^2+4\tau_{xy}^2]}}$$

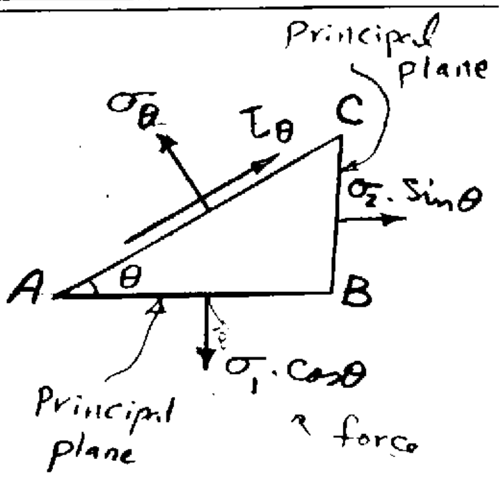
$$= \frac{1}{2}(\sigma_y+\sigma_x) \pm \frac{1}{2}\sqrt{(\sigma_y-\sigma_x)^2+4\tau_{xy}^2}$$

Hence, the <u>2-principal stresses</u> are :

$$\sigma_1 = \sigma_{max} = \frac{1}{2}(\sigma_y+\sigma_x) + \frac{1}{2}\sqrt{(\sigma_y-\sigma_x)^2+4\tau_{xy}^2}$$

$$\sigma_2 = \sigma_{min} = \frac{1}{2}(\sigma_y+\sigma_x) - \frac{1}{2}\sqrt{(\sigma_y-\sigma_x)^2+4\tau_{xy}^2}$$

Maximum Shear Stress



Let AB & BC be the principal planes and σ_1 & σ_2 the principal stresses.

Resolving in τ_θ direction:

$$\tau_\theta = (\sigma_1 . \cos\theta)\sin\theta - (\sigma_2 . \sin\theta)\cos\theta$$
$$= (\sigma_1 - \sigma_2)\sin\theta\cos\theta$$

$$\therefore \tau_\theta = \frac{1}{2}(\sigma_1 - \sigma_2)\sin 2\theta$$

Hence $Max(\tau_\theta)$ occurs when $\sin 2\theta = 1$

i.e., $2\theta = 90^\circ \Rightarrow \theta = 45^\circ$

which means the max shear stress occurs at 45° with the principal planes, and its magnitude:

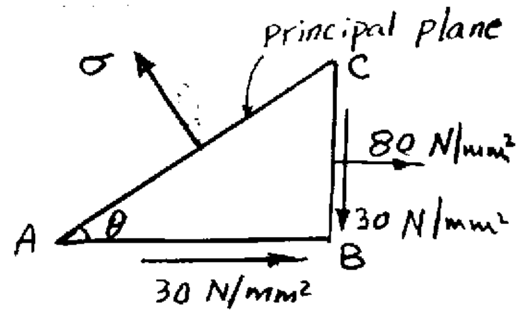
$$\tau_{max} = \frac{1}{2}(\sigma_1 - \sigma_2)$$

i.e. $$\tau_{max} = \frac{1}{2}\sqrt{(\sigma_y - \sigma_x)^2 + 4\tau_{xy}^2}$$

The max shear stress is one half the algebraic difference between the principal stresses.

Ex.

At a section in a beam, the tensile stress due to bending is 80 N/mm^2 and there is a shear stress of 30 N/mm^2. Determine the magnitude and direction of the principal stresses and calculate the maximum shear stress and its direction.



Let 'AC' be one of the principal planes and 'BC' the plane on which the bending stress acts. There is no normal stress on plane 'AB'

$$\sigma_{1,2} = \frac{\sigma_y + \sigma_x}{2} \pm \frac{1}{2}\sqrt{(\sigma_y - \sigma_x)^2 + 4\tau_{xy}^2}$$

$$= \frac{0+80}{2} \pm \frac{1}{2}\sqrt{(0-80)^2 + 4(30)^2}$$

$$= 40 \pm 50$$

$\therefore \ \sigma_1 = 90 \ N/mm^2$ (tension) $\quad$ & $\sigma_2 = -10 \ N/mm^2$ (comp.)

principal stress

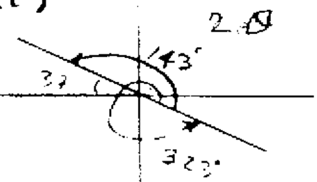
$$\tan 2\theta = \frac{2\tau_{xy}}{\sigma_y - \sigma_x} = \frac{2 \times 30}{-80} = -0.75$$

$2\theta = (180^\circ - 37^\circ) = 143^\circ$ (in 2nd quadrant)

$\therefore \ \theta = 71.5^\circ$ $\quad$ direction of principal stress

or, $2\theta = (360 - 37) = 323^\circ$ (in 4th quadrant)

$\theta = 161.5^\circ$



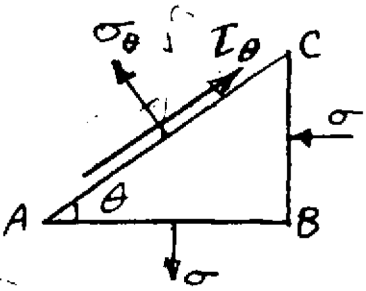
The max shear stress

$$\tau_{max} = \frac{1}{2}(\sigma_1 - \sigma_2) = \frac{1}{2}(90 - (-10)) = \underline{50} \ N/mm^2$$

this is acting at 45° to the principal planes

i.e., at $\alpha = 71.5 - 45^\circ = 26.5^\circ$ // or $\alpha = 161.5 - 45^\circ = \underline{116.5^\circ}$

(2) Principal Stresses Equal Tension & Compression



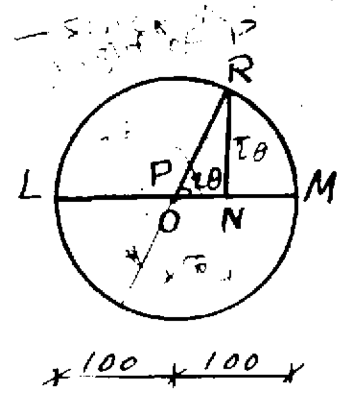
To Construct Mohr's circle:
From 'P' draw $PM = \sigma$ (numerically to the right)(tens.)
Draw $PL = \sigma$ (to the left)(comp.)
Hence 'O' coincides with 'P'.

$\sigma_\theta = PN$ is tensile for (2θ between ($90°$ & $-90°$)
i.e., for θ between $-45° < \theta < 45°$

$\sigma_\theta = PN$ is compressive for 2θ between $90°$ & $270°$, i.e., $45 < \theta < 135°$.

$\tau_\theta = RN$ $\quad 2\theta = 90°$

P.S. When $\theta = 45°$, τ_θ reaches its max value, numerically equal to 'σ'.



P.S. on planes where the normal stress = 0, (i.e., pure shear).

Ex.

One principal stress is compressive = 100 N/mm² and the other is tensile = 100 N/mm². Find the components of stresses at a plane making $\theta = 30°$ with the plane 'AB'.

$\rightarrow \frac{1}{2}(\sigma_1 - \sigma_2) = \frac{1}{2}[\sigma - (-\sigma)] = \sigma$

From above, $\quad OR = \sigma = 100\ N/mm^2$

$\sigma_\theta = PN = OR \cos 2\theta$

$= 100 \cos 60° = 100 \times \frac{1}{2} = 50\ N/mm^2$ (tensile) since $-45° < \theta < 45°$

$\tau_\theta = RN = 100 \sin 60 = 100 \times \frac{\sqrt{3}}{2} = 50\sqrt{3}$

$= 86.6\ N/mm^2$ (+ve)

Resultant $\quad \sigma_r = \sqrt{(50)^2 + (50\sqrt{3})^2} = 50 \times 2 = \underline{100\ N/mm^2}$

$\tan\phi = \frac{\tau_\theta}{\sigma_\theta} = \frac{100 \sin 60}{100 \cos 60} = \tan 60°$

$\phi = 60° = 2\theta$

Ex 1

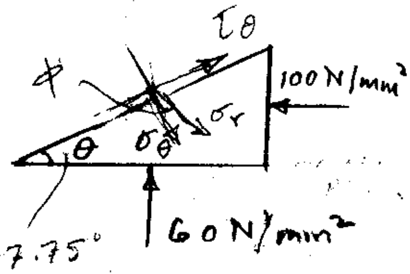
A piece of material is subjected to two principal compressive stresses at right angles, their values being $60\ N/mm^2$ and $100\ N/mm^2$ respectively. Find the position (i.e. $\theta = ?$) of the plane across which the resultant stress is most inclined to the normal and determine the value of this resultant stress. Find also τ_θ & σ_θ.

i.e., max value of ϕ

Construct Mohr's circle:

Draw $PL = 100$

$PM = 60$



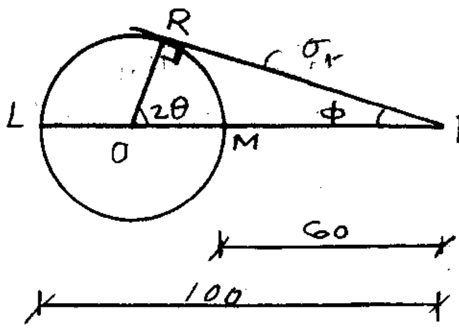
Max. ϕ is obtained when PR is tangent to the stress circle.

$\therefore\ OR = 20\ N/mm^2$

$PO = 80\ N/mm^2$

$$\sin\phi = \frac{OR}{PO} = \frac{20}{80} = 0.25$$

$$\phi = 14.5° = 14°\,30'$$



$$\sigma_r = PR = \sqrt{(80)^2 - (20)^2} = 10\sqrt{60}$$

$$= 77.5\ N/mm^2 \leftarrow \text{the resultant stress}$$

(or $\sigma_r = 80\cos 14.5° =$)

$$\angle 2\theta = 90° - \phi$$

$$= 90 - 14.5 = 75.5°$$

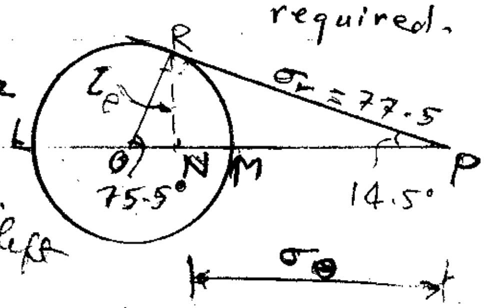
$\therefore\ \theta = 37.75° = 37°\,45' \leftarrow$ the position of the plane required.

$$PN = \sigma_\theta = 77.5\cos 14.5 = 75\ N/mm^2 \leftarrow \text{comp. to the left of P}$$

$$RN = \tau_\theta = 77.5\sin 14.5$$

$$= 19.4\ N/mm^2$$

Clockwise +ve since above $\angle P$



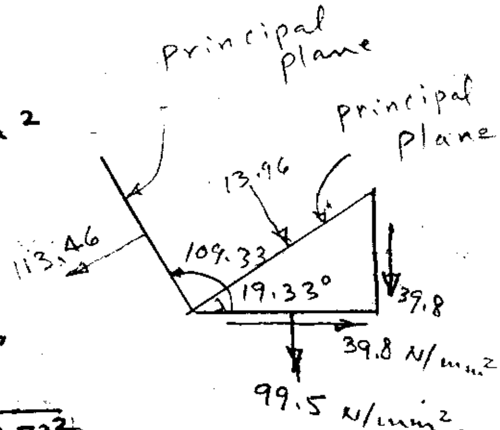
Ex. 3

A circular bar of diameter (16mm) is subjected to an axial pull-force of (20 KN) together with a shear force of (8 KN).

(1) Determine the magnitude and direction of the principal stresses within the bar.

(2) Find the max shear stress and its direction.

(3) Draw Mohr's circle for the principal stresses and hence find σ_θ, τ_θ, σ_r & ϕ.



(1) $A = \dfrac{\pi d^2}{4} = \dfrac{\pi (16)^2}{4} = 201 \ mm^2$

$\sigma_y = \dfrac{P}{A} = \dfrac{20 \times 10^3}{201} = 99.5 \ N/mm^2$

$\tau_{xy} = \dfrac{8 \times 10^3}{201} = 39.8 \ N/mm^2$

$\sigma_{1,2} = \frac{1}{2}(\sigma_y + \sigma_x) \pm \frac{1}{2}\sqrt{(\sigma_y - \sigma_x)^2 + 4\tau_{xy}^2}$

$= \frac{1}{2}(99.5 + 0) \pm \frac{1}{2}\sqrt{(99.5-0)^2 + 4(39.8)^2}$

$= 49.75 \pm 63.71$

$\therefore \boxed{\sigma_1 = 113.46} \ N/mm^2$ (tens.) & $\boxed{\sigma_2 = -13.96} \ N/mm^2$ (comp)

$\tan 2\theta = \dfrac{2\tau_{xy}}{\sigma_y - \sigma_x} = \dfrac{2 \times 39.8}{(99.5 - 0)} = 0.80 \Rightarrow 2\theta = 38.66^\circ$

$2\theta = 38.66^\circ$ or $= 38.66 + 180 \Rightarrow 2\theta = 218.66^\circ$

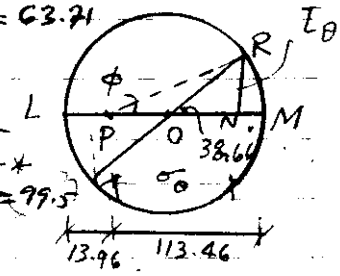
$\theta = 19.33^\circ$ or $\theta = 109.33^\circ$ ← direction of princ. stress

(2) $\tau_{max} = \frac{1}{2}(\sigma_1 - \sigma_2) = \frac{1}{2}(113.46 + 13.96) = 63.71 \ N/mm^2$

direction of τ_{max}: $\theta_1 = 19.33 - 45 = -25.67^\circ = 360 - 25.67 = 334.33^\circ$

& $\theta_2 = 109.33 - 45 = 64.33^\circ$

(3) From Mohr's circle, $\tau_\theta = RN$, $OR = \dfrac{13.96 + 113.46}{2} = 63.71$



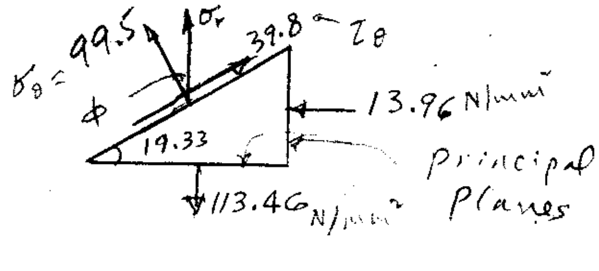
$\tau_\theta = OR \sin 38.66 = 39.8 \ N/mm^2$ τ_{xy}

$\sigma_\theta = PN = PO + ON$, $PO = 63.71 - 13.96 = 49.75$

$ON = 63.71 \cos 38.66 = 49.75 \Rightarrow \sigma_\theta = 49.75 + 49.75 = 99.5$

$\sigma_r = \sqrt{(39.8)^2 + (99.5)^2} = 107.16 \ N/mm^2$

$\tan\phi = \dfrac{39.8}{99.5} = 0.4 \Rightarrow \phi = 21.8^\circ$



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Ex. 4

At a point in a material, the max. shear stress is 25 N/mm^2 and the max. principal stress is twice the min. principal stress (both compressive).

(1) Determine the magnitudes of the 2-principal stresses and draw their Mohr's circle.

(2) From Mohr's circle determine the normal stress and the shear stress on a plane making 30° with the plane of max. principal stress

(3) Find the resultant stress and its direction.

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(1) $\tau_{max} = \frac{1}{2}(\sigma_1 - \sigma_2)$, put $\sigma_2 = \sigma$

$\therefore \sigma_1 = 2\sigma$

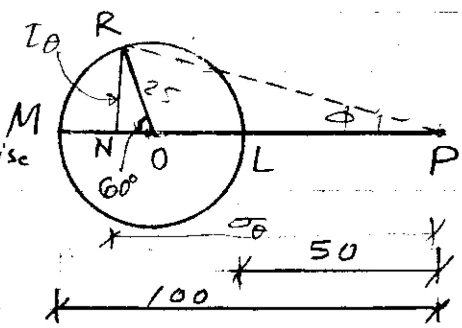
$\tau_{max} = 25 = \frac{1}{2}(2\sigma - \sigma) \Rightarrow \sigma = 50\ N/mm^2$

$\therefore \sigma_1 = 100\ N/mm^2$ & $\sigma_2 = 50\ N/mm^2$

(2) $OR = \frac{100-50}{2} = 25$

$\tau_\theta = RN = 25 \sin 60 = 25 \times \frac{\sqrt{3}}{2}$

$\tau_\theta = 12.5\sqrt{3} = \underline{21.65}\ N/mm^2$ (+ve) clockwise shear stress (above PM)



$\sigma_\theta = ON + OP$

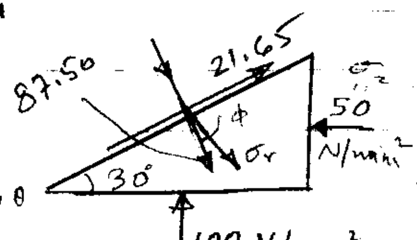
$ON = 25\cos 60 = 25 \times \frac{1}{2} = 12.5\ N/mm^2$

$OP = \frac{\sigma_1 + \sigma_2}{2} = \frac{100+50}{2} = 75.0\ N/mm^2$

$\therefore \sigma_\theta = 12.5 + 75.0 = \underline{87.5}\ N/mm^2$ (comp.) (to left of P)

(3) $\sigma_r = \sqrt{\sigma_\theta^2 + \tau_\theta^2} = \sqrt{(87.5)^2 + (21.65)^2} = 90.14\ N/mm^2$

$\tan\phi = \frac{21.65}{87.5} = 0.2474 \Rightarrow \phi = 13.90°$



Check $\theta = 30°$

From eq.(1) pg(13): $\sigma_\theta = \sigma_y \cos^2\theta + \sigma_x \sin^2\theta + 2\tau_{xy} \sin\theta\cos\theta$

$\sigma_\theta = 100 \times \frac{3}{4} + 50 \times \frac{1}{4} = 75 + 12.5 = 87.5\ N/mm^2$

Eq.(2) $\tau_\theta = \frac{1}{2}(\sigma_y - \sigma_x)\sin 2\theta - \cancel{\tau_{xy}}\cos 2\theta$

$\tau_\theta = \frac{1}{2}(100-50)\sin 60 = \frac{1}{2} \times 50 \times \frac{\sqrt{3}}{2} = 12.5\sqrt{3} = \underline{21.65}\ N/mm^2$

Same as above

~~Ex.5~~

At a point in a material, the maximum shear stress is 30 N/mm^2 and the max. principal stress (tensile) is 3-times the min. principal stress (comp.)

(1) Determine the magnitude of the 2-principal stresses.

(2) Draw Mohr's circle and hence determine the shear stress and the normal stress on a plane making 40° with the plane of max. principal stress and find the resultant and its direction on this plane

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(1) $\tau_{max} = \frac{1}{2}(\sigma_1 - \sigma_2)$, $\sigma_1 = 3\sigma$, $\sigma_2 = -\sigma$

$30 = \frac{1}{2}[3\sigma - (-\sigma)] = 2\sigma \Rightarrow \sigma = 15$ N/mm^2

$\therefore \sigma_1 = 45$ N/mm^2 & $\sigma_2 = -15$ N/mm^2

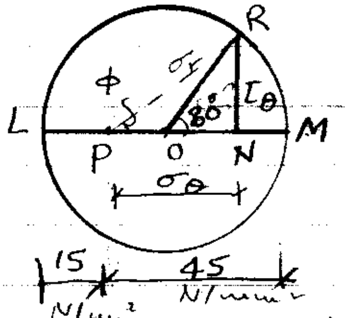
(2) Radius of circle

$= \frac{45+15}{2} = 30$ N/mm^2

Draw OR at $2\theta = 80°$

$OR = \frac{45+15}{2} = 30$ N/mm^2

$\underline{\tau_\theta} = OR \sin 80 = 30 \sin 80 = 29.54$ N/mm^2

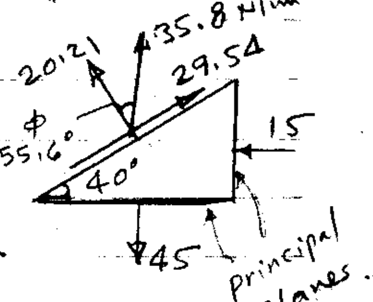


$\sigma_\theta = PO + ON$

$ON = 30 \cos 80° = 5.21$ N/mm^2

$PO = 30 - 15 = 15$ N/mm^2

$\therefore \underline{\sigma_\theta} = 15 + 5.21 = 20.21$ N/mm^2



$\sigma_r = \sqrt{\sigma_\theta^2 + \tau_\theta^2} = \sqrt{(20.21)^2 + (29.54)^2} = \underline{35.8}$ N/mm^2

$\tan\phi = \frac{\tau_\theta}{\sigma_\theta} = \frac{29.54}{20.21} = 1.46 \Rightarrow \phi = 55.6°$

6

Ex. (6)

Direct stresses of $80\ N/mm^2$ ($\sigma_y =$) in tension and $60\ N/mm^2$ ($\sigma_x =$) in compression are applied to an elastic material at a certain point on planes at right angles. The greater principal stress is limited to $100\ N/mm^2$.

(1) What shearing stress may be applied to the given planes?

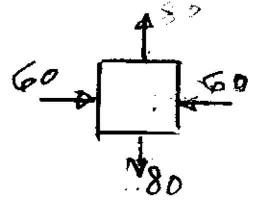
(2) What is the max. shearing stress at that point?

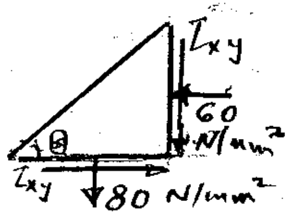
(3) Find the direction of the principal planes.

(4) Draw Mohr's circle for the two principal stresses and hence find σ_θ & τ_θ & also σ_r.

Max principal stress

(1) $\sigma_1 = \frac{1}{2}(\sigma_y+\sigma_x) + \frac{1}{2}\sqrt{(\sigma_y-\sigma_x)^2+4\tau_{xy}^2}$





$100 = \frac{1}{2}(80-60) + \frac{1}{2}\sqrt{(80+60)^2+4\tau_{xy}^2}$

$180 = \sqrt{19600+4\tau_{xy}^2}$

$32400 = 19600 + 4\tau_{xy}^2 \Rightarrow \tau_{xy} = 40\sqrt{2} = 56.57\ N/mm^2$ the reqd. shear stress

(2) $\sigma_2 = \frac{1}{2}(80-60) - \frac{1}{2}\sqrt{19600+12800}$

$= 10 - 90 = -80\ N/mm^2$ comp.

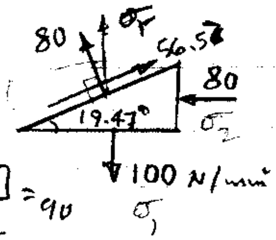
$\tau_{max} = \frac{1}{2}(\sigma_1-\sigma_2) = \frac{1}{2}(100+80) = 90\ N/mm^2$ max shear stress

(3) $\tan 2\theta = \frac{2\tau_{xy}}{\sigma_y-\sigma_x} = \frac{2\times 40\sqrt{2}}{80+60} = 0.808$ (+ve in 1st & 3rd quadrant)

$\therefore 2\theta = 38.94°$ or $(180+38.94 = 218.94°)$

$\therefore \theta = 19.47°$ or $\theta = 109.47°$

direction of principal planes



(4) $OR = OR' = \frac{100+80}{2} = 90$ $\quad OR = \frac{1}{2}[100-(-80)] = 90$

$\therefore RN = \tau_\theta = OR \sin 38.94 = 90\times 0.6285 = 56.56\ N/mm^2$

$ON = 90\cos 38.94 = 70$

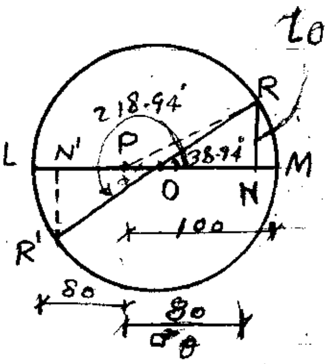
$PO = 100 - 90 = 10$

$PN = \sigma_\theta = PO + ON = 10 + 70 = 80\ N/mm^2$

i.e., $\sigma_\theta = 80\ N/mm^2$, $\tau_\theta = 56.56\ N/mm^2$

$\sigma_r = \sqrt{(80)^2+(56.56)^2} = 97.97\ N/mm^2$

$\simeq 98\ N/mm^2$



$\tan\phi = \frac{\tau_\theta}{\sigma_\theta} = \frac{56.57}{80} = 0.707$

$\phi = 35.26°$

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